A Manual for
Dryland Afforestation and Management

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महानिदेशक
भारतीय वानिकी अनुसंधान एवं शिक्षा परिषद्
डाकघर न्यू फॉरेस्ट, देहरादून
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FOREWORD

FAO has defined 'drylands' based on the length of growing period of 1–59 days in arid, 60-119 days in semi arid and 120-179 days in dry sub-humid regions, whereas according to the UNCCD classification, drylands are characterized by a precipitation to potential evapo-transpiration ratio between 0.05 and 0.65. Drylands cover about 40% of the terrestrial area sustaining about 2.1 billion human population of the world. More than 40% human population of both Africa and Asia; and about 25–30% of the rest of the world's population resides in drylands. About 60-70% area of these drylands are under varying extent of desertification. This is affected by potential changes in the amount of carbon, water and atmospheric gases, losses of soil and vegetation cover, and increased amount of gaseous dust. These all are ultimately going to influence biogeochemistry, solar radiation balances and climatic changes. Preventing land degradation and supporting sustainable development in dry areas has major implications for food security, climate change and human wellbeing. Many countries in dry regions have recognized the crucial economic, social and ecological significance of forest resources and have launched massive forestation programmes both for productive and protective purposes, i.e. increase the production of wood, and non-wood forest products like gums, resins, cork as well as for watershed protection, combating desertification and sand drift, and slope stabilization. However, the success of the reforestation and afforestation in obtaining the desired benefits varies significantly among different regions of drylands.

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Most ecological functions are related closely to economic functions, but many important forest functions have not been assigned any economic value. This is the reason why forests are neglected particularly in dry areas. As a result most of the forests of dry areas are under varying degree of degradation, but there are enormous opportunities of restoring these dry forests. These forests have substantial potential to not only sequester large amount of carbon but also to help in lifting people out of poverty. They also reduce the vulnerability of the rural population and ecosystems through restoration of forests of tropical dry regions. The recent international conventions including COP to the Convention on Biological Diversity held in Nagoya, Japan adopted a target to restore at least 15% of degraded ecosystem by 2020.

The book *"A Manual for Dry land Afforestation and Management"* prepared by Dr. G. Singh, Dr. Bilas Singh, Dr. U.K. Tomar and Smt Shruti Sharma, is an highly valuable guide encompassing practical and research oriented studies from a wide range of drylands, their analysis and presentation in a practicable manner. This book will be an interesting document and useful to beaurocrates, researcher, teachers, forest managers, forest field functionaries and progressive farmers who wish to move forwards in restoring degraded lands and forests irrespective of political boundaries.

This publication will be an important contribution in expanding the knowledge base on drylands restoration with particular emphasis on restoring dryland forests. This can help in increasing green covers, supporting people livelihoods and improving the environmental conditions of dry land ecosystems.

With best wishes,

(Ashwani Kumar)

PREFACE

World's drylands are suffering from the problems of land degradation and desertification as a result of anthropogenic activities and exacerbated by frequent droughts of varying kinds. In most of the cases these degradation processes have been endured by the ecosystems themselves, but predicted changes in climate are likely to worsen the situation in the upcoming years. At present ecological restoration coupled with adaptive management is effective tool in response to the varying environmental and socio-economic problems in dry areas. Although people use to be innovative in their efforts to cope up with the immense challenges of dry areas in general and arid region in particular, but degrading resources and lack of access to the existing technologies leads to partial success of many restoration programmes. Community-oriented water harvesting, promotion and protection of trees in different land uses and conservation of forests including sacred groves are some examples to deal with the climatic adversities of dry regions.

Reforestation and afforestation are traditionally used restoration actions to recuperate degraded (forests) lands for production and to tone down the continuing degradation processes. Increasing tree cover is a big challenge in dry areas particularly in arid and semi-arid regions in view of ongoing desertification and climatic adversities. In some cases restoring barren land generate a lavish forest, but in other cases the impacts are relatively poor. Such variations in output are due to lack of appropriate restoration actions and ineffective utilization of the available scientific and technical informations. There is need therefore for better technical information to promote tree planting and vegetation cover in water deficient soils and manage dry forests judiciously benefiting drylands population. This book has been prepared based on the past and present research literature and field studies carried out by different organizations, research institutions, field level reports and direct observations with the support from the State Forest Department, Rajasthan. This work demonstrates a better way of understanding the degradation processes and developing vegetation cover of drylands.

This book has been covered in 15 chapters. The book initiates with physiographical and climatic characteristics of Rajasthan and the problems associated with it. The other chapters include: understanding the ecology of dry lands; concept of desertification and land degradation; the economic perceptions of land degradation; restoration strategies including site quality and species selection; wind erosion and sand drift control, reclamation and management of salt-affected, waterlogged and effluent inflicted soils; seed quality, nursery management, planting stock improvement; plant production and planting techniques; the relationship between water and forest, water management and plant irrigation; assisted regeneration and seed sowing; forest protection and post planting care; plant growth and biomass production of dry forests; and people participation and dry forest management. This publication has been prepared as a manual. The aims are to provide readers a wide range of knowledge on methods and tools that help enhance tree cover, resilience and people livelihoods and to improve the environmental conditions of the degrading dryland ecosystems for global benefit. We believe this book will be beneficial to forest managers, forest field functionaries, tree growers and the environmentalists in framing their programmes in increasing vegetation cover, quality material and (forest) land production and improving environmental quality. This will be useful to policy makers, academician and researchers equally.

Prof. G. Tripathi, Head, Department of Zoology, JNV University, Jodhpur, Dr. R.P. Dhir (former director CAZRI), Dr. D.C. Joshi and Dr. Satish Lodha, Principal Scientists (Ret), CAZRI, Dr. Praveen Kumar, Head, Division II and Dr. J.C. Tewari, Principal Scientist CAZRI, Jodhpur, Sri, CJSK Emanuel, Scientist F (Ret), AFRI, Dr. Pradeep Chaudhary, Addl PCCF, UT, Itanagar, Arunachal Pradesh, Dr. Kishan Kumar VS, Scientist G, FRI, Dehra Dun, Dr. M.L. Gaur, Principal, College of Agricultural Engineering and Technology, Godhara, Gujarat have reviewed and read the different chapters of this book. Dr Sangeeta Singh, Scientist D and her team have helped in preparing chapter 13. It could not happen without the supports and contribution of varying form from Sh N.K. Vasu, Director, AFRI, Dr. T.S. Rathore, former Director, AFRI, Sri. Rahul Kumar, PCCF (Ret), Dr. S.S. Chaudhari, PCCF, Late Shri A.K. Upadhaya, Addl. PCCF, Rajasthan Forest Department, Jaipur and Sh. A.K. Sinha, Scientist D, AFRI, Jodhpur. Km Priyanka Garhwal, Research Scholar and Smt Kusum Lata Parihar have helped in arranging the texts and computer drawing. We acknowledge all of them for their contribution sincerely.

We hope that this book will help in extending knowledge by promoting tree cover, and conserving and managing tropical dry forest and maintain its ecological and socioeconomical services.

Suggestions and comments from the readers of this book are sincerely invited for future improvements.

Jodhpur

G. Singh
Bilas Singh
U.K. Tomar
Shruti Sharma

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1

BACKGROUND CONTEXT OF RAJASTHAN

History of Rajasthan dates back to pre-historic times. Archaeological excavations establish a relation with the Harappan culture trailing back to 1000 BC. Rajasthan also had Paleolithic settlements indicated by paintings in some areas tracking back to this period. The first Aryan settlement has also been discovered at Dundhmer, now known as Dundhar. The ancient Hindu scriptures like Mahabharata and Ramayana make references to the holy city of Pushkar in Ajmer, Sitamata Sanctuary in Pratapgarh and Ghotiyamba temple in Banswara district in Rajasthan. Known as the "Land of Princes", Rajasthan was ruled by several dynasties, who contributed to the development of the state. Rajasthan fell under the empires of Magadha, Kushanas, Guptas, and Mauryas. Today Rajasthan includes almost the entire Rajputana. It was at the time of Indian independence when the erstwhile Rajput kingdoms and the British provinces were merged to form the state. The present Rajasthan is an integration of Rajasthan in seven stages during 1948-1956 under the State Re-organization Act, 1956 (SRA, 1957).

1. LOCATION

Located in the north-west of India, Rajasthan is the country's largest state. It lies between latitudes 23º3' and 30º12' North and longitudes 69º30' and 78º17' East. Rajasthan is bound on the west and northwest by Pakistan, on the north and northeast by the States of Punjab, Haryana, and Uttar Pradesh, on the east and southeast by the States of Uttar Pradesh and Madhya Pradesh, and on the southwest by the State of Gujarat. The southern part of Rajasthan is about 225 km from the Gulf of Kutch and about 400 km from the Arabian Sea. The Tropic of Cancer passes through its southern tip, i.e. in the Banswara district. Compared to many other countries situated in a similar latitudinal belt like Arabian countries, Rajasthan has a less harsh climate.

2. PHYSIOGRAPHY

Rajasthan is the largest State in India covering an area of 34.2 million ha (i.e., 0.342 million square kilometres) and accounting to 10.4 percent of the total geographical area of India. The main physiographic feature of Rajasthan is the Aravalli Range, which runs across the state from southwest (Mount Abu) with peak height of 1,722 m to Khetri in Jhunjhunu district situated in the northeast running for almost more than

850 km. This range divides Rajasthan into 60% in the North West of the lines and 40% in the southeast. There are four physiographic divisions of Rajasthan.

2.1 Western Sandy Plain

It is covered by Hanumangarh, Sriganganagar, Bikaner, Jaisalmer, Barmer, Jalore, Sirohi, Pali, Jodhpur, Nagaur, Churu, Sikar and Jhunjhunu districts covering an area of about 1, 96,747 sq km spanning in 640 km length and 300 km breadth. It is a wide expanse of windblown sand, poorly watered and sterile. Its western portion is known as Thar Desert which is perfectly dry and habitated with desert plants. Western Sandy Plain further divided into two parts like (i) Sandy Arid Plain; and (ii) Semi-Arid Plain/Bangur Region. The *Sandy Arid Plain* covers about 61% of total area of Western sandy plain with vast expanses of sand and rock outcrops mainly of limestone and are found in Jaisalmer, Barmer, Bikaner, Churu, Hanumangarh and Sriganganagar. This area of Bikaner, Barmer, Jaisalmer, Jodhpur, Nagaur, Churu covering about 120500 sq km is known as '**Marusthali'**, where sand dunes of 6 m to 60 m height are common feature. Longitudinal, Crescent-shaped and Transverse dunes are three types of dunes on the basis of shape, size and wind direction. Other than the Marusthali is **Dune Free Tract** covering about 65 sq km in Bikaner, Jaisalmer, Phalodi and Pokhran area, where Limestone and Sandstone rocks exposes (to lay open) that belong to Jurassic and Eocene formations.

The ***Semi-Arid transition plain*** covers about 7500 sq. km area and is distributed in Jaipur, Jodhpur, Nagaur, Pali, Jalore and Barmer districts. In this, **Luni Basin** comprises Barmer, Jalore, Jodhpur and Nagaur districts covering about 34866.4 sq km area and is drained by the Luni River and its tributaries Bandi, Sagi, Mithri, Sukri, Jawai etc. Topography is marked by hills with steep slopes and extensive alluvial plains locally known as Naid (Rel) and is one of the best alluvial plains. Churu, Sikar, Jhunjhunu and part of Nagaur form the **Shekhawati Region.** Aravalli hills run through this region from south to north, almost dividing it in two parts. Topography of this tract is characterized by an undulating sandy terrain traversed by longitudinal sand dunes. The only river in this region is **Kantli,** which is seasonal in nature. The **Nagaur upland** is observed only in Nagaur district with an average height of 300 m to 500 m from sea level. This region is full of sandy hills and low depressions, where deposits of salt and soda are found because of high temperature and evaporation. The **Ghaggar Plain** is comprised of Hanumangarh and Sriganganagar districts, is without any drainage except Ghaggar Nali which flows through the ancient bed of Ghaggar river for which this region is known as Ghaggar Plain. It is a sandy plain interspersed with sand-dunes and small sand-hills. Sand ridge dunes are found on the bank of ancient rivers that varies from 6 m to 30 m in height. Northern part of this region is fully canalled and thus is made productive.

2.2 Aravalli Range & Hilly Region

This region is distributed in Alwar, Jaipur, Ajmer, Rajsamand, Udaipur, Sirohi and south west part of Tonk districts. Total length is about 692 km running from Palanpur in Banaskantha district of Gujarat to Delhi with an average height of 600 m. The highest peak of Aravalli is Gurushikhar (1722 m) in Mount Abu (Sirohi). In Rajasthan, Aravalli Range starts from Sirohi and end at Khetri in Jhunjhunu district, though discontinuous in nature. Structurally, it is composed of rocks which are originally related to the Delhi System. In south this range opens out to form several ridges. The Aravalli range and hilly tract are divided into four parts. The ***North Eastern Hills*** are distributed in Jaipur, Sikar, Jhunjhunu, Alwar and Sawai Madhopur districts. Average heights of the hills are 300 m to 670 m with highest peak, Raghunathgarh (1055 m), situated in Sikar district. Hill tops are flattered and form small plateau. The valleys between the hills are wide and in some cases stretch for many kilometers. Some of the important lakes in this region are Sambhar, Ramgarh and Pandupole. In the east and north, this region merges with Ganga- Yamuna plain. The ***Central Aravalli Range*** covers Ajmer, Jaipur and South Part of Tonk district extending from Sambhar Lake to the Bhorat Plateau. The characteristics of this region are: (i) a sharp and well defined boundary in west, (ii) eastward followed by a system of two to three parallel ridges rising to an altitude of 600 m; (iii) The edge of Mewar Plateau represented in large sections by a prominent scarp that is often coincident with the shear zone; and (iv) The south east directed transverse drainage. The ***Mewar Rocky Region*** is distributed in Udaipur, Rajsamand, Dungarpur, Sirohi, Bhilwara and Chittorgarh districts and covers an area of 17007 sq km. Average height of this region is about 1225 m. The highest portion of Aravalli range lies between the forts of Kumbhalgarh and Gogunda in the form of plateau locally known as 'Bhorat', which is one of the highest table lands of Aravalli. The ***Abu Block*** covers about 5180 sq km mostly confined in Sirohi district in a stretch of 10 km length and 8 km width. It contains granite and has been separated from the main Aravalli range by the wide valley of the West Banas.

2.3 Eastern Plain region

This region occupies about 23.3% of total area of Rajasthan and distributed in Tonk, Bundi, Amjer, Sawaimadohpur, Bhilwara, Chittorgarh, Kota and Bhatratpur districts covering 23.3% area of Rajasthan. Eastern plain is subdivided into three parts. The ***Chambal Basin*** is situated in Kota, Bundi, Baran, Tonk, Sawaimadhopur, Dholpur district with an area of about 4500 sq km with an average width of about 10 km. Main river is Chambal, which enters from Madhya Pradesh and the tributaries are Kali Sindh and Parbati. The ***Banas Plain*** is distributed in Udaipur, Chittorgarh, Bhilwara, Tonk, Jaipur, Alwar, Sawaimadhopur with an average height of 280 – 500 m and covers about 187400 sq km area. It is essentially a pen plain of Banas divided further into Mewar Plain and Malpura-Karauli Plain. The ***Middle Mahi Plain*** covers an area of 7056 sq km and is lying east of the Mewar hills and south of the Banas plain. Dungarpur and Banswara are the district constituting this region with an average height of 200-400 m. The central and eastern part is known as Chhappan, whereas the dissected plain along with the hill tracts are locally known as `Bagar'.

2.4 South-East Rajasthan Plateau

Locally called Pathar and Uparmal, this region comprises of the eastern and south-eastern part of the state and is known as Hadoti. It is situated in Bhilwara, Bundi, Kota, Baran and Jhalawar districts containing about 9.6% of the area of Rajasthan. East of the plateau has a general slope toward Gwalior and is catchment of river Betwa. This plateau is further sub-divided into two units. The ***Vindhyan Scarplands*** is distributd in Sawaimadhopur, Bundi and Kota districts with an undulating topography strewn with boulders, blocks and depressions with an average height of 350-550 m. Vindhyan Scarps are formed by sandstone and mark the topography in Chambal and Sindh Basins. The ***Deccan Lava Plateau*** is the western parts of the Vindhyan plateau, which lies in the form of three concentric escarpments. These three concentric escarpments are formed by the exposed rocks of three main sandstones.

3. CLIMATE

Average state of the weather determined by observations made over a long period is generally defined as climate, whereas weather refers to short periods. Because of its location in the western part of India and varying topography, Rajasthan exhibits varying climate. The weather pattern in the state can be divided into (i) Pre-monsoon; (ii) Monsoon; (iii) Post-Monsoon; and (iv) Winter. **Pre-monsoon is** summer and the most parched and hot season of the year and precedes the monsoon and extends from April to June. The temperature ranges from 32°C to 45°C. The desert lies in the west and the north west of the Aravali region becomes drier due to the scorching heat of the sun and the highest temperature is recorded sometime about 47-48°C during April/May. The single hill station of the state – the Mount Abu records the lowest temperature. Temperature however falls steeply at night in the arid regions. Heavy winds blow from the south-western boundary and bring dust storms, which are generally known as ‘Andhi’ or ‘Kali-Pili Andhi’. **Monsoon** brings relief to the sultry and sun-baked terrain of this state during the month of June in the eastern region and mid- July in the western arid regions. The temperature drops from 40 to 35 degree. With the fall in temperature, humidity increases. The state receives 80 to 90 per cent rainfall during this period. There is a second phase of monsoon that continues from July to September. **Post-Monsoon** season is followed by the monsoon that commences from mid-September and continues till November. This season is once again characterized by increased air temperature, when average maximum temperature ranges between 33°C and 38°C. The average minimum temperature is between 18°C and 20°C. **Winter** in Rajasthan extends from December to March, and January is the coldest month of the year. Temperature varies throughout the state and the lowest temperature has been recorded even below 0°C especially in the Churu district. There is slight rainfall in the north and north eastern regions of the state. During this period, relative humidity ranges from 50% to 60% in the morning and 25% to 35% during noon time. On the average basis, winter temperature ranges from 8°C to 28°C.

3.1. Temperature

The temperature sometimes falls below the freezing point at Ganganagar and Bikaner. In summer temperature rises above 40ºC, whereas maximum temperature reaches about 50ºC at Marusthali. The mean monthly maximum temperature in May and June is about 45ºC and mean monthly minimum temperature is about 23ºC over a large part of Rajasthan. December and January are the coldest months, the mean monthly temperature being 12.9ºC. Maximum temperature ranges between 43 to 48ºC, while minimum temperature ranges between -2 to 10ºC (Table 1.1). However, there is much variation in temperature indicated by trends in mean temperature of +0.52ºC in Jaisalmer and +0.29ºC in Jodhpur (Weber et al., 2013). Pant and Hingane (1998) observed a decreasing trend in mean annual surface air temperature during 1901 to 1982 over the northwest Indian region consisting of Punjab, Haryana, west Rajasthan, east Rajasthan and west Madhya Pradesh.

Table 1.1 Changes in temperature and rainfall in India including western India.

Region	Study	Temperature	Rainfall
All India	Hingane et al., 1985	Increase in 0.4ºC/100 years in the mean annual temperature	-
All India	Rupakumar et al., 1994	Increase in maximum temperature (0.60ºC/100 years). Minimum temperature trend less. General increase in the diurnal range.	-
All India	Thapliyal and Kulshrestha, 1991		Monsoon rainfall is trendless and is mainly random in nature over a long period
North west India	Pant and Hingane, 1988	Fall in air temperature by -0.52ºC in the past 100 years	Marginal increase in the rainfall by 141 mm in spite of large inter annual variation
Luni River basin, Rajasthan	Singh et al., 2001	Rising trend at Barmer, Jodhpur, Ajmer and Pali and a decreasing trend at Udaipur and Jawai bandh	Increasing tendency at 19 stations in upper and a decreasing trend at remaining 9 stations in lower Luni basin
Luni, Sabarmati/ Mahi river basin	Jain and Kumar, 2012	-	Decrease in rainfall and number of rain-days. But pre-monsoon, post-monsoon and winter rainfall have increased over the years, with maximum increase in the pre-monsoon season
Rajasthan	Kharol et al., 2013		Decrease in eastern Rajasthan and minor increase in western Rajasthan
Thar desert	Poonia and Rao, 2013	Increasement in temperature by +3.3ºC at Bikaner, +3.4ºC at Jaisalmer, +2.9ºC at Jodhpur and +2.5ºC at Pali, if the present rate of warming continues	Annual rainfall during 1960-2011 increased @ 0.56 mm/ year. The increase will be by +100 mm at Bikaner, +124 mm at Jaisalmer, -40 mm at Jodhpur and +21 mm at Pali

3.2 Rainfall

Average rainfall of Rajasthan is 531 mm as compared to 1125 mm for India. It is not only low and erratic but variable also throughout the Rajasthan. Annual rainfall is from 100 mm to 400 mm on eastern edge of Indo-Pak border. Rainfall decreases from East to West and from South West to North East. There is a very rapid and marked decrease in rainfall towards west of the Aravalli range making the western Rajasthan arid. Average annual rainfall in western Rajasthan ranges from less than 100 mm in north-west part of Jaisalmer to 200-300 mm in Ganganagar, Bikaner and Barmer regions, 300-400 mm in Nagaur, Jodhpur, Churu and Jalor regions and more than 400 mm in Sikar, Jhunjhunun and Pali regions and along the western fringes of the Aravalli range. On the eastern side of the Aravalli range, the rainfall ranges from 550 mm in Ajmer to 1020 mm in Jhalawar regions. In plains, Banswara (920 mm) and Jhalawar (950 mm) districts receive the maximum annual rain. Mount Abu in Sirohi district in the south-west, however, receives the highest rainfall in the state i.e. 1638 mm. The yearly total rainfall is highly variable at different places all over the state and it is most erratic in the western half with frequent spells of drought, punctuated occasionally by heavy downpour in some years. The number of rainy days varies widely in different places, ranging from 10 days in Jaisalmer to 40 days in Jhalawar and 48 days in Mount Abu.

Droughts of severe to very severe intensities have occurred in all the districts in approximately 20 years in the past 100 years while moderate droughts were in 10-15 years in the same period. There has been a trend of slight increase in rainfall in western Rajasthan and a decrease in eastern Rajasthan during 1951-2007 (Kharol et al., 2013). Trends in annual rainfall of 1901-1935 vs 1971-2005 indicate a decrease by 14.3% at Jaisalmer but no change in Jodhpur, whereas Jaipur received highest 24-hour rainfall during 1961-1980 in Rajasthan. Jodhpur recorded highest rainfall of 29 cm on August 5, 1996, whereas the annual mean rainfall is about 36 cm (Khaladkar et al., 2009). Extreme northwest region of India, i.e. Thar Desert received a record rainfall of 55 cm during August 16-25, 2006 within 10 days (Jayanthi et al., 2006), when more than 100 persons lost their lives, many animals died and agriculture sector was highly damaged due to the floods in western Rajasthan. During 2003-2012, average rainfall for the state ranged from 385.1 mm in 2009 to 737.4 mm in 2011. It varied widely among the districts also with an average value ranging from 225.8 mm in Jaisalmer to 976.9 mm in Banswara with overall average value of 582.2 mm annually during this period (Fig 1.1).

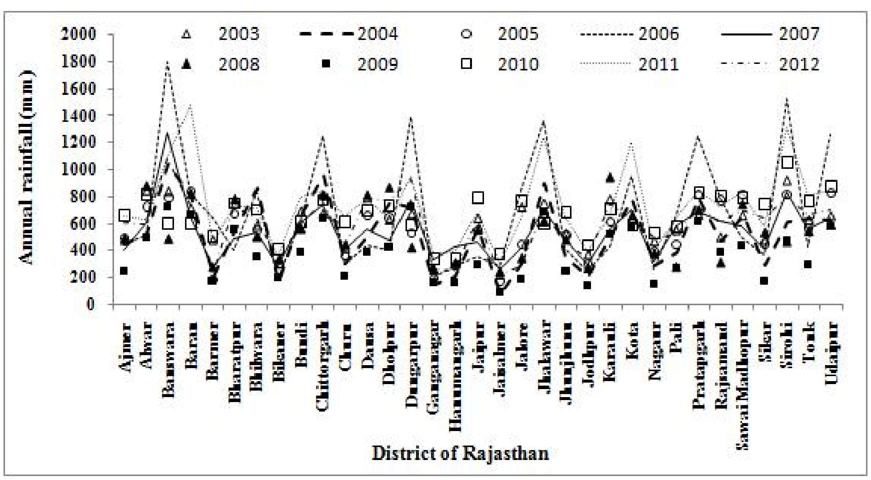


Figure 1.1 Rainfall pattern during 2003-2012 in different districts of Rajasthan.

3.3 Humidity and moisture

The highest mean relative humidity is found in the months from July to September. It varies between 55% to 70% from March and May. It is lowest varying from 30% to 40% in general. The mean cloud formation is highest in July and August, varying from 2 to 6. October is cloud free month. The mean annual potential evapotranspiration (PET) varies from a maximum of more than 2000 mm in northwestern parts to a minimum of under 1301 mm in Banswara and Dungarpur districts. Average annual potential evapotranspiration is 1470 mm and 1400 mm in arid and semi-arid region, respectively as compared to annual rainfall of 320 mm and 780 mm in the respective zone (Mudrakartha, 2010). On an average, maximum PET of 225 mm to 300 mm is obtained during April and May and a minimum of 50 mm to 80 mm in the month of December. In arid regions, chances of increase in PET during monsoon period are by 0.1 to 0.4 mm day^{-1} by 2020, 0.2 to 0.8 mm day^{-1} by 2050, 0.4 to 1.2 mm day^{-1} by 2080 and 0.5 to 1.6 by 2100. By the end of 21st century, the PET requirements during monsoon period will increase by 9 to 20% from the current levels of PET. The projected rise in temperatures will increase winter PET by 0.1 to 0.4 mm/day by 2020, 0.2 to 0.6 mm day-1 by 2050, 0.3 to 0.8 by 2080 and 0.4 to 1.1 mm/ day by 2100 (Mudrakartha, 2010).

3.4 Winds and storms

The wind blows from west and south west during the hot and rainy season with high velocity. Daily average wind speed ranges between 4.58 and 28.62 km hr^{-1} with an average of 13.84 km hr^{-1} at Jaisalmer, though it reaches up to 50-55 km hr^{-1} during dust storms (Santra et al., 2013). However, highest wind speed during onset of a dust storm is approximately 66.1 km hr^{-1} at 1 m height and 83.2 km hr^{-1} at 3 m height. Dust storm arriving over the western Rajasthan is from south to south westerly direction up to monsoon but changes to south east and finally to southerly after withdrawal of dust storm (Singh et al., 1992). On an average Sriganganagar receives 27 dust storms, Bikaner 18, Jodhpur 8, Jaipur 6, Kota 5 and Jhalawar 3 each per year (Pandya and Meena, 2010). Dust storms are more frequent in the arid west and decrease progressively over the semi-arid regions with higher rainfall. Among all the months, June receives the maximum number of dust storms in the northwestern districts, while in the south-eastern areas they occur in May. The number of dust storms decline rapidly after June but in the northwest the storms continue even up to September, though their numbers have declined in recent years. Thunderstorms are more common in eastern Rajasthan than in western Rajasthan. They occur mostly from May to September but more particularly in June and July. There are 40-45 thunder days in a year in Jaipur and Jhalawar districts, 30-35 days in Ajmer and Kota districts, about 25 days in Jodhpur district and about 10 days in Bikaner and Barmer districts. The hailstorms are rare in Rajasthan. Their frequency is maximum in Jaipur area, where it occurs thrice in two years. They are extremely uncommon in the desert areas. Ganganagar for instance, gets only one hailstorm in 10 years, while Bikaner, Barmer and Ajmer get one in about three years.

3.5 Solar radiations

The annual global radiation varies from 1600 to 2200 kWh m^{-2} (kilo watt hour per sq meter), which is comparable with radiation received in the tropical and sub-tropical regions. The highest annual global radiation is received in Rajasthan, northern Gujarat, Tamilnadu and parts of Ladakh region in India (Polo et al., 2011). India has solar power reception of about 5000 trillion kWh/year and 300 clear sunny days in a year. The daily average solar energy incident over India varies from 4 to 7 kWh m^{-2} with about 2,300–3,200 sunshine hours annually, depending upon the location. This is far more than current total energy consumption. The daily average global radiations are around 5 kWh m^{-2} in north - eastern and hilly areas to 7 kWh m^{-2} in the Western regions. Rajasthan has more than 325 sunny days in a year with solar radiation of about 6-7 kWh m^{-2} day^{-1}. Jodhpur, which is known as Sun City of India in Rajasthan, receives maximum solar radiation, where average solar insolation values ranges between 4.11 kWh m^{-2} day^{-1} in December and 5.79 6 kWh m^{-2} day^{-1} year round (Meena et al., 2014).

4. CLIMATIC ZONES

Three systems of climatic classification are usually followed in which **Köppen Climate Classification System** is the most widespread and was developed by German climatologist and botanist Wladimir Köppen (1846-1940), who divided the world's climates into several major categories based upon general temperature profile related to latitude based empirically on observable features. The other systems are genetic and based on the causes of the climate like solar radiation, air masses, pressure systems, etc and are mostly 'applied' in nature (i.e., an outgrowth of a particular climate-associated problem like 'Thornthwaite classification system' based on potential evapotranspiration). Among different index Thornthwaite's Index or aridity index (AI) equals a ratio of mean annual precipitation (R) to mean annual potential evapotranspiration (PET) that defines different regions like (i) Hyperarid (AI<0.05), ii) Arid (0.05> AI < 0.20), (iii) Semi-arid (0.20 < AI <0.50), dry subhumid (0.50 < AI <0.65), humid (0.65 < *I* <0.75) and Perhumid (0.75 < AI <PET) etc. **Moisture index** (MI) is defined as: MI= 100S- 60d / PET, where S is water surplus and d is water deficiency. A region is considered having desert climate if MI is below -60 and this limit on MI generally agrees with Koppen's classification BW for the deserts. Lettau (1969) defines a dryness ratio by comparing Q against heat required to evaporate rainwater as Dryness ratio = Q* / LR, where L is latent heat of vapourization. For the hyper-arid regions dryness ratio > 10, for arid regions it is 7 to 10 and for semi-arid regions it is 2 to 6.

According to Koppen‘s classification, Rajasthan can be divided into four climatic regions (Fig 1.2), each of which shows variable climatic characteristics (Table 1.2). These climatic regions are: (i) Tropical Humid region (AW), (ii) Tropical and Sub-Tropical Steppe- Hot Dry semi-arid hot (Bshw) Climatic region, (iii) Tropical Desert - Dry-arid hot (Bwhw) Climatic region, and (iv) Moist sub-tropical (Cwg) climatic region. This classification emphasizes the vegetation and climatic data, but the influences of surface features, variation in air pressure and the direction of winds have been ignored. This leads to best fitting of this classification for lower plains but are less appropriate for high lands. However, the climate classification concept developed in the first half of the 20th century by Köppen and Geiger still appears to meet the needs of today's climate scientists (Essenwanger, 2001; Kraus, 2004).

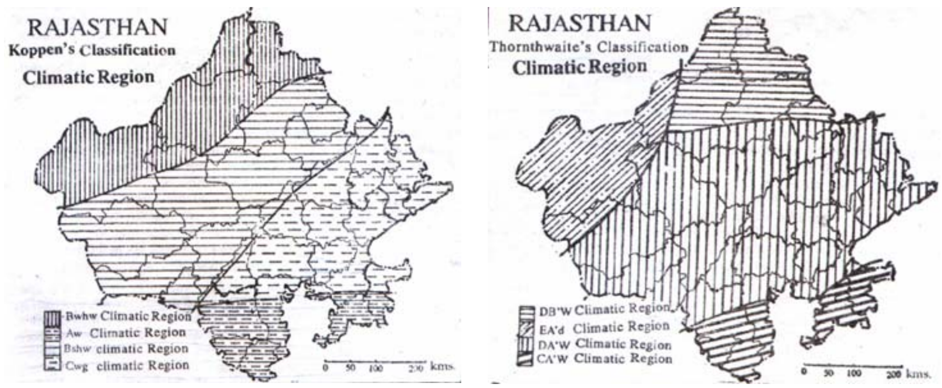


Figure 1.2 Climatic regions according to Koppen (left) and Thornthwaite (right) classification of Rajasthan.

Table 1.2 Classification, climatic condition and distribution of Koppen's climatic region in different districts of Rajasthan

Climatic region	Summers	Winters	Rainfall	Vegetation	Districts
Bwhw (Hot desert type)	Hot scorching heat	Dry	very meager rainfall (<120 mm)	Hot arid-hot desert climate. Thorny shrubs with grasses	West Jodhpur, Jaisalmer, Bikaner, Ganganagar, Hanumangarh and Western parts of Churu
Bshw (Semi-arid Steppe type)	Hot, scorching	Cool Dry	Less amount of rainfall (120-250 mm)	Hot semi arid type and characterized by thorny bushes and grasses	Barmer, Jalore, Jodhpur, Sirohi, Pali, Nagaur, Churu, Sikar, Jhunjhunu
Cwg (Monsoon type with dry winters)	Hot, dry warm and humid summers	Dry mild winters	Rains limited to a few months of summer (dry winter)	Tropical grassland and monsoon type deciduous trees	Northern part of Udaipur, Chittorgarh, Kota and Baran, Rajsamand, Bhilwara, Ajmer, Tonk, Jaipur, Sawai Madopur, Karauli, Dausa, Alwar, Bharatpur, Dholpur
AW (Tropical Savanah type)	Summer is exceedingly hot; tempera-tures in low-lying areas may exceed 50°C	Arid and cool	averages between 750–1,500 mm across the region	Tropical grassland and monsoon type deciduous trees	Southern part of Udaipur, Chittorgarh, Kota, Baran Dungarpur, Banswara, Pratapgarh and Jhalawar

Thornwaite's classification is similar to Koppen‘s classification in the way that it takes into account the amount of rainfall and evaporation as well as seasonal and monthly distribution of temperature and rainfall. Thus, it has become more popular and been accepted widely. According to this Rajasthan can broadly be divided into four regions (Table 1.3) like (i) CA‘w Climatic region, (ii) DA‘w Climatic region, (iii) DB‘w Climatic region, and (iv) Tropical desert climatic region (EA‘d).

Table 1.3 Classification, climatic condition and distribution of climatic region in different districts of Rajasthan according to Thornthwaite's Classification.

Climatic region	Summers	Winters	Rainfall	Vegetation	Districts
CA'w (Dry climate)	Rain occurs during summer	Dry	Relatively better. T/E index is 128 and above but P/E index falls to 32-63.	Savanna and Monsoon type of vegetation. Grass lands	Banswara, Baran, Dungarpur, Jhalawar, Pratapgarh and Kota
DA'w (Tropical semi-arid climate)	Hot, rain occurs during summer	Dry	Rainfall is meager T/E index is 128 or above while P/E index is 16 to 31.	Semi-desertic vegetation	Sirohi, Jalore, Jodhpur, Pali, Ajmer, Chittorgarh, Bundi, Sawai Madhopur, Tonk, Bhilwara, Bharatpur, Jaipur, Dausa, Alwar and Sikar
DB'W (Tropical semi-arid climate)	Long with rains in summer	Short and dry under deficient rain	Rainfall is less. T/E index is 64-127 while P/E index is 16-31.	Thorny bushes and semi-arid vegetation	Ganganagar, Hanumangarh, Churu, Jhunjhunu and Bikaner
EA'd (Extremely hot and dry climate)	Hot and scroaching heat with rain in summer	Cool and dry	Deficient throughout the year. T/E index is over 128 and P/E index remains below 16	Xerophytic vegetation	Barmer, Jaisalmer, South-Western Bikaner.

In a recent classification Raju et al. (2013) has applied Moisture index (MI) = [(P-PE)/PE] × 100 derived from rainfall (P) and potential evaporation (PE) to classify India into different climatic zones. Here P is average annual rainfall and PE is the average annual potential evapo-transpiration. In this Moisture Index (MI) value for arid, semi-arid, Dry sub-humid, Moist sub-humid, Humid and per humid are < –66.7, –66.6 to –33.3, –33.3 to 0, 0 to + 20, +20.1 to + 99.9 and 100 or more, respectively. According to this, Rajasthan is divided into two regions. Arid region covers Jalore, Pali, Barmer, Jodhpur, Jaisalmer, Nagaur, Ajmer, Sikar, Jhunjhunu, Churu, Bikaner, Ganganagar, Hanumangarh, whereas Jaipur, Duasa, Alwar, Bharatpur, Dholpur, Karauli, Sawaimadhopur, Tonk, Bhilwara, Bundi, Sirohi, Kota, Rajsamand, Udaipur, Dungarpur, Banswara, Pratapgarh, Chittorgarh, Jhalawar, Baran districts fall under semi-arid region (Fig 1.3). However, to understand implications and role of climatic and edaphic resources in agricultural and allied sectors, the NBSS & LUP prepared an agro-ecological map, based on the physiography, soils, bioclimate and length of growing period (GP), and refined it through several approximations (Sehgal and Abrol, 1994; ICAR, 2010). Based on this result, India has been broadly grouped into 20 agro-ecological regions or zones (Sehgal et al., 1992). However, considering climatic conditions and prevailing agricultural practices, Rajasthan is further divided into ten agro-climatic zones covering following threes agro-ecological regions (Fig 1.4) namely: (i) Hot arid eco-region with desert and saline soils (M9E1), (ii) Northern Plain (and Central Highlands) including Aravallis, hot semi-arid eco-region (N8D2), and (ii) Hot semi-arid eco-region with medium and deep black soils (I5D2).

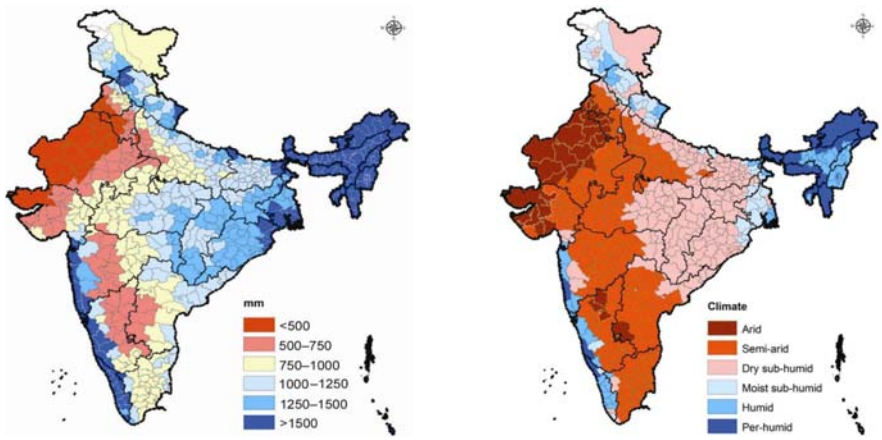


Figure 1.3 Estimated district-level annual rainfalls (mm) for 1971–2005 (left) and corresponding climatic classification (right) according to Raju et al. (2013).

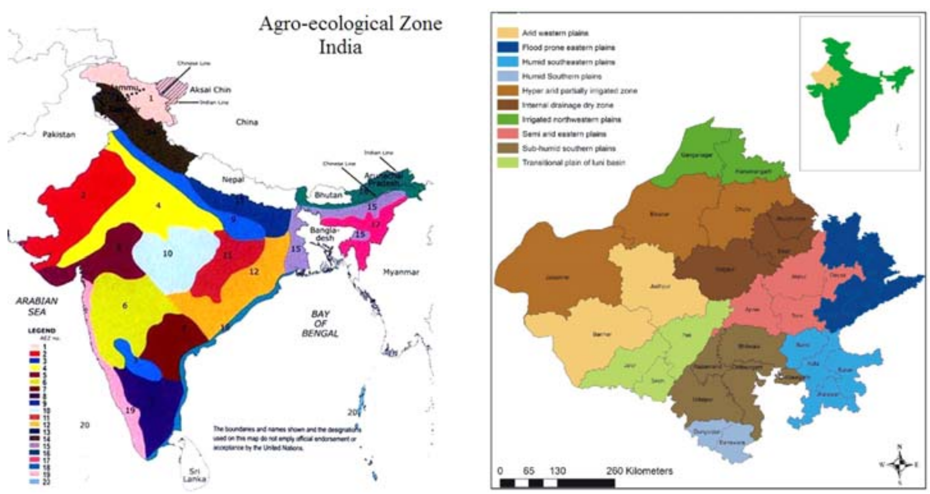


Figure 1.4 Agro-ecological zones of India and agro-climatic zones of Rajasthan. Courtesy: Gajbhiye and Mandal (2013) and SIA (2013).

5. DRAINAGE AND WATER RESOURCE

5.1 Drainage system

The Luni River and its tributaries are the major river systems of Rajasthan in west of the Aravali. It rises near the Pushkar valley of Ajmer district and flows 320 km before emptying southwest into the Greater Rann of Kutch - a wetland in neighboring Gujarat state of India and drains the western slopes of the Aravallis. This river is saline in the lower reaches and remains potable only up to Balotara in Barmer district, before receiving the industrial effluents from Pali, Jodhpur and Balotara industrial area in Rajasthan. Northeast of the Luni basin, in the Shekhawati tract, is an area of internal drainage characterized by salt lakes, some of them are Didwana and Sambhar Salt Lakes. The Ghaggar, a river originating in Haryana, is an intermittent stream that disappears into the sands of the Thar Desert in the northern corner of the state particularly in Hanumangarh district and is seen as a remnant of the primitive Saraswati River. Eastern and southeastern Rajasthan is drained by the Banas and Chambal rivers, the tributaries of river Ganges. The Chambal River is the only large and perennial river in the state that originates from its drainage to the east of this region and flows northeast. Its principal tributary, the Banas, rises in the Aravali near Kumbhalgarh in Rajsamand district and collects all the drainage of the Mewar plateau. Further north is the Banganga, which after rising near Jaipur in Rajasthan, flows east-wards before disappearing.

5.2 Water resource

Rajasthan has only 1.16 percent of country's surface water with very uneven distribution of the resource. Almost 50% of the area of the state, i.e. the western arid area, is outside of any river basin with mere 10% of the total surface water resources. More than 50% of the state’s surface water resource is from inter-state transfers. There are eight major river basins in the state but Chambal and Mahi are the only perennial rivers. The highest per capita water availability of 1,798 m^3 is in the Chambal basin, followed by the Sabarmati (1,729 m^3) and the Mahi (1,120 m^3), whereas the lowest (190 m^3) is in the Banganga basin. There are 203 major and medium tanks and reservoirs in the state, which store about 13.72 billion cubic meters (BCM) of water at their full capacity and a reduced volume of 11.51 BCM during dry years.

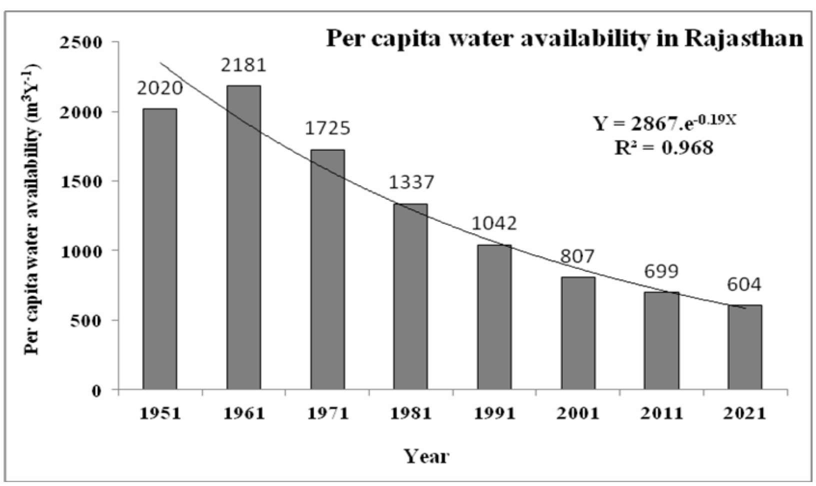


Figure 1.5 Trend of annual per capita water availability in Rajasthan.

In addition, there are large numbers of minor rainwater harvesting structures with a storage capacity of about 2.28 BCM, thus increasing the total storage at full-capacity level to 16 BCM. However, during droughts, the estimated total surface water availability generally reduces to 12.88 BCM resulting in a shortfall of about 3.12 BCM (Narain et al., 2005). The annual per capita water availability was observed highest in 1961 (2181 m^3) that decreased exponentially to 699 m^3 in 2011 and is likely to decrease to 604 m^3 in 2021 and 439 m^3 by the year 2050 indicating a severe water scarcity in the comings years (Fig 1.5).

6. ROCKS AND SOILS

A wide range of rocks and minerals and a large variety of soils occur in the Indian subcontinent (Bhattacharyya et al., 2013). Soil-forming factors like climate, vegetation and topography acting for varying periods on a range of rock formations and parent materials, have given rise to different kinds of soils.

6.1 Rocks in Rajasthan

In Rajasthan, the Aeolian deposits belong to Pleistocene and recent times. The dune-free areas of Barmer, Bikaner and Jaisalmer contain exposed marine deposits of Jurassic and Eocene periods, showing an anamoly in the nature of rock deposits of the region. Besides, the Vindhyan system crops out around Jodhpur, where there are small patches of Malani volcanic and granite rocks formations. The alluvium, covering a part of the eastern plain, south-eastern plain and flood plain, belongs to the recent and sub-recent periods. The ravines flanking the river Chambal and its tributaries are of recent origin. The entire rock system of the state belongs to Palaeozoic, Proterozoic and Archaen era. The Aravalli system is largely composed of argillaceous deposits, metamorphosed to mica schists, which crop out around Alwar, Udaipur, Ajmer and their surroundings. The Deccan trap covers south-eastern part of the state forming Malwa plateau of the state.

The Aravallis, one of the most ancient mountains in the world, have the oldest granitic and gneissic rocks at their base, overlain by the rocks of the Aravalli Super group, Delhi Super group, the Vindhyan Super group and younger rocks. These rocks are highly metamorphosed at certain places and show rich occurrences of minerals of great commercial importance. The central part of the Aravalli ranges is occupied by a great synlinorium composed of Aravalli and Delhi rocks. Because of the thin layer of sand deposited in the region, the rocks are often engulfed in sandy alluvium and desert sands. The **Aravalli super group** is composed of basal quartzites, shales, conglomerates, composite gneisses and slates. The Delhi Super group overlies the Aravallies and is divided into lower Ralio group, middle Alwar group and upper Ajabgarh group. Ralio group is rich in crystalline limestones, grits, schistose rocks and quartzites. The marble of Makrana in Nagaur district belongs to this group. Alwar group and Ajabgarh group consist of mostly calc-silicates, quartzites, grits and schistose rocks. Other important lithological formations consist of a thick series of sedimentary rocks comprising sandstone, limestone and shales classified as upper and lower Vindhyans in the east and Marwar in the west. The deposition of these rocks in western Rajasthan was preceded by igneous activity, which included a thick pile of lava, mostly of an acidic nature. The plutonic equivalents of this lava are seen in the form of granite bosses and sills in Jalore, Siwana and Mokalsar in Barmer and Jodhpur areas. Rocks of the above mentioned igneous activity have been designated as Erinpura granite and Malani igneous costume.

There was an encroachment of sea from the south-western direction into western Rajasthan during the Jurassic period, which is noticeable around Jaisalmer, where some fossils of this age are found in these rocks. The outcrops of these rocks are, partly, covered by wind-blown sands. Of special interest are the Bap (Jodhpur district) and Pokran (Jaisalmer district) beds of upper Carboniferous age, which have now been exploited for ground water. They are composed of boulders of Malani rhyolites showing the effects of glaciations. The Deccan traps are found in southern and south-eastern Rajasthan extending over a vast area in southern Jhalawar and in the eastern parts of Chittorgarh and Banswara districts. The south-eastern area is higher in elevation (100 to 350 m above sea level) and more fertile with much diversified topography. In the south lies the hilly tract of Mewar of Rajasthan, in the southeast a large area of the districts of Kota and Bundi forms a tableland, and to the northeast of these districts is a rugged region (badlands), following the line of the Chambal River. Further north the country levels out; the flat plains of the northeastern Bharatpur district are part of the alluvial basin of the Yamuna River.

6.2 Soil in Rajasthan

The National Bureau of Soil Survey and Land Use Planning (NBSS&LUP), Nagpur has developed a database on soils with field and laboratory studies over the last 30 years. The soil texture is determined by the size of constituent particles which have been named differently by the international society of soil science. These particles are gravel (>2.00 mm), coarse sand (2.00 mm to 0.2 mm), fine sand (0.2 mm to 0.02 mm), silt (0.02 mm to 0.002 mm) and clay (<0.002 mm). **Sandy soils** mainly consist of sand particles. These soils are loose dry and poor in nutrients. The water holding capacity of such soils are poor. **Clay soils** are mainly of clay particles, which are of colloidal dimensions. They have high plasticity and possess high water holding capacity. Clay particles have very small interspaces between them. On getting water these soils become water logged and in such circumstance are not suitable for plant growth. The **loam soils** have sand, silt and clay particles in more or less equal proportions. Such soils are the most suitable for plant growth. **Sandy loam** soils are those soils in which sand particles predominate, whereas Clay loam soils have a predominance of clay particles. Both sandy and clay loam soils are suitable for plant growth. Silt loam soil predominant in silt, but on getting water, silt loam becomes water logged with poor air circulation.

The western zone of India consists of three states covering about 16.5% area of the country. Number of soil families indicates greater variation in soils in Gujarat followed by Rajasthan (Table 1.4). Aridisols type soil dominates in Rajasthan. Interestingly, these states have Alfisols and Ultisols, the formation of which are not permitted in the present-day climate in Gujarat and Rajasthan. The soils indicate a change of climate from wetter to dry regime (Bhattacharyya et al., 2013). Rajasthan soils have been classified into 5 orders, 8 suborders, 16 great groups and 32 subgroups. The Entisols cover about 36% area, followed by Inceptisols, Aridisols, Vertisols and Alfisols with 23%, 20%, 2% and <1% of total area of Rajasthan

(Shyampura and Sehgal, 1995). The soil mapping unit rock outcrops and active dunes together cover 99.7% of total geographical area (TGA), and salt flats, water-bodies and habitation constitute only 0.3%. Physiographic regions together with source rock variability are significant factors in governing distribution of soils. Eastern plain derived from schists and gneisses are dominated by Haplustalfs. Chappan plain derived from schists and shales has Ustochrepts and Chromusterts. Hadoti plateau formed from the alluvium of Deccan basalts and Vindhyan shales has Chromusterts, Ustochrepts and Ustifiuvents. In western part parent material is important but climate is the dominant factor in highly restricted profile development (Sharma et al., 2010).

Table 1.4 Different categories ($x10^3$ ha) of soil taxonomy in soil resource mapping of states on north western India. (Sources: Bhattachryya et al., 2013).

State	TGA	Soil order						
		No.	Vertisol	Entisols	Aridisols	Alfisols	Inceptisols	Others
Rajasthan	34224	5	989	13799	8287	251	8317	2580
Gujarat	19607	5	1877	2529	2027	101	10135	2933

According to the old classification, soils of Rajasthan are classified into eight soil groups like: (i) Desert/sandy, (ii) Dunes and associated soils, (iii) Brown soils, (iv) Sierozems soils, (v) Red loams, (vi) Hill soils, (vii) Saline sodic soils, and (viii) Alluvial soils and black soils.

Desert soils occur in Nagaur, Jodhpur, Jalore, Barmer, Hanumangarh, Sriganga-nagar, Churu, Jhunjhunu and Sikar districts having less than 400 mm rainfall and are sandy to sandy loam in texture. In general it contains a high percentage of soluble salt and has high pH value. It has varying percentage of calcium carbonate and generally poor in organic matter. These soils are pale brown, single grained, deep and well drained. Calcium carbonates sometime occur in form of Kankar nodules which increases with depth. In most of the desert soils, nitrogen is low (0.02% to 0.07%).

Dunes and associated soils occur in Barmer, Bikaner, Jaisalmer, Jaipur, Jodhpur and Churu districts and are loamy fine sand to coarse sand in texture, but may or may not be calcareous. These soils are yellowish brown in colour, sandy to sandy loam, deep and well drained. Sometimes calcium carbonate occurs in the form of Kankar nodules which increases with depth. These have been grouped separately from desert soils as they are only deposited in sand and little profile development has taken place. Dunes are of varying heights from low shifting dunes to high and very high stabilized dunes.

Brown soils have been observed in Tonk, Bundi, Sawai Madhopur, Bhilwara, Udaipur and Chittorgarh districts where annual rainfall is 500 mm to 750 mm. It is sandy loam to clay loam in texture. The colour of soil ranges from grayish brown to yellow brown. Major area of this soil is in the catchment area of Banas River. They are rich in calcium salt but have poor organic matter.

Sierozems occur in Pali, Nagaur, Ajmer, Jaipur, Dausa (lie on both sides of Aravalli Hills) having annual rainfall of 500 mm to 700 mm and sandy loam to sandy clay in texture. These soils are mostly yellowish brown in colour. Natural vegetation is also seen at some places. The soils are suitable for cultivation.

Red Loams soils are common in Dungarpur, Banswara and parts of Udaipur, Chittorgarh having rainfall 700 mm to 1000 mm and are sandy loam to sandy in texture. These soils are reddish in colour with granular/crumb structure and are well drained. These soils have rich content of iron-oxide and devoid of calcium salts because calcium salts are soluble in water and are easily washed away. Parent material of these soils is the red sandstone or yellow sandstone which is found in Vindyan rocks.

Hill Soils (Lithosols) are common in the foot hills of Aravalli in Sirohi, Pali, Nagaur, Udaipur, Rajsamand, Chittorgarh, Bhilwara and Ajmer districts and are reddish to yellowish red and yellowish brown in colour. Texture is sandy loam to clay. This soil is well drained but shallow in nature.

Saline sodic soils (Solonchaks) are common in the natural depressions like the Pachpadra, Sambhar, Deedwana and Ranns of Jalore and Barmer. Saline Sodic soils are seen in the far flood plains of river Ghaggar and also in Luni Basin. This type of soil is dark grey to pale brown in colour.

Alluvial soil/and black soils occur in the districts Kota, Bundi, Baran and Jaipur. In Sriganganagar district, the soil is alluvium deposited by Ghaggar river.

6.3 Soil fertility and status

Soils of Rajasthan are largely deficient in nitrogen (N), while phosphorus (P) is low to medium in nature but adequate in potassium (K). Salinity and alkalinity are present to some extent in all the zones with wide variation in proportion of problematic soils under salinity or alkalinity. As a percentage of total net sown area in a zone, semi-arid eastern plain is nearly 18% of its soils classified as problematic. Overall nearly 6% of the total net sown area of Rajasthan can be categorized as problematic (Table 1.5).

Table 1.5 Fertility status and problematic soils in different agro-climatic zones of Rajasthan (Source: SIA, 2012-13)

SNo.	Agro-climatic Zones	Fertility status			Problematic soils (ha)		
		N	P	K	% Soil saline	% soil Alkaline	Total soil (ha)
1	IA-Arid Western plain	VL	M	M	-	-	-
2	IB-Irrigated North Western plain	VL	M	M	20.13	79.87	14418
3	IC-Hyper-arid partly Irrigated Zone	L	M	M	70.83	29.17	39831
4	IIA-Internal Drainage Dry Zone	VL	M	M	48.95	51.05	28877
5	IIB-Transitional Plain of Luni Basin	L	M	M	48.70	51.30	133153
6	IIIA-Semi arid Eastern Plain	L	M	H	32.81	67.19	134672
7	IIIB-Flood Prone Eastern Plain	L	M	H	37.01	62.99	305340
8	IVA-Sub humid Southern Plain	L	M	M	27.87	72.13	263684
9	IVB-Humid Southern	L	M	H	64.11	35.89	86710
10	V-Humid Southern Eastern Plain	L	M	H	40.50	59.50	26137
	State	M	M	H	49.71	50.29	34949

Note: L = Low, VL = Very Low, M = Medium, H = High

7. LAND USE PATTERN

Land use pattern determines the ecological balance in the region. Land use classification based on different uses indicates that a little more than half of total land mass is used for agriculture (Table 1.6). In Rajasthan, it includes 16.97 million ha net sown area under cultivation and 4.10 million ha for non-agricultural uses. Another 2.74 million ha area is under forest, which is 7.98% of the total geographical area of Rajasthan (SIA, 2013).

Table 1.6 Changes in land use pattern (in lakhs ha) in Rajasthan during 1990-90 to 2011-12.

Use type	Year						%
	1990-91	2001-02	2005-06	2009-10	2010-11	2011-12	change-2012-2002)
Geographical area	342.50	342.24	342.24	342.24	342.24	342.70	0.06
Forest	23.5	26.45	26.75	27.35	27.43	27.35	16.38
Area under non-agricultural uses	14.9	17.52	18.23	19.76	18.89	18.88	26.71
Barren & unculturable land	27.9	25.21	24.39	22.92	23.79	23.80	-14.70
Permanent pastures & other grazing lands	19.1	16.99	17.08	16.97	16.94	16.97	-11.15
Land under misc. trees and groves	0.2	0.13	0.21	0.17	0.21	0.17	-15.00
Culturable waste land	55.7	47.31	45.90	44.75	42.33	44.75	-19.66
Fallow lands other than current fallows	19.3	23.21	22.64	20.48	17.26	20.48	6.11
Current fallows	18.1	18.19	19.10	20.55	12.35	20.55	13.54
Net area Sown	163.8	167.65	168.36	169.74	183.49	169.74	3.63
Net irrigated area	39.04	-		58.5			0.06

Source: GoI (2011-12; http://data.gov.in/dataset-export-tool?nid=5914).

7.1 Area under non-agriculture uses

This category belongs to the land put to non-agriculture uses such as residential, roads/paths, water bodies etc. The share of such land use is only about 5 percent of the total reporting areas. Across the zones, this proportion varies from 3 percent to 8 percent.

7.2 Barren and un-culturable Land

About 7 percent of the reporting area is barren and uncultural waste land and is considered non-suitable for agriculture operation and cannot be developed for vegetation cover, i.e. rocky or snow area. Across the zones like semi-arid eastern plain, sub humid southern plain and humid southern, this varies between 10 and 20 percent of the reporting area. In irrigated North Western Plain, this category of land is less than 1 percent. In other zones it varies from 3 to 6 percent.

7.3 Grazing lands/permanent pastures

This is one of the most important categories of land use. The availability of permanent pasture and grazing land determines the status of livestock economy in the region. It constitutes about 5 percent of the reporting area in Rajasthan. In irrigated North Western Plain, the grazing land is also found negligible. The sub humid Southern Plain is endowed with pastures and grazing lands in one-tenth of the reporting area. Largely, it constitutes about 4 to 7 percent across the zones. According to Board of Revenue (Land Records), Government of Rajasthan (2008-09), the area under grazing land is highest in Barmer (202462 ha) and lowest in Ganganagar (140 h) districts (Fig 1.6).

7.4 Land under miscellaneous tree crops and groves

Area under fruit crop falls under this category of land use. In Rajasthan, the area under fruit crops is also negligible, i.e. less than one percent. Among the districts, it ranges between almost zero in Rajsamand to 4733 ha in Ganganagar (Fig 1.6). This indicates that in certain regions, area under fruit crop is absolutely missing.

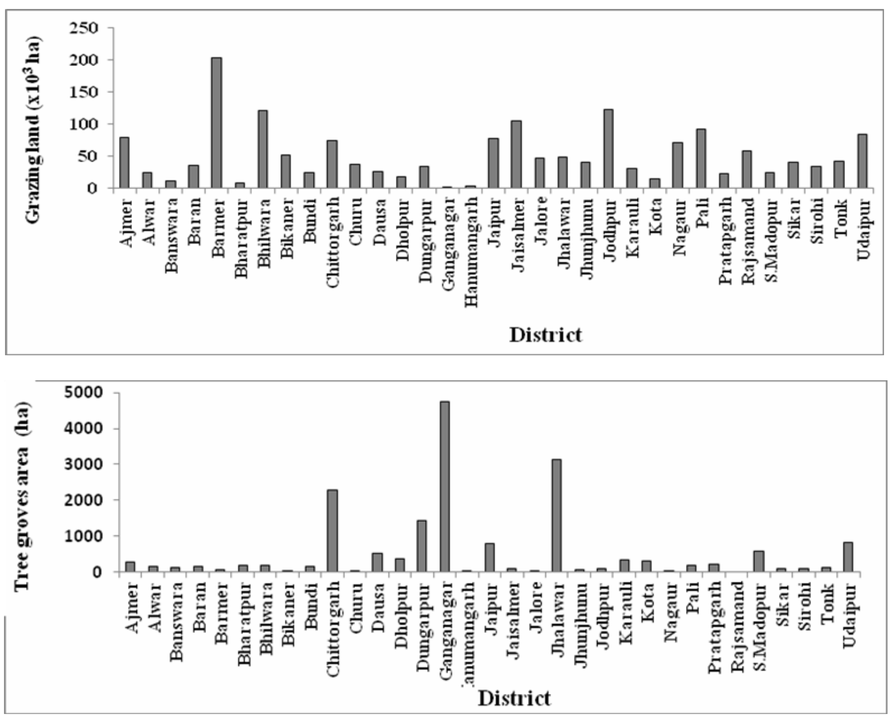


Figure 1.6 Distribution of grazing lands and land under miscellaneous trees and groves in different districts of Rajasthan

7.5 Culturable Waste Land

This is also one of the major categories of land use, where agriculture operations are possible. It constitutes a substantial proportion of the reporting area of Rajasthan, i.e.

about 13%. In Hyper -arid partial Irrigated Zone, land under culturable waste is about 40% followed by sub humid southern and Irrigated North Western Plain zones with 15% and 12%, respectively. In rest of the agro-climatic zones, it varies from 2 to 8 percent.

7.6 Fallow land

There are two types of fallow lands viz. current fallow and long fallow. The land is treated as current fallow when the farmer suspends agriculture operation for one to five years. After five year suspension of agriculture operation it is treated as long fallow. At the state level estimates, there is no considerable variation in the proportionate terms as in case of both types of fallows, i.e. 6 and 5%. In irrigated north western plain, there is considerable proportion of land under current fallow. In other zones there is slight difference in these categories of land uses.

7.7 Agricultural land

The most important category of land use pattern is agriculture land under net area sown. About half of the total reported area is under agriculture operation. The irrigated northern-western region and internal drainage dry zones are leading ahead as compared to other agro-climatic zones. The other regions like –Transitional Plain of Luni Basin, Semi-arid Eastern Plain, Flood Prone Eastern Plain regions have nearly half or more than half area under agriculture production. There are only three zones, Hyper-arid partial Irrigated Zone, Sub humid Southern Plain and Humid Southern zone, having limited proportion of land, i.e. more than one-fourth to more than one-third available for agriculture production, but this proportion is on an increase. Among all the districts, highest percent of area under this land use is in Hanumangarh (85.4%) followed by Churu (84.5%), whereas the lowest area is in Jaisalmer, i.e. 16.1 (Fig 1.7).

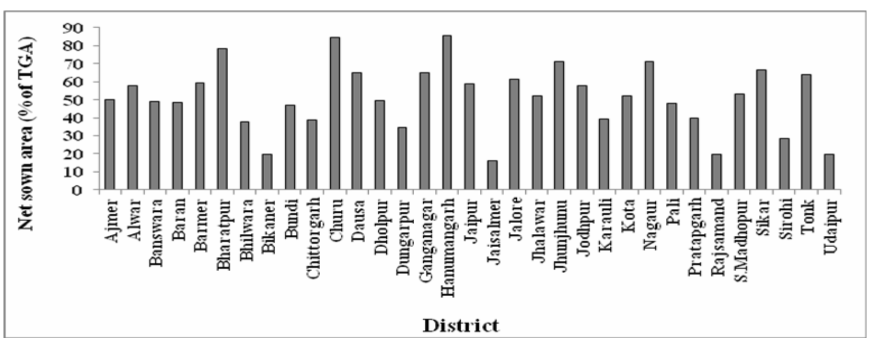


Figure 1.7 Percent net sown area in different districts of Rajasthan.

The main Kharif crops are bajra, jowar, pulses, maize and groundnut. However, the Rabi crops include wheat, gram, pulses and oilseeds, mainly mustard and rapeseed. Food grains account for almost two-third of the cultivated area and dominate in the cropping pattern. In some areas of south Rajasthan like Banswara, Udaipur and Dungarpur, which have rich black cotton soils, cotton is being grown also. Food grains production in 2012-13 was 18.03 million tons as compared to 19.47

million tons in 2011-12 at an average yield of 1482 kg per ha and 1348 kg per ha in the respective year. Average annual production is around 13 million tons of food grains and 4.4 million tons of oilseeds. Despite about 27% contribution of agriculture sector in the state's domestic product, farmers are unable to get minimum support price because of monopolistic behaviour of the informal buyers/ traders who purchase the agriculture production at the lower price as compared to prevailing market price (GoR, 2012a).

7.7.1 Irrigated area: Average irrigated area in Rajasthan is about 26.4% of the net cropped area against India average of 48.3% indicating significant increase in the area under irrigation. A significant change has also been observed in cropping pattern under Indira Gandhi Canal Irrigation in arid western Rajasthan (Pandya et al., 2004). Net irrigated area has increased from 17.52 lakh ha in 1960-61 to 58.5 lakh ha in 2009-10 (Sharma, 2013). Groundwater in Rajasthan is overexploited in many districts, whereas the irrigated area in most of the districts (except in Jodhpur) is higher than the state average irrigated area. There is an increasing trend in irrigated area in all the districts with Jaipur and Alwar indicating a sharp increase (SIA, 2012-13). Main source of irrigation is well/tube well in most of the agro-climatic zones, where it ranges between 11.48% in Arid Western region and 76.63% in Flood Prone Eastern Plain. However, in Irrigated North Western plain the main source of irrigation is canal, i.e. Indian Gandhi Canal (Table 1.7). Jodhpur has recorded an increase in area under irrigation, while Bundi has shown a fall in irrigated area. There is an increase in cropped area by 54 to 60% at present as compared to 4 to 15% during 1951-2007 periods in western Rajasthan (Kharol et al., 2013). Jaipur and Alwar district are largely irrigated by groundwater. This indicates that increase in irrigated area is at the cost of increased overexploitation of groundwater, which has already been depleted (EAMF, 2012).

Table 1.7 Net irrigated area under different sources of irrigation in different agro-climatic zones of Rajasthan.

Agro-climatic Zones	Irrigated area (%) by source				Irrigated area ($x10^3$ ha)	Sown area ($x10^3$ ha)	% Irrigated area to sown area
	Canal	Tank	Wells	Others			
IA-Arid Western plain	0.0	0.0	99.1	0.9	334	2908	11.48
IB-Irrigated North Western plain	98.4	0.0	1.6	0.0	925	1544	49.91
IC-Hyper-arid partly Irrigated Zone	46.2	0.0	53.8	0.0	429	3002	14.30
IIA-Internal Drainage Dry Zone	0.0	0.0	100.0	0.0	741	2217	33.41
IIB-Transitional Plain of Luni Basin	4.7	12.2	83.0	0.1	518	1459	35.51
IIIA-Semi arid Eastern Plain	10.1	0.7	87.2	1.9	729	1731	42.11
IIIB-Flood Prone Eastern Plain	1.4	0.0	96.9	1.7	1139	1486	76.63
IVA-Sub humid Southern Plain	4.0	7.2	87.9	0.9	458	935	48.97
IVB-Humid Southern	21.6	5.7	40.9	6.8	250	635	39.41
V-Humid Southern Eastern Plain	40.6	1.2	79.8	3.4	7366	18275	40.30

7.8 Forest coverage

Forests are an important part of any ecosystem and contribute by not only providing humans with food, fodder and fuel but also by enriching and aiding the nutrient cycle in the ecosystem. As nearly 11 districts of western Rajasthan are under desert ecosystem. Rajasthan has a very sparse forest cover as compared to other Indian states. About 38% of forests are reserved forests where no human activity is permitted, while 56% are categorized as protected forests within which rights holders are entitled to exercise their rights to meet the demand for major and minor forest produce. Unclassified forest area constitutes about 6 percent of the total forest cover. In these types, there appear significant decreases (showing quadratic relationship with slight increase in latter periods) in total forest area at the rate of 125.95 ha per year during 1961-62 to 2013-14. The decrease is even higher in unclassified forest area, i.e., 175.91 ha per year. Corresponding increase in reserved forests and protected forests areas is 36.40 ha per year and 13.36 ha per year during the same period (Fig 1.8).

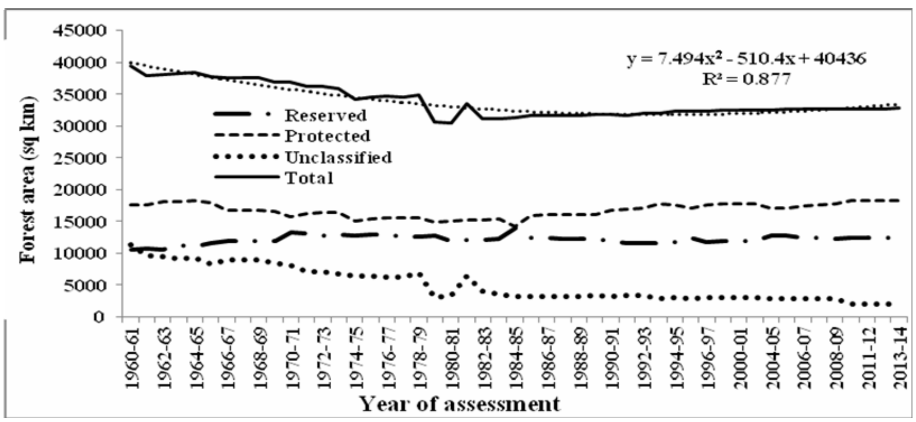


Figure 1.8 Changes in area under different category of forests viz. reserve forests, protected forests and unclassified forests.

Among different districts, highest area is in Udaipur (4.14 lakhs ha) and lowest area is in Churu (7122 ha) district (Fig 1.8 upper). In different agro-climatic zones, the arid western zone has negligible area under forest cover, whereas in Hyper-arid partial irrigated, Irrigated North Western Plain and Internal Drainage Dry area, have about 2 to 4 percent of the total reporting area under forest. There are only two zones namely, the Humid Southern and the Humid Southern Eastern Plain, which are endowed with one-fourth of the total reporting area under forests. In rest of the zones it varies from 6 to 15 percent. Although the recorded forest area of the state is 9.54 percent of the total geographical area, the satellite based data of FSI (2013), the forest cover of the state is only 4.7 percent of the total geographical area (against the India's value of 21.23%) indicating a decrease in medium density forest cover by 24 km^2 and an increase in open forest cover by 23 km^2 with a net decrease by 1 km^2 as compared to the data in 2011 and tree cover only 2.42 percent.

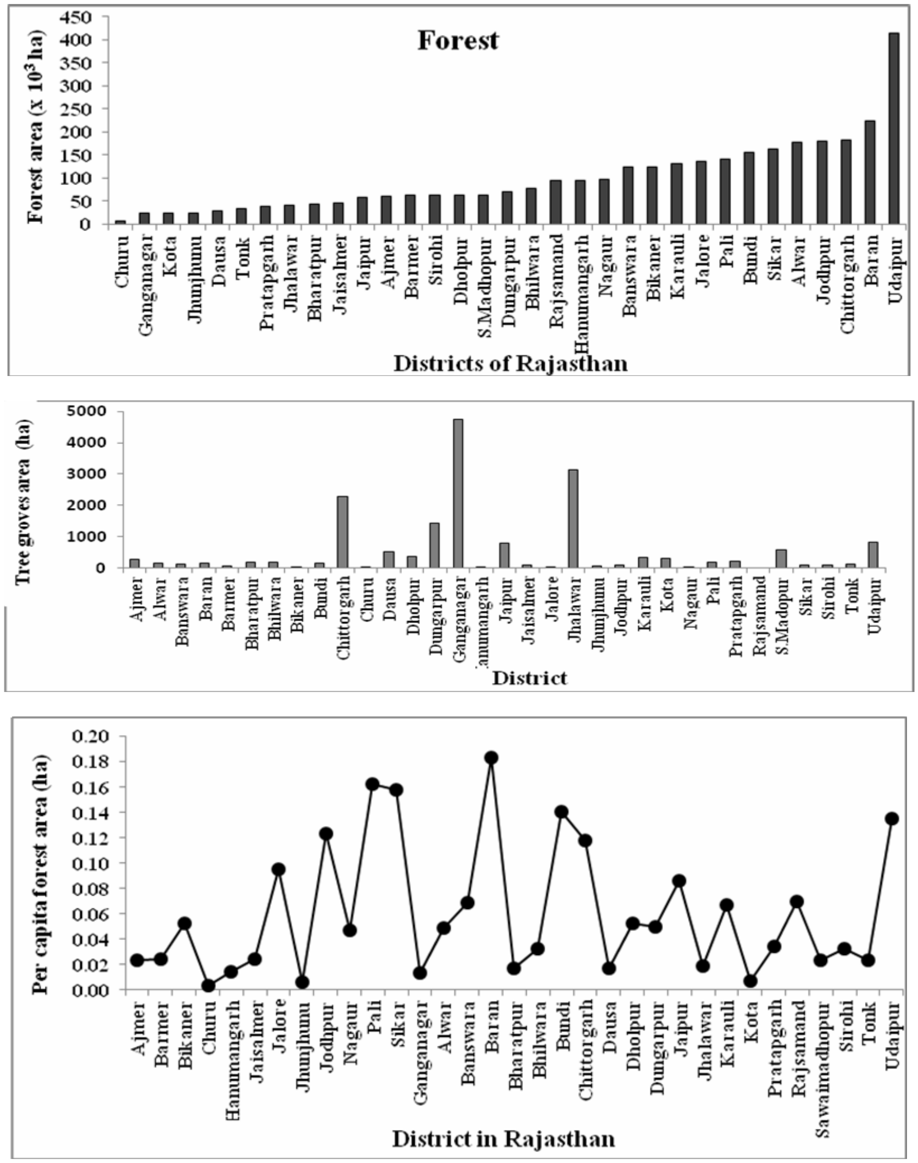


Figure 1.9 Distribution of forest area in different districts and per capita availability of forest area in different districts of Rajasthan.

These forests are unevenly distributed in the various districts. Most of the forests are over the hilly areas, i.e. in Udaipur, Rajasamand, Kota, Baran, Sawai Madhopur, Chittorgarh, Sirohi, Bundi, Alwar, Jhalawar and Banswara districts, which make up for about 50 per cent of the forests of the state. Dense natural forests are in protected patches, mostly confined to various national parks and wild-life sanctuaries. Remaining forests of state are in various stages of plant growth. Rajasthan have mainly Tropical Dry Deciduous and Tropical Thorn Forests. These are dominated mostly by dry teak forests, *Anogeissus pendula* forest, mixed deciduous forests (RFS, 2013), which are further divided in almost 31 sub types of forests including plantation and *Prosopis juliflora* (Singh, 2014b). The Aravalli Hills of Rajasthan are covered with mostly deciduous forest, which turns lush green during monsoon period. Mt. Abu area of Sirohi district has semievergreen forest owing to its towering height and relatively high rainfall in Rajasthan. The increase in human population results in per capita forest area reduction. As per the census 2011, per capita forest availability (ha) ranges from <0.01 ha in Churu to 0.18 ha in Baran district (Fig 1.9). This indicates a decreasing trend in per capita availability of forest with increased pressures on this resource.

8. SOCIO-ECONOMY

8.1 Human population

According to population census 2011, the population of Rajasthan is 68.62 million with a density of 201 persons km^{-2}. It is well below the national average of 324 person km^{-2}. Rajasthan is still the eighth-most populous state in India and constitutes 5.67% of the total population. Population density ranges between 7 persons km^{-2} in Jaisalmer to 595 persons km^{-2} in Jaipur. In this the contribution of rural and urban population are 75.04% and 24.96%, respectively. Out of the total population of Rajasthan, nearly 30 percent belongs to the vulnerable communities- Scheduled Castes comprising 19.2 percent and Scheduled Tribes 13 percent of the total population. Decadal growth is 21.4% during 2001-2011. However, population growth was observed higher in tribal and desert area. Among all the districts, the highest decadal growth is in Barmer followed by Jaisalmer, whereas it is lowest in Ganganagar followed by Pali district (Fig 1.10).

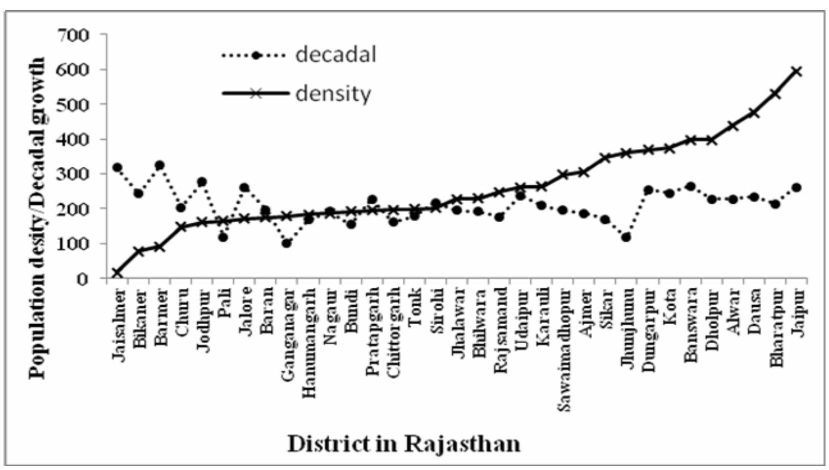


Figure 1.10 Human population density (number per s. km) and decadal growth (number per thousand) in Rajasthan

The decadal rate of urban population was observed higher (29.7%) as compared to rural population (18.9%) in 2001-2011 periods. In arid (including Ajmer now) and semiarid regions, the population densities in the respective region are 139.7 persons km^{-2} and 305.7 persons km^{-2} according to census 2011 (GoI, 2011a).

8.2 Livestock population

Rajasthan is the second largest in livestock population amongst Indian states and contributes about 10 percent of the country's milk and 30 percent of mutton production (GoR, 2012b). Livestock population in Rajasthan comprises large and small ruminants. Cow and buffaloes are the main large animals, while sheep and goats are the major small ruminants. According to estimates of Livestock Census of 2012, the share of cattle population is about 23 percent and buffaloes constitute about 22.5 percent of the total livestock population. During 1951 to 2012 the share of cattle, sheep and camel in the total livestock population declined from about 42.3 percent, 26.1 percent and 1.4 percent to 23.1 percent, 15.7 percent and 0.56 percent in 2012, respectively (Fig 1.11).

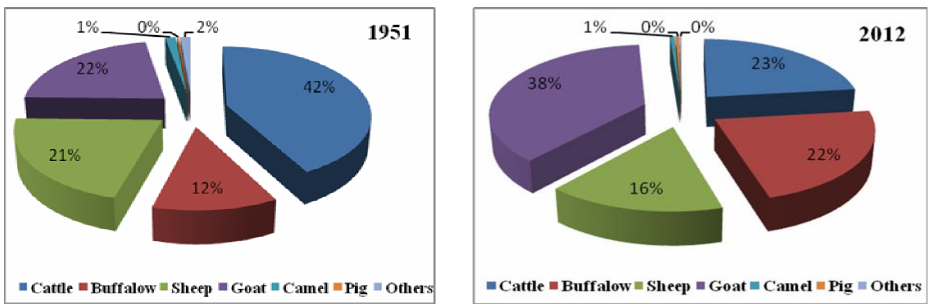


Figure 1.11 A comparison of change per cent livestock categories in 1951 and 2012 census.

However, shares of buffaloes, goats and pigs have increased from 11.9 percent, 21.8% and 0.2% of the total livestock population to 22.5%, 37.5% and 0.4%, respectively during the same period. Small ruminants comprising of sheep and goats account for 52.2% of the total livestock population in the state. Increased profitability and slackening of social rigidities has led to adoption of goats and sheep rearing by all caste and classes of households, hence the increased number of sheep and goats in Rajasthan. However, decrease share of small ruminants as compared to that in 2007 (i.e., 58%) indicates an increase in the population in favour of large milch animal (Table 1.8).

Table 1.8 Changes in livestock population (number in lakhs) in Rajasthan during 1951 to 2012. Source: Livestock Census (GoI, 2012).

Year	Cattle	Buffalo	Sheep	Goat	Camel	Pig	Others	Total
1951	107.82	30.45	53.87	55.62	3.41	0.55	3.44	255.16
1956	120.73	34.3	73.73	87.3	4.36	0.73	3.13	324.28
1961	131.36	40.19	73.6	80.52	5.7	0.71	3.01	335.09
1966	131.23	42.23	88.06	103.23	6.54	0.83	2.64	374.76
1972	124.7	45.92	85.56	121.62	7.45	1.17	2.36	388.78

Year	Cattle	Buffalo	Sheep	Goat	Camel	Pig	Others	Total
1977	128.96	50.72	99.38	123.07	7.52	1.3	2.64	413.59
1983	135.04	60.43	134.31	154.8	7.56	1.79	2.57	496.50
1988	109.21	63.44	99.32	125.78	7.19	2.07	2.16	409.17
1992	116.66	77.75	124.91	152.85	7.46	2.53	2.29	484.45
1997	121.41	97.7	145.85	169.71	6.69	3.03	2.16	546.55
2003	108.54	104.14	100.54	168.09	4.98	3.37	1.7	491.36
2007	121.2	110.92	111.9	215.03	4.22	2.09	1.27	566.63
2012	133.25	129.76	90.8	216.66	3.26	2.38	1.23	577.33

8.3 Socioeconomic indicators

According to census 2011, the average literacy rate of Rajasthan is 67.06% (varied between 55.58% in Jalore and 77.48% in Kota), which is low as compared to the average literacy rate (74.04%) in India. In this male literacy rate is 80.51% (ranging from 70.13 in Pratapgarh to 87.88% in Jhunjhunu) and female literacy rate is 52.66% (ranging from 38.73 in Jalore to 76.63% in Kota) for female. The overall sex ratio is 926 females per 1,000 males and the sex ratio amongst the 0-6 year population is 883 females per 1,000 males. The sex ratio at birth is also in favour of male, i.e. 877 female births per 1,000 male births, which is lower than that of India (905 female births per 1,000 male births) (GoR, 2012b).

Rapidly growing population affects per capita income at INR 23,669 as compared to the national average of INR 33,731 (GoI, 2015). Rajasthan ranks 20 out of 29 Indian states on human development indicators with Human Development Index (HDI) value of 0.434 (2007-08). An effect of increasing population is also reflected by decreasing land holding, which is 3.07 ha (0.47 ha to 15.87 ha) in 2010-11 as compared to 3.38 ha (ranging from 0.49 ha for marginal farmers to 17.88 ha for large farmers) in 2006 and 3.96 in 1996 (GoR, 2011, MoA, 2014). This indicates an increase in operational land holding number by 11.35% and a decrease in operational land holding area by 0.94% in 2011 (68.88 lakhs number and 21.14 lakhs ha) than in 2006 (MoA, 2014).

9. CONCLUSION AND RECOMMENDATIONS

Being largest state in India and having wide physiographic feature there are large variations in climatic conditions, i.e., rainfall, temperature etc. The Aravalli Range, which runs across the state from southwest to north-east running almost more than 850 km, divides the state in almost two parts, hence influence climatic conditions and land use pattern. The rainfall has been slightly erratic in recent years. Climate change may initially have small positive effects but is likely to be very damaging when temperature increases influencing evaporation losses of water (Stern, 2006). The increased potential evaporation has resulted in putting whole Rajasthan into arid and semi–arid region, which has shifted Ajmer district to arid region. Increase in human and livestock population are reducing operational land holding. Increase in population density has positive and significant impact on agricultural intensification controlling the regional differences in agro climatic conditions (Ricker-Gilbert et al., 2014). The corresponding increase in requirement of food and fodder are putting land, water and forests resources under high pressure. Non sustainable agricultural and industrial practices and relatively small scope for further expansion of agricultural land makes it more important to understand the relationship between population pressure, changes in land use and environmental degradation. This emphasizes judicial use of available resources on the one side and reducing already degraded land resources including forests on the other side.

2

UNDERSTANDING THE ECOLOGY OF DRY LANDS

Scarcity of water in drylands leads to clustering of human settlements around water sources and is predicted to increase with increase in aridity. Drylands are home to 36% of the global human population and they have massive amount of some key natural resources like petroleum, gold, copper, silver and other minerals. A wide range of latitudinal, altitudinal and climatic conditions observed in drylands have resulted in varieties of habitats and soils. Such diversities are essential to the survival of species, maintenance of diversity and to sustain livelihoods of people living in the region. Drylands host about 20 per cent of the major plant diversity centres available in nationally-designated protected areas. Plant and animal species residing in drylands show remarkable ways of adaptation like change in life span, growth pattern, biochemical and physiological make up. Some plants exhibit mechanisms like ability to escape, evade, resist and endure drought stress. Ephemeral annuals, succulent perennials, and non-succulent perennials are three major plant forms observed in the drylands. Likewise wildlife inhabiting drylands adapt themselves by migrating, burrowing, hoarding food, engaging in rapid reproduction and enduring large fluctuation in temperature.

Rajasthan covering about 34.23 million hectare area with 68.62 million humans and 57.73 million livestock population exhibit typical dryland characteristics with large spatial variations in environmental and biological features. There are 31 sub types of forests and varieties of species of varying habits, though the species richness and diversity are relatively low. However, the climatic vagaries like variable rainfall and increasing temperature, increasing human and livestock population coupled with natural resource devastation will promote the process of land degradation as the aridity increases. This leads to reduction in standing biomass and carbon storage and affects people livelihood. There is a need to conserve existing biological diversity and natural resources to maintain functional behaviour of the dryland ecosystems and reduce dependency of the poors on the rich ones.

1. INTRODUCTION

Drylands are characterized by reduced availability of water and include cultivated lands, scrublands, shrublands, grasslands, savannas, semi-deserts and true deserts regions. Scarcity of water affects the production system as well as ecosystem services of the drylands. Most of the climate change predictions models indicate that major parts of the world will become hotter and drier with a loss of biodiversity, increased water scarcity and increased natural resource devastation (El-Beltagy and Madkour, 2012; Murray, 2013; Solh and van Ginkel, 2014). Drylands have strong spatial variations ranging from cold deserts of Gobi in Asia to hot deserts like the Sahara through Mediterranean types.

Environmental conditions of the drylands are characterized by cool and dry winter season, followed by a relatively hot and dry summer, and then by a moderate rainy season (Singh et al., 1992). Significant diurnal variability in temperature hampers the growth of plants within these seasons. However, variations in plant growth are species-specific depending upon maximum and minimum temperatures. Severity of the maximum and minimum temperatures in drylands are damaging to both plants and animals. Though plants survive high temperatures by compensating the transpiration, but their growth rates are negatively affected. High temperatures of the surface layer of the soil result in a rapid loss of soil moisture because of the high evaporation and transpiration rates (Sikka, 1997; Brown, 2014). Changing environmental conditions and the nature of rainfall during last six decades combined with ruthless destruction of forest cover on the hills has resulted in increase in soil erosion, sediment transportation, siltation, drying-up of lakes, dams and surface water sources and lowering of water table. These are further aggravated by increasing pressure of human and livestock population on the water resources and depletion of environmental resources particularly vegetation and soil resources (Backlund et al., 2008; Rathore and Verma, 2013).

Importance of drylands for human beings can be seen in multiple ways. For example, about 36 percent of the global human population lives in drylands. Drylands possess a massive amount of key resources that includes petroleum, gold, copper and silver etc. (OPEC, 2010; White and Nackoney, 2003), and region is crucial for achieving global sustainability and well-being of human populations (Reynolds et al., 2007; Munasinghe, 2009). Over 90 percent of the dryland human population resides in developing countries, and a substantial part of this population is lagging far behind the rest of the world with regards to developmental indicators (Safriel and Adeel, 2005).

2. LAND AND WATER

A global survey of 224 dryland ecosystems in 16 countries has indicated presence of 26 different types of soils (Maestre et al., 2012). Soils vary in their origin, structure, physical and chemical properties depending upon available rocks and dryland environments, which are frequently encountered by large diurnal changes in temperature (Rücknagel et al., 2013). The large diurnal changes in temperature result in mechanical and physical disintegration of rocks and wind-blown sands that score and abrade the exposed rock surfaces. The physical disintegration of rocks leaves relatively large fragments which are then slowly broken up by chemical weathering (Furukawa and Handawella, 1976). Existing vegetation also plays important role in the process of soil formation by breaking up of rock particles, chemical weathering and enriching the soil with organic matter added through litter addition and fine root turn over (Filipov and Slonovschi, 2007; Karpachevskiy and Zubkova, 2009). The roles of plants are favoured in dryland environment because of the sparse vegetation. Though development of above-ground plant parts are limited, the root systems are often extensive both laterally as well as vertically affecting the soils structure. Soil depth and texture influence the amount of water that a soil can hold (Kumar et al., 2013). However, the depth of soil in most of dryland regions is often limited by availability of hardpan layer that restricts water-holding capacities and rooting depth. These hardpans, often consist of $CaCO_3$ aggregates or silicaceous materials and are more-or-less continuous and occur between 5 and 80 cm below the soil surface unless meters of sands deposit over the ground- a general feature in sand drifting areas under Aeolian activity (Williams and Eldridge, 2011; Verheye, 2006). The landscape-level processes of sand deposition indicate a marked effect on soil nutrient pools by enhancing the accumulation of plant-available nitrogen on organic crust or material. However, little deposition, accumulation, or decomposition of organic material affects availability of soil organic matter and thus affect soil fertility in dryland environments. The limited organic matter available in the soil is quickly lost when cultivated. Further, soils are also characterized by the extensive leaching of nutrients and intensive weathering of minerals on older exposed surfaces (Chen et al., 2000; Gautam, 1992; Sharma and Sharma, 2011a).

Water availability has an important bearing for human well-being and supports the two key functions of land, i.e. primary production and nutrient recycling. Water scarcity is an important feature of drylands. Rainfall typically varies from season to season and from year to year, though heavy rains occur occasionally (Mall et al., 2006; Jayanthi et al., 2006). Most of the rainfall is lost by evapotranspiration, whereas groundwater recharge is negligible and confined only by seepage through the soil profile (Chattopadhyary and Hulme, 1997; Murray, 2013). Surface runoff, soil moisture storage and ground water recharge in drylands are highly variable, whereas withdrawal of groundwater far exceeds the rates of recharge in most of the drylands (Jain et al., 2007; Mzezewa and van-Rensburg, 2011). For example in north-west India, a simulation study indicates considerable increases in runoff by 2070–2099, with a mean change of 189 mm/year for 2 ºC climate change (Murray, 2013). However, rainfall is shown to have an important bearing on runoff generation, and degree will also affect the magnitude of future runoff (Guhathakurta et al., 2011). Furthermore, water available for general use is affected generally by salinity (Armitage, 1987). Surface water available to the people living in drylands regions is confined to the large rivers that originate in areas of higher elevation (Liniger et al., 1998). Some of these rivers are the Nile in the Sudan and Egypt, the Tigris in Iraq, the Indus and the Ganges in Indo-Pakistan region, the Senegal and the Niger in African region and the Colorado in the western United States etc (IUCN, 2008; FAO, 2011). Scarcity of water leads to clustering of human settlements along these rivers or around some water sources like springs, wells and oases. The gap between demand and supply of water is highest in the drylands, and water scarcity increases with the increase in aridity. A person requires a minimum of 2,000 cubic meters of water per year for basic well-being. In India, the per capita water availability in 1951 was 5177 m^3 per year with total population of only 361 million. In 2001, as the population increased to 1027 million, the per capita water availability reduced to 1820 m^3 per year. However, the projected per capita water availability is 1341 m^3 in

2025 and 1140 m^3 in 2050. Water scarcity affects most of the people in the drylands, where access to water is below 1300 m^2 per person per year. Under the climate change scenario, nearly half of the world's population will be living in areas of high water stress by 2030. Traditional cultures have developed the ways of finding, conserving and transporting water, including specialised land management techniques and structures to capture and retain precipitation, or to encourage groundwater recharge as the adaptation in the drylands.

3. BIOLOGICAL DIVERSITY

Varying level of water scarcity is an important driver of biological diversity in the drylands, but variations in topography, geology, soil type and quality are other important factors influencing biodiversity. Seasonal patterns of rainfall, fires, grazing pressure as well as the influence of human management over centuries are other drivers of biological diversification in drylands. Interactive effects of these drivers since centuries have resulted in a patchy habitats with varying topography determining distribution of living organisms (Youssef et al., 2014). A wide range of habitats, vegetation and soil types are essential to the survival of species and to the livelihoods of people in the region. The review of Hironaka et al. (1990) on the basic concepts of soil and vegetation development indicates that vegetation and soils are mutually associated with each other, both being the product of the same environmental variables. Availability of 26 different types of soils in global drylands are also responsible for diversified vegetation pattern (Maestre et al., 2012). Though lesser in extent, available wetlands, oases and other water resources in patches are the final destination for many migratory bird species illustrating that their value may extend far beyond the boundaries of the drylands. Some of the regions are often of crucial in supporting endemic species like the Mediterranean Basin, which is home to more than 11,700 endemic plant species (CBD, 2012).

3.1 Vegetation

Drylands are sometime more diverse than those found in some of the more productive biomes (Kier et al., 2005; Field et al., 1998). Plant and animal diversity in drylands are not only influenced by climate and latitude but also influenced by altitude (MEA, 2005; Singh, 2014a; Youssef et al., 2015). For example, altitude of drylands ranges from low lying areas of the Danakil Depression of Ethiopia to high altitude drylands of Afghanistan in Asia or Bolivia in South America. These drylands not only have high plant diversity, but are also highly diverse in microbial and soil communities (Fierer and Jackson, 2006; Housman et al., 2007). Besides this, drylands support about 20 percent of the major centres of plant diversity of the world (White and Nackoney, 2003). Species occurring in drylands have remarkable ways of adaptation by change in life span, growth pattern and physiology. They exhibit various mechanisms like ability to escape, evade, resist and endure drought as the adaptation strategies of the species during extended drought.

Ephemeral annual, succulent perennial, and non-succulent perennial are three plant forms observed in the drylands. Ephemerals are those species that appear after rains and complete their life cycle during a very short period of rainy season. They are small in size having shallow roots and, at times, form relatively densest surface. Succulent perennials store water by enlargement of the parenchymatous tissue, thereby reducing transpirational water loss. The stored water is then utilized in periods of water stress. Cacti are typical succulent perennials that occur in relatively more dry areas. However, some plants develop water storage tissues, like swollen roots (i.e., *Butea monosperma*) or stems, which allow them to draw saved water to survive during the dry season (Al-Busaidi et al., 2013). Non-succulent perennials are those species that withstand the stress of dryland environments. These non-succulent perennials are further divided into evergreen, dry deciduous and cold-deciduous observed in the drylands. Evergreen plants are active biologically and remain green throughout the year. The dry deciduous plants are dormant in the dry season. Characteristic feature of the plants of dry forest is deciduousness, i.e. the shedding of leaves (Chaturvedi, 2010). Plants drop their leaves before the start of the dry season, i.e. summer, particularly in order to halt photosynthesis, which otherwise promotes water losses that plant cannot sustain during the dry season (Orwa et al., 2009). However, some plants like *Ceiba trichastandra* and *C. pentandra* possess an alternative source of photosynthetic energy as they have green bark rich in chlorophyll that lets them continue to photosynthesize even when they have no leaves, whereas the plants like *Samania saman* (rain tree) shows 'nyctinasty' character (drupping leaves during night) to minimize the transpiration loss (Balliett, 2014). The temperate deciduous plants remain dormant during cold season.

Many plants have adapted to such a way which enables them to reproduce, survive, and grow in harshest environments. Some plants have evolved specialized rooting system, while others have unique leaf characteristics that allow them to withstand prolonged periods of drought through reduction in transpiring surfaces. Mesquites (including *Prosopis velutina*) have very strong roots from 10 to 30 m long that enable the plant to tap into underground lenses of fresh water and provide multifunctional role of anchoring and feeding (Canadell, 1996; Pandey et al., 1994; Singh and Rathod, 2002). This morphological adaptation let mesquites to occupy flood plains and other sites with relatively shallow groundwater table and by doing so, it avoids stresses that other plants undergo during drought stress.

Many plants have an extra waxy layer on the outer surface of the leaves, i.e. layers of cutin, the impregnation of cell walls with cutin to form a water-tight layer; and special arrangement of stomata in recesses and grooves to provide protection from the dry atmosphere and reduce water loss through evaporation (del-Campo, 2007). Some plants need grazing pressures and fire as an ecological requirement for successful reproduction and propagation and can be a criterion for the selection of species to withstand in a similar environment (Thompson et al., 2009).

3.2 Forests

A wide variation in climatic variables like air temperature, relative humidity and available soil water in dry areas leads to develop a variety of vegetation pattern and thus forest types (Schmitt et al., 2013). Increased temperature and decreased water availability also influence litter/woody debris quality and quantity. These forests and woodland patches play similar roles within wider landscapes, often providing seasonal refuge for migratory species as well as people, in addition to harbouring their own unique biodiversity. At present nationally-designated protected areas cover approximately 9% (i.e., 5.4 million km^2) of the world's drylands. Protected drylands make up 3.6% of the world's land area. However, as compared to 12.9% of the worlds land area under protection outside Antarctica, the protected areas in drylands are relatively less. Among different dryland categories, dry sub-humid areas are relatively well protected (10.8%), closely followed by hyper-arid areas (10.3%). Semi-arid and arid areas are relatively less protected, i.e. 8.1% and 8.0%, respectively (Table 2.1). Since forest ecosystem acts as carbon reservoirs by storing large amounts of carbon in trees, undergrowth vegetation, forest floor and soil (Rotter and Danish, 2002); and contain from 62% to 78% of the total terrestrial carbon (Hagedorn et al., 2002). The response of forests to the rising atmospheric CO_2 concentrations is crucial not only at regional but at global level also.

Table 2.1 Distribution of protected areas in drylands of the world.

Dryland type	Total area (km^2)	Protected area (km^2)	Protected area (%)
Hyper-arid	8,969,237	927,435	10.3
Arid	15,169,575	1,219,185	8.0
Semi-arid	22,673,686	1,840,242	8.1
Sub-humid	12,962,403	1,399,659	10.8
Total	59,774,901	5,386,521	9.0

Source: UNEP-WCMC (2010).

3.3 Wildlife

Like plants, species of indigenous wildlife inhabiting dryland regions often have physiological and ecological advantages to cope up with water scarcity and extreme temperatures, lack of shade and harsh relative humidity (Abere and Oguzor, 2011; Joshi, 2011). To make themselves adapted, these animals migrate, burrow, hoard food, engage in rapid reproduction and endure large fluctuating temperature. Most significant one is their ability to thrive without an abundance of surface water by way of moving in time and space, use of the sparse vegetation for food and protective cover, and their minimal impacts on the environment when their populations are balanced properly by the environment (Ffolliott et al., 1995; Than, 2005). Some birds and large mammals can escape critical dry spells by migrating along the desert plains, residing in the area with sufficient water availability or move up into the mountains. Smaller animals cannot migrate but regulate their environment by seeking out cool or shady places. In addition to flying to other habitats during the dry season, birds can reduce heat by soaring. *Stenocara* beetles, found in Namibia, do "headstands" on the ridges of sand dunes frequently blanketed by coastal fogs to catch droplets of water on their carapace. Kangaroo rats in the drylands of Central and North America obtain virtually all of their water by the oxidation of fats in dry seeds (metabolic water). Some important species adapted to Indian drylands include Indian Lion of Gir forest, Wild Ass in Little Rann of Kutchh and the Great Indian Busturd occupying grassland habits.

The International Union for the Conservation of Nature (IUCN) and the World Wildlife Fund (WWF) have identified 234 Centres of Plant Diversity (CPD) worldwide, of which 42 are within drylands (White and Nackoney, 2004). Many rodents, invertebrates, and snakes avoid heat by spending the day in caves and burrows searching out food during the night. Animals active in the day reduce their activities by resting in the shade during the hotter hours. Many species of frogs and insects simply burrow deep into damp mud, or their own excavated chambers, and go to sleep, reducing their metabolism and food and water needs. When the rains return, the increased moisture awakens these animals, and they return to the surface to breed. Many wildlife species possess attributes of tolerances to disease, heat, and drought, and have more efficient reproductive and meat production ability even than the livestock.

4. HUMAN AND LIVESTOCK POPULATION

Total human population of drylands is about 2.1 billion (Table 2.2). Over 40% of the human population of both Africa and Asia, and about 25–30% of the rest of the world's population live in drylands (Reynolds et al., 2007). Average population growth rate in the drylands is about 18%, which is faster than that of any other ecological zone. Population density decreases with increase in aridity. On an average, population density ranges from 10 people per km^2 in typical deserts to 71 people in the dry sub-humid areas. Either rural or urban drylands are home of around billions of people who rely directly on dryland ecosystem services for their livelihoods. Indeed, some of the biggest and populous cities of the worlds like Cairo, Mexico City and New Delhi are located in the drylands.

Table 2.2 Population of different ecosystems of the world drylands and their share to the global population.

Ecosystem	Total Population	% Share of Global Population
Desert	101,336	1.7
Semi-desert	242,780	4.1
Grassland	855,333	14.4
Rangelands	909,972	15.3
Total	2,109,421	35.5

Livestock is one of the few assets owned by the poor in drylands and as such play a significant role in their livelihoods in the region. Pastoral systems are adapted to dryland environments and have been able to fully exploit these characteristics through regular mobility in areas that would otherwise remain unutilized (Jamsranjav, 2009; Oteros-Rozas et al., 2013). Mobility is a highly efficient way of managing the fragile ecosystem of dryland characterized by sparse and fragile vegetation and relatively low fertile soils (Weber and Horst, 2011; Selemani, 2014). However, dryland ecosystems may be more ecologically resilient as long as livestock mobility or resource-use management is maintained judiciously. One of the main interactions between the poor and the environment in drylands is through their high dependence on common property grassland resources (Lee and Neves, 2009).

Common property resources in relation to rangeland, low-rainfall forest, or bush and khans lands in southern Asia or similar other areas represents an economically rational form of land use under specific conditions of low intrinsic resource productivity. These common lands are used by almost all of the rural communities in drylands and are a central feature of the coping and survival strategies of the poor and the landless or marginal people (V&A Programme, 2009). A typical poor rural family harvest fuel wood for sale, graze whatever animals they have and gather fruit, plant material, medicinal plants, game and building materials for their own use from these common lands. However, such systems are now undergoing rapid changes because of land use change and inappropriate policies like constraining herd mobility (Rosales and Livinets, 2006; Sharma et al., 2002). Indeed, survival and viability of pastoral systems strongly relies on mobility, which is increasingly being threatened by other forms of land uses that constrain the inherent flexibility of pastoral systems. In contrary protecting pooled private and common lands, in combination with soil and water conservation measures, are found effective for raising the productivity of the land to a level that sustains the communities' fodder requirement throughout the year even if rainfall is below average and highly variable (V&A Programme, 2009; Singh and Singh, 2010).

5. ECOLOGY OF RAJASTHAN

Rajasthan has been divided into ten agro-climatic zones (Table 2.3) to understand implications and role of climatic and edaphic resources on agricultural and allied sectors (Sehgal and Abrol, 1994; ICAR, 2010).

Table 2.3 Agroclimatic zones and their distribution in different districts of Rajasthan (Source: http://agropedia.iitk.ac.in/content/agro-climatic-zone-rajasthan).

S.No	Agro-climatic Zone	Rainfall (mm) range	District
1	IA-Arid Western plain	200-370	Barmer, Jodhpur
2	IB-Irrigated North Western plain	100-350	Sriganganagar, Hanumangarh
3	IC-Hyper-arid partly Irrigated Zone	100-350	Bikaner, Jaisalmer, Churu
4	IIA-Internal Drainage Dry Zone	300-500	Nagaur, Sikar, Jhunjhunu
5	IIB-Transitional Plain of Luni Basin	300-500	Jalore, Pali, Sirohi
6	IIIA-Semi arid Eastern Plain	500-700	Jaipur, Ajmer, Dausa, Tonk
7	IIIB-Flood Prone Eastern Plain	500-700	Alwar, Dholpur, Bharatpur, Karauli and S. Madhopur
8	IVA-Sub humid Southern Plain	500-900	Bhilwara, Rajsamand, Chittorgarh
9	IVB-Humid Southern plain	500-1100	Dungarpur, Udaipur, Banswara and Pratapgarh
10	V-Humid Southern Eastern Plain	650-1000	Bundi, Kota, Baran, Jhalawar

5.1 Climatic conditions in Rajasthan

Because of its location in the western part of India and varying topography, Rajasthan exhibits varying climates. The rocky Aravali hills, the western arid plains, the eastern fertile plains etc experiences different climatic conditions. The weather pattern in the state is divided into pre-monsoon, monsoon, post-monsoon and winter. Rainfall is very low, highly erratic and variable throughout the Rajasthan. Rainfall decreases while moving from East to West and from South East to North West. During monsoon season from July to September, the area receives about 90% of the annual rainfall. However, the region often suffers of frequent drought due to poor and delayed monsoon rainfall, abnormally high temperature and insufficient water resources. The average annual rainfall in western part of Aravalli ranges from less than 100 mm in north-west part of Jaisalmer to 200-300 mm in Ganganagar, Bikaner and Barmer regions, 300-400 mm in Nagaur, Jodhpur, Churu and Jalore regions and more than 400 mm in Sikar, Jhunjhunu and Pali regions and along the western fringes of the Aravalli range.

On the eastern side of the Aravalli range, the rainfall ranges from 550 mm in Ajmer to 1020 mm in Jhalawar region. In plains, Banswara (920 mm) and Jhalawar (950 mm) districts receive the maximum annual rain. However, highest rainfall in the state, i.e. 1638 mm occurs in Mount Abu in Sirohi district. Pant and Hingane (1988) has observed an increasing trend in mean annual and SW monsoon rainfall over meteorological sub-divisions of Punjab, Haryana, western Rajasthan, eastern Rajasthan and western Madhya Pradesh during the period 1901–1982. However, some data analysis indicates a decreasing trend in annual rainfall in western Rajasthan (Khaladkar et al., 2009; Singh and Kumar, 2015). Using the data of 316 rain gauges, Singh et al. (2005) have observed a decreasing trend in annual rainfall since the 1960 over major basins in Central India like Sabarmati, Mahi, Narmada, Tapi, Godavari and Mahanadi. Multidecadal variability during 1951-2007 in annual rainfall amount and total number of rainy days reveal that the annual rainfall over eastern Rajasthan varies from a minimum of about 380 mm during 2002 to a maximum of about 1000 mm during 1961, while over western Rajasthan, the rainfall varies from about 130 mm during 2002 to about 540 mm during 2006 (Kharol et al., 2013). However, number of rainy days shows nonsignificant decreasing trends over eastern Rajasthan, whereas western Rajasthan exhibits an increasing trend (Kharol et al., 2013).

Pre-monsoon summer (April to June) is the hottest season with temperature varying from 32ºC to 45ºC. In western Rajasthan the air temperature rises some time up to 50ºC, where the prevailing westerly winds cause dust storms. Pant and Hingane (1988) found a decreasing trend in mean annual surface air temperature for 1901–1982 over the northwest Indian region consisting of the meteorological sub-divisions of Punjab, Haryana, western Rajasthan, eastern Rajasthan and western Madhya Pradesh. Chaudhari et al. (2009) have also observed a negative response of yields to increased minimum temperatures for all the crops, where the reduction in crop yields upto 13.4% is observed with unit increase in minimum temperature and upto 10.3% and 5.3% for rice and wheat crop, respectively in response to increased maximum temperature. The reduction in wheat yields is predicted to decline by 21% in Eastern Rajasthan followed by 18% in Western Rajasthan and 14% in East Madhya Pradesh during 2071-2100 (Chaudhari et al., 2009).

5.2 Human population growth and dynamics

Population of Rajasthan in 2011 was 68.6 million; out of this 75.1 per cent was rural population (GoI, 2011a). Population is significantly less in western districts like Barmer and Jaisalmer, where people live in the groups of the hamlets (village) surrounded by the sand dunes (Plate 2.1). Population growth during 1971 to 2011 has been observed increasing in a quadratic way, where urban growth is relatively low as compared to the rural population (Fig 2.1). The decadal growth was lower during 2001-11 (21.44 per cent) and higher in 1971-81 (32.95 per cent) as compared to the other decades. The population density in the State has increased by about 22 percent, i.e. from 165 per sq km in 2001 to 201 in 2011. When compared with the population density in 1971, the increase in population density in 2011 is 2.68-fold. While considering the districts, the decadal growth during 2001-2011 has been observed highest in Barmer followed by Jaisalmer, whereas the lowest decadal growth is in Ganganagar (10.0 per cent), which is very close to Jhunjhunu and Pali districts in decadal population growth (Table 2.4). Population density in 2011 also shows high variations ranging from 17 persons per square km in Jaisalmer to 595 persons per square km in Jaipur district.

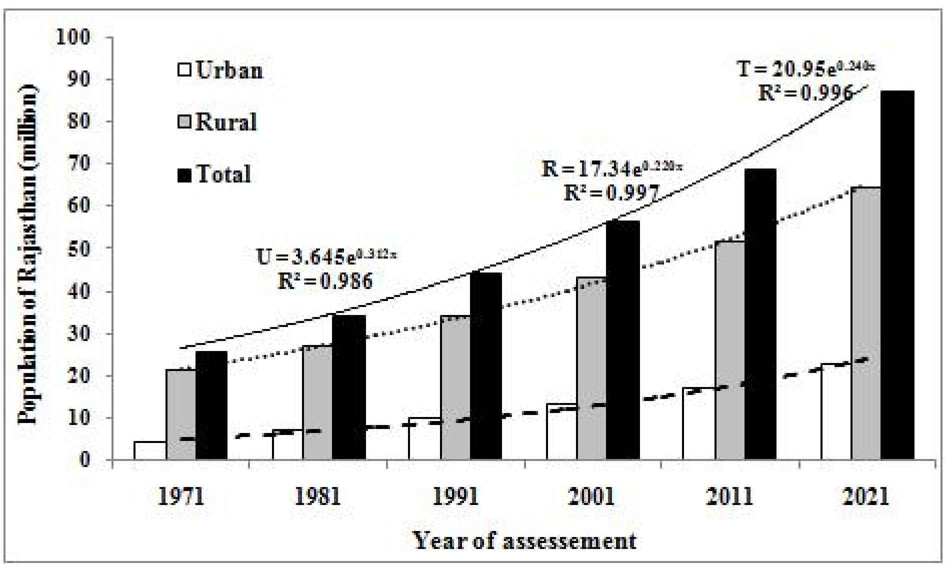


Figure 2.1 Decadal population growths in urban and rural areas of Rajasthan.

Table 2.4 Total geographical area and district-wise distribution of population, its decadal growth and density in Rajasthan.

SNo.	District	TGA (km^2)	Population (Nos)	Forest area (mha)	% of TGA	Per cent decadal growth & population density	
						Growth	Density (nos. km^{-2})
1	Ajmer	8,481	25,84,913	61310	7.23	18.6	305
2	Alwar	8,720	36,71,999	178495	20.47	22.8	438
3	Banswara	4,536	17,98,194	123667	27.26	26.5	397
4	Baran	6,955	12,23,921	223962	32.20	19.7	175
5	Barmer	28,387	26,04,453	62722	2.21	32.5	92
6	Bharatpur	5,044	25,49,121	43494	8.62	21.4	530
7	Bhilwara	10,455	24,10,459	77876	7.45	19.2	230
8	Bikaner	30,382	23,67,745	124906	4.11	24.3	78
9	Bundi	5,500	11,13,725	156678	28.49	15.4	192
10	Chittorgarh	7,880	15,44,392	182019	23.10	16.1	197
11	Churu	13,792	20,41,172	7122	0.52	20.3	147
12	Dausa	3,420	16,37,226	28263	8.26	23.5	476
13	Dholpur	3,009	12,07,293	63845	21.22	22.7	398
14	Dungarpur	3,770	13,88,906	69273	18.37	25.4	368
15	Ganganagar	11,604	17,79,650	23946	2.06	10	179
16	Hanumangarh	9,580	66,63,971	94566	9.87	16.9	184
17	Jaipur	11,061	6,72,008	58129	5.26	26.2	595
18	Jaisalmer	38,401	18,30,151	45261	1.18	31.8	17
19	Jalore	10,640	14,11,327	134979	12.69	26.2	172
20	Jhalawar	6,219	21,39,658	40535	6.52	19.6	227
21	Jhunjhunu	5,928	36,85,681	24303	4.10	11.7	361
22	Jodhpur	22,250	14,58,459	180206	8.10	27.7	161
23	Karauli	5,039	19,50,491	131082	26.01	20.9	264
24	Kota	5,204	33,09,234	24093	4.63	24.4	374
25	Nagaur	17,718	20,38,533	96358	5.44	19.2	187
26	Pali	12,357	8,68,231	140704	11.39	11.9	164
27	Pratapgarh	4,360	11,58,283	39658	9.10	22.8	195
28	Rajsamand	4,636	13,38,114	93772	20.23	17.7	248
29	Sawaimadhopur	5,221	26,77,737	63935	12.25	19.6	297
30	Sikar	7,881	10,37,185	163865	20.79	17	346
31	Sirohi	5,136	19,69,520	63344	12.33	21.8	202
32	Tonk	7,200	14,21,711	33597	4.67	17.9	198
33	Udaipur	11,761	30,67,549	414170	35.22	23.7	262
	State	342,327	68,621,012	3270135	9.55	21.3	201

Sources: Directorate of Economics and Statistics, Government of Rajasthan, Jaipur.

5.3 Livestock populationin Rajasthan

Livestock Census of 2012 indicates 23 per cent cattle and 22.5 per cent buffaloes population in total livestock population in Rajasthan, i.e. 57.73 millions. There has been 2.26-fold increase in total livestock population in 2012 as compared to the livestock population in 1951. This population has increased by a power factor of 0.307 multiplied by 248.9 (Fig 2.2A). However, there is a decline in share of cattle, sheep and camel in the total livestock population by 42.3%, 26.1% and 1.4% in 1951 to 23.1%, 15.7% and 0.56% in 2012, respectively. However, shares of buffaloes, goats and pigs have increased from 11.9%, 21.8% and 0.2% of the total livestock population to 22.5%, 37.5% and 0.4%, respectively during the same period (Fig 2.2B). Small ruminants comprising of sheeps and goats account for 52.2% of the total livestock population in the state and has significant contribution in the livestock population of India.

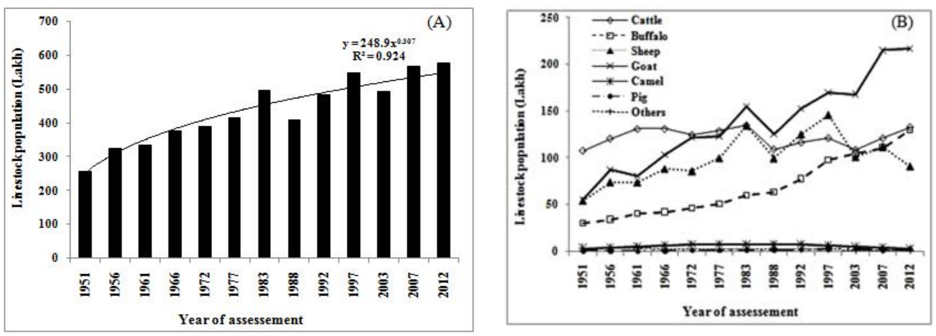


Figure 2.2 Trend in livestock population in Rajasthan during 1951 to 2012. Total livestock population (a), and livestock category (B).

5.4 Land use pattern

Out of total geographical area (TGA) of 34.27 million hectares in Rajasthan, about 57 per cent of state consists of desert which accounts for 61 per cent of the desert of the country. The forest area has covered around 8 per cent of the TGA, while the net area sown has been largely fluctuating in the state over the years, which has declined during recent past, i.e. from 175.5 lakh hectares in 2008-09 to 169.7 lakh hectares in 2009-10. However, the gross cropped area (GCA) has increased by about 7% points (to reporting area) in 2009-10 over 1990-91. The increase in GCA is due to significant increase in area sown more than once. The cropping intensity has also been considerably increased over the years. It has increased from 121.2% in 2000-01 to 129.9 per cent in 2007-08 and thereafter has declined to 128.1% in 2009-10. It may be also worth to note that gross irrigated area has declined from 80.9 lakh hectares in 2007-08 to 73.1 lakh hectares in 2009-10. On the other hand, land put to non-agricultural uses has successively increased from 14.9 lakh hectares in 1990-91 to 19.8 lakh hectares in 2009-10. Compared to Indian averages, Rajasthan has slightly better proportion of total cropped area and net shown area (Table 2.5).

5.4.1 Area Under Non-agriculture Uses

This category belongs to the land put to non-agriculture uses such as residential, roads/paths, water bodies etc. The share of such land use is only about 5 percent of the reporting areas. In different climatic zone, it varies from 3% to 8%.

Table 2.5 Land used statistics in India and Rajasthan. Area is in 1000 ha.

Land use	India	Rajasthan
Reporting area for land utilization statistics	305611	34270
Forests	70042	2735
Not available for cultivation	42954	4268
Permanent pastures & other grazing lands	10149	1697
Land under misc. tree crops & groves	3351	17
Culturable waste	12857	4475
Fallow lands other than current fallows	10484	2048
Current fallows	15753	2055
Net area sown	140022	16974
Total cropped area	192197	21745
Area sown more than once	52175	4770

Source: GoI (2012-13; http://data.gov.in/dataset-export-tool?nid=5914).

5.4.2 Barren and Un-culturable Land

This category of land is considered as non-suitable for agricultural operation. About 7% of the total area of Rajasthan is categorized as barren and un-culturable waste land. In different zones it varies between 10% and 20% area. However, in irrigated North Western Plain, this category is negligible, i.e. <1%.

5.4.3 Grazing Lands

This is one of the most important categories of land use and main stay for livelihood in Rajasthan (Jodha, 1986; Ray and Bijarnia, 2007). The availability of permanent pasture and grazing land determines the status of livestock economy in the regions. There is about 1.7 million hectare (about 5% of the total area in Rajasthan) area as pasturelands. These common lands however has been severely degraded over a period of time; as over 40% of area has become less productive or unproductive (Plat 2.2). This is because of over grazing, soil erosion under vegetation removal and neglect of/by the community (Hegde et al., 2003; Mishra and Kumar, 2007). In irrigated North Western Plain, the grazing land is negligible, whereas in eastern areas it constitutes about 4 to 7% area. Despite of large investment in developing pasturelands the depletion is still continued. Overgrazing, trees and bushes removal, damage in boundary walls or fencing, stealing of stones/bricks of the check dams just after the project is over, are features observed in the region (Kumar and Mishra, 2001; Singh and Singh, 2010).

5.4.4 Land under Misc-Tree Crops and Groves

Area under fruit crop falls under this category of land use. In Rajasthan, it is less than 1%. In certain regions, area under fruit crop is absolutely missing.

5.4.5 Culturable Waste Land

This is also one of the major categories of land use covering about 13% of the total reported area of Rajasthan. Agriculture operations are possible on these lands. In Hyper - arid partial Irrigated Zone, land under this category is in substantial proportion, i.e. 40% followed by sub humid southern and Irrigated North Western Plain zones with 15% and 12%, respectively. In rest of the zones it varies from 2 to 8 percent.

5.4.6 Fallow Land

There are two types of fallow lands, i.e. current fallow and long fallow. Lands with suspended agriculture operation for one to five years fall under this category. Current fallow means uncultivated land during a given year, but other fallow or long fallow land refers to that land which has not been cultivated for a period not less than one year and not more than five years. At the state level, it covers about 11% area of Rajasthan.

5.4.7 Agriculture

About half of the total reported area is under agriculture operation. The irrigated northern-western region and internal drainage dry zones are leading ahead as compared to other zones in bringing larger proportion of area under agriculture. It depends upon the availability and access to irrigation facilities, status of aquifer and geophysical features of the regions. The major crops grown in different parts of Rajasthan are bajra, wheat, jowar, maize, cotton, rapeseed and mustard, groundnut and horticultural crops. However, share of total cereals has declined drastically by 10% (i.e., 52% in 1990-91 to 42.0% in 2010-11); while the share of oilseeds has increased by 6 percent (i.e., 15% in 1990-91 to 21% 2010-11).

5.4.8 Forests in Rajasthan

Forests are an important part of any ecosystem and contribute to providing humans with food, fodder and fuel and enrich the soils with nutrients. In Rajasthan, coverage of forests is 9.54% (i.e., 3.27 million ha) of total geographic area as compared to the country's average of 20.6%. However, total forest cover of the state is 15,850 km^2 which constitute about 4.63% of the geographic area of the state (SFR, 2013). By combining the area under scrublands, it becomes about 2 million hectare as compared to the values of 2.74 million hectare reported under the land use statistics (Table 2.4) and 3.27 million hectare reported in forest working plan (Table 2.5). Forest area among different districts of Rajasthan varies from as low as 0.52% of the total geographical area of Churu district to 35.22% of the total geographical area of Udaipur. About 30% forests area falls in arid region and 70% forest falls in semi-arid region of Rajasthan. Diversity of tree and shrub species varies largely between the forests of different districts. Number of species (R) and Shanon-Weiner diversity index (H') of the trees and shrub species recorded in 0.10 ha and 5 × 5 m^2 plots indicate highest values in Sirohi for trees and shrubs both (Table 2.6). The lowest values of these diversity indices are in Bikaner district. The Shannon diversity index for real communities is often found to fall between 1.5 and 3.5, whereas the present values are significantly low indicating low diversity of both trees and shrubs in the region (Magurran, 2004).

The Aravalli hill region of south Rajasthan experiencing environmental change during last six decades with ruthless destruction of forest cover over the hills follows with increase in soil erosion, sediment transportation, siltation, drying-up of lakes, dams and surface water sources, lowering of water table from 5 to 10 m to 50 to 100 m and decrease in number of rain days from 101 in 1972 to 46 in 2010 (Rathore and Verma, 2013). Forests of Rajasthan have been categorized into 3 main types of forests (Champion and Seth, 1968). These are Tropical dry deciduous forest, Tropical Thorn Forests, and Southern Tropical Hill forest. In this, latter one has been confined to Mt Abu area only. Further division of these forests has led to 24 sub-types based on climatic and edaphic factors. Indian Council of Forestry Research and Education, Dehradun has also classified the forest of India through revising the eraliear studies and field observations (ICFRE, 2013). According to this there are 15-subtypes of forests in Rajasthan. In a recent study of Arid Forest Research Institute, Jodhpur Singh (2014b) has identified 31 sub types of forests in Rajasthan that include plantation and *Prosopis juliflora* as the sub types (Annexure 2.1). However, the earlier studies describe 24 sub types (Champion and Seth, 1968) and 15 sub-types (ICFRE, 2013a) of the forests in Rajasthan. Dominant tree species observed in >10% sampling sites are *Prosopis juliflora* (36.7%), *Anogeissus pendula* (23.7%), *Acacia tortilis* (22.8%), *A. leucophloea* (21.4%), *A. senegal* (19.1%), *Butea monosperma* (16.2%), *P. cineraria* (13.2%), *Capparis decidua* (12.0%), *Diospyros melanoxylon* (11.4%) and *Maytenus emarginata* (10.3%). Two most important invasive species *P. juliflora* and *Lanata camara* have been observed in 36.7% and 7.4% forest block distributed in 32 and 12 districts, respectively (Table 2.6).

Table 2.6 Forest area in different districts, number of forest blocks infested by invasive species *P. juliflora* (PJ) and *Lantana camara* (LC) and tree and shrub diversity in Rajasthan forests.

S No	District	Forest area (ha)	Forests blocks	Surveyed area		Blocks with invasive species		Tree species diversity		Shrub species diversity	
			(Nos)	Block	Plots	Pj	Lc	H'	R	H'	R
1	Ajmer	61310	199	27	28	24	-	4.18	0.98	3.56	0.78
2	Alwar	178495	346	48	48	17	-	3.17	0.65	2.52	0.63
3	Banswara	123667	203	25	32	7	17	5.41	1.09	1.86	0.33
4	Baran	223962	207	30	30	4	2	4.59	1.02	2.81	0.77
5	Barmer	62722	192	25	27	13	-	3.32	0.59	1.68	0.30
6	Bharatpur	43494	55	12	12	5	-	2.92	0.76	2.25	0.63
7	Bhilwara	77876	338	50	50	10	1	2.78	0.63	1.84	0.33

8	Bikaner	124906	387	45	45	6	-	1.97	0.36	2.50	0.66
9	Bundi	156678	153	20	20	15	2	3.00	0.60	1.00	0.00
10	Chittorgarh	182019	185	26	32	4	4	4.53	0.88	2.76	0.59
11	Churu	7122	46	12	12	3	-	3.09	0.71	1.78	0.29
12	Dausa	28263	48	10	10	7	-	3.50	0.81	3.50	0.89
13	Dholpur	63845	32	5	5	3	-	3.60	0.77	1.50	0.30
14	Dungarpur	69273	86	13	22	8	3	4.00	0.99	1.75	0.40
15	Ganganagar	23946	562	26	26	9	-	2.40	0.52	1.91	0.47
16	Hanumangarh	94566	258	16	19	8	-	3.16	0.76	1.40	0.24
17	Jaipur	58129	107	26	32	4	-	3.32	0.69	2.42	0.50
18	Jaisalmer	45261	71	31	32	6	-	2.03	0.38	2.14	0.52
19	Jalore	134979	100	19	24	15	-	3.04	0.66	2.50	0.64
20	Jhalawar	40535	160	23	23	9	8	4.26	0.81	2.45	0.53
21	Jhunjhunu	24303	39	6	12	8	-	2.25	0.35	1.90	0.38
22	Jodhpur	180206	147	136	136	65	-	2.20	0.48	2.01	0.45
23	Karauli	131082	117	16	16	6	-	4.00	0.81	3.47	0.94
24	Kota	24093	175	26	27	18	2	2.61	0.54	2.33	0.47
25	Nagaur	96358	88	16	18	5	-	2.17	0.45	2.56	0.56
26	Pali	140704	100	15	18	12	1	4.17	0.93	3.89	0.93
27	Pratapgarh	39658	80	15	17	-	10	5.53	1.10	2.07	0.37
28	Rajsamand	93772	127	13	13	3	-	4.73	0.86	3.69	0.88
29	Sawaimadhopur	63935	42	12	12	8	-	5.50	1.05	2.64	0.73
30	Sikar	163865	95	15	31	3	-	2.54	0.51	1.79	0.41
31	Sirohi	63344	79	17	17	7	3	7.18	1.22	4.47	1.04
32	Tonk	33597	47	9	9	4	-	2.11	0.41	1.67	0.38
33	Udaipur	414170	428	48	48	5	10	5.08	1.07	2.40	0.60
Rajasthan state (Total)		3270135		833	903	317	63	3.59	0.74	2.39	0.54

Out of the total forest area of 3.27 million hectare, 0.96 million hectare area is under four national parks covering about 0.39 million hectare and 24 sanctuaries covering about 0.57 million hectares area in Rajasthan. The area under dense (>40% canopy cover) and open forest (10-40% canopy cover) in 2013 was 4496 km^2 and 11590 km^2, respectively. This shows an increasing trend as compared to the area under respective category as 3048 km^2 and 9430 km^2 in 1987 (Fig 2.3). Such changes indicate additional area through afforestation otherwise there is a decrease in dense forest covers in latter assessments (SFR, 2013). However, significantly high fluctuation during 1999 and 2001 appears to be due to change of methodology in forest assessment indicating a net increase in forest covering by 2496 km^2 area during this period.

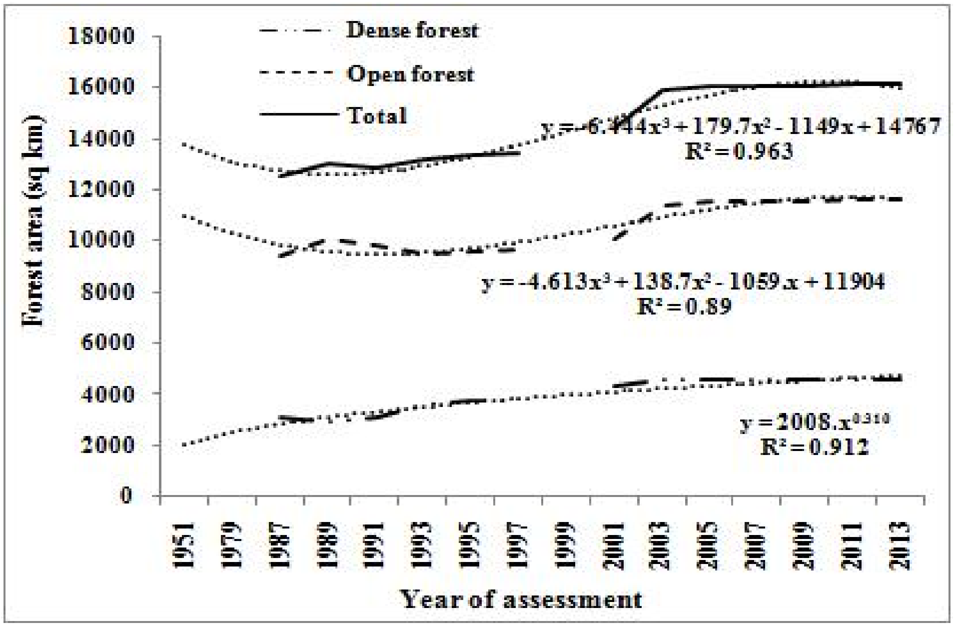


Figure 2.3 Trends in dense, open and total forests cover in Rajasthan during 1987 to 2013.

5.5 Natural vegetation

A wide range of topographical, environmental and pedological variation in Rajasthan has strong influence on vegetation types and their compositions. Recently published article in *Vadose Zone Journal* indicates that the number of soil types in an area (the "pedodiversity") and the biodiversity of that area – the number of species of vascular plants, amphibians, reptiles, birds, and mammals are observed strongly correlated on a global scale. This study suggests that the biodiversity of an area depends on the extent of that area as well as its environmental heterogeneity and the variety of habitats available for plants and animals (Ibáñez and Feoli, 2013).

Rajasthan is bestowed with a variety of plants ranging from ephemerals herbaceous to perennial trees (Sharma and Tiagi, 1979; Shetty and Pandey, 1983; Singh, 1983; Shetty and Singh, 1987; 1991; 1993; Bhandari, 1990; Awasthi, 1995; Aery and Tyagi, 2009). Vyas (1964) has studied the flora of Alwar district, whereas Majumdar (1976) and Maheshwari and Singh (1976) have carried out an appreciable work on flora of Kota, where about 700 species have been recorded from the region. Ecology and vegetation of Kota and Shahabad have been studied indicating the persistence of native species (Jain and Kotwal, 1960; Gupta, 1965). The Thar Desert of India exhibits 682 plant species (Khan, 1997). However, Shetty and Singh (1993) listed 775 plant species belonging to 91 families and 385 genera in Rajasthan. In this 588 species are of dicots and 186 species are of monocots and one is gymnosperm. Most dominant family is Poaceae followed by Cyperaceae with 125 and 35 species, respectively. Of this, forty-five plant species are considered to be rare and/or endangered. However, there are further additions of species in subsequent studies (Sharma et al., 2005; Meena and Yadao, 2010; Singh et al., 2011; Joshi and Shringi, 2014).

5.5.1 Vegetations of Western Rajasthan

Major portion of the Thar is occupied either by dry open grassland or by grassland-Dichanthium-Lasiurus-Cenchrus type (Dabadghao and Shankarnarayan, 1975) and interspersed with trees and thorny bushes. Most of the vegetation consists of drought resistant stunted, thorny or prickly shrubs and perennial herbs (Bhandari, 1990). These species can be categorized into herbs, grasses, climbers, undershrubs and shrubs and trees (Annexure 2.2 to 2.6). In the western region, sparse vegetal cover comprises mainly xerophytic plants, which are thorny and have stunted growth. Vegetations of Thar are divided into following habitats depending on the physiography of the region and the adaptability of the species to varying habitats (Gupta, 1975; Mares, 1999).

Sand dunes and interdunal plains: Nearly 48% of the Thar is covered with sand dunes and interdunal plains. Many shifting dunes are bare. The dunes in community lands or forest lands have been in the process of plantation particularly with *Acacia tortilis*. The stabilized and semi-stabilized dunes are generally occupied with *Capparis decidua* (Ker), *Calotropis procera* (Aak), *Calligonum polygonoides* (Phog), *Acacia senegal* (Kumat), *Prosopis cineraria* (Khejri), *Aerva javanica*, *Aristida funiculata*, *Aristida adsensionis*, *Dactyloctenium aegyptium*, *D. sindicum*, *Cyperus arenarius* and other psammophytic species. At the base of the dunes and interdunal plains, where soil moisture availability is relatively greater, the vegetation may consist of trees and shrubs such as *Acacia senegal*, *A. jacquemontii* (Bhui Bavali), *Prosopis cineraria*, *Tecomella undulata* (Rohida), *Salvadora persica* (Jal) and *Zizyphus nummularia* (Jhar Ber). *Citrulus colosynthesis* and *C. lanatus* are the creepers of the sandy areas. Occasionally some species like *Moringa concanensis* and *Delonix elata* are also observed.

Sandy plains: Besides some of the trees and shrubs mentioned above for sand dunes and interdunes, sandy plains may also have herbs and shrubs like *Arnebia hispidisima, Crotalaria burhia, Convolvulus microphyllus, Farsetia hamiltonii, Heliotropium marubifolium, Indigofera cordifolia, Leptadenia pyrotechnica, Tephrosia purpurea* etc.

Gravelly pediments: Beside, the sandy plains and sand dunes, the most common feature of the Thar is gravelly pediments and low hills seen in Barmer, Jaisalmer and Jalore. The dominant trees are *P. cineraria* and *Salvadora oleoides*. Dominant shrub species are *Maytenus emarginata* (Kankera), *Calotropis procera*, *Euphorbia* spp., *Capparis decidua* and *Zizyphus nummularia*. Common grass is *Aristida funiculata*.

Hilly and rocky outcrops: This feature exists in some parts of Barmer. However, it spreads about 13,200 sq km areas in western Rajasthan, mainly near Barmer, Kailana-Mandore in Jodhpur, Jalore, Sirohi and Ajmer. The characteristic plants of these rocky outcrops are thor (*Euphorbia caducifolia*), kumatha (*Acacia senegal*), dhok (*Anogeissus pendula*), ker (*Capparis decidua*), gugal (*Commiphora wightti*), kankera (*Maytenus emarginata*) and dholken (*Grewia tenax*). There are large number of shrubs, annual herbs and climbers recorded in the region.

Saline depressions: There are many saline depressions in the Thar. These are Sambhar, Pachpadra, Tal Chhapar, Falaudi and Lunkaransar where Sodium chloride salt is produced from salt water. The Didwana lake produces Sodium Sulphate salt. Ancient Archaeological evidences of habitations have been recovered from Sambhar and Didwana lakes which show their antiquity and historical importance. The characteristic halophytic vegetation in the region consists of *Salvadora persica*, *S. oleoides*, *Tamarix aphylla*, *Salsola baryosoma*, *Chenopodium*, *Haloxylon salicornicum* and *Sueda fruticosa*. The major grasses and sedges are *Eleusine compressa*, *Eragrostis ciliaris*, *Dactyloctenium aegyptium*, *Cyperus rotundus* and *C. arenarius*. The most famous saline depressions are in Pachpadra, Sambhar etc. The other depression is at Kawas and has tree species *Tamarix auriculata*, *Fagonia cretica*, *Prosopis juliflora* etc.

Riverbeds: Luni and its tributaries flow only during the monsoon for three to four months, although pools remain for a much longer period. It originates from the Ajmer hills and passing through Jodhpur, Pali, Barmers it enters into Sanchor tehsil of Jalore division. At Gandav village in Barmer, this river receives water from Sukari flowing through the Bagoda and Sanchor tehsil of Jalore district. Most of the riverbed is covered with *P. juliflora* as the dominant species, but occasionally some trees of *Acacia nilotica* are also visible. *Tamarix ericoides* is also common in some of the places. The grasses are generally represented by *Aeluropus lagopoides*, *Desmostachya bipinnata* in association with *Prosopis juliflora*, *Dactyloctenium aegyptium* and *Eragrostris ciliaris*. The main sedge is *Cyperus rotundus*.

Wetlands: Interestingly there are many water bodies called ‘Nadi’, ‘Bavadi’ and ‘Ponds’ in the villages of the Thar Desert for storing and collecting rainwater for its utilization in drinking and irrigating agriculture crops. These smaller wetlands and village ponds have *Potentila supine*, *Pullicaria crispa*, *Cyperus rotundus*, *Fimbristylis dichotoma* and *Scirpus roylei* species along the edge and *Ceratophyllum*, *Hydrilla verticillata*, *Ipomea aquatica*, *Nymphoea* and *Vallisneria spiralis* in the water.

5.5.2 Vegetation of Southern and Eastern Rajasthan

Vegetation of this region ranges from mixed deciduous forests to subtropical evergreen forests, but it has been adversely affected by reckless cutting and grazing. Forest in the eastern region comprises many trees, shrubs and grass species (Annexure 2.2A to 2.2E). Among these *Anogeissus latifolia* (Safed Dhavada), *Boswellia serrata* (Salar), *Lannea coromandelica* (Gurjan) etc occupy hill ridges and high slopes. *Anogeissus penduala* (Kala Dhav) is most common species of Aravalli hills as either pure crop or associated with other species like *Boswellia serrata*, *Zizyphus* spp. *Tectona grandis* (teak) is common to the region found associated with *Lannea coromandelica, Dalbergia paniculata, D. dalbergioides, Diospyros melanoxylan* (Tendu) etc. *Acacia catechu* (Khair), *Azadirachta indica* (Neem), *Madhuca indica* (Mahuva), *Syzygium cumini* (Jamun), *Terminalia arjuna* (Arjun), *Mitragyna parviflora* (Kalam), *Acacia nilotica* (Babul) etc (Plat 2.3) are other tree species observed in the region with relatively high soil water availability or along the water courses (i.e., *S. cumini*, *T. arjuna*, *M. parviflora*). *Cassia auriculata* (Aunwal), *Euphorbia* spp., *Woodfordia fruiticosa*, *Adhatoda vasica*, *Rhus mysorensis* including *Lantana camara* (an invasive species) are the common shrubs. Dominant grass species are *Apluda mutica*, *Cenchrus ciliaris*, *C. setigerus*, *Chrysopogon montanus*, *Chloris barbata*, *Cymbopogon martini*, *C. jwarncussa*, *Cynodon dactylon*, *Dichanthium annulatum*, *Heteropogon contortus*, *Iseilema laxum*, *Sehima nervosum*, *Themada quadrivelvis* etc.

Some of the protected areas in the region are heavily occupied by some invasive species either one species or the other. For example Kumbhalgarh Sanctuary is occupied by both *P. juliflora* and *Lantana camara*, Sariska Sanctuary is occupied by *Adhatoda vasica*, Kevaladeo Ghana Bird Sanctuary is occupied by *P. juliflora* etc. Infestation of *P. juliflora* is appeared to be due to overgrazing or removal of the local vegetations and dispersal of seeds of *P. juliflora* through animals dropping in foothills and pediments.

6. CONCLUSION AND FUTURE PERSPECTIVES

A wide range of latitudinal, altitudinal and climatic diversities in drylands have resulted in varieties of habitats and soils. Such diversities are essential to the survival of species, support and maintain plant and animal species and sustain livelihoods of people living in the dry regions. Drylands congregate about 20% of the major plant diversity centres available in nationally-designated protected areas covering about 5.4 million km^2 of the world's drylands. Changing life span, growth pattern, physiology and biochemical behaviour are the ways by which plants and animals adapt themselves towards adversities of the environmental conditions of the drylands. Life forms like ephemerals, annuals and succulent and non-succulent perennials among the plants; and migration, burrowing, hoarding food, rapid reproduction and tolerance towards large fluctuation in temperature in animals are important ways of adaptations.

Except in few cases species richness and diversity of both plant and animal species are generally low in the dryland as compared to the other regions with relatively high water availability. But varieties of habitats and isolation of populations result in higher within-species diversity and appeares positively related to multiple functions of the ecosystem (Maestre et al., 2012). However, increasing climatic adversities with increase in aridity and the exponential increase in human population over the past century have caused pressures on the landscape accelerating various processes of desertification. Community assemblage and biotic attributes of plant communities that help maintain multiple ecosystem functions will be affected by predicted increasing aridity under changing environmental conditions. Further implications of overgrazing and encroachments by woody perennials will also affect functioning of dryland ecosystems.

Increased land use change, CO_2 level and predicted climate changes will lead to habitat loss and land degradation. The consequences are changes in ecosystem services (e.g. biodiversity, water supply, soil functioning, resilience) and a reduction in economic profitability threatening the livelihoods.

Variable rainfall and increasing trend in air temperature in Rajasthan, which covers about 34.23 miliion hectare areas, 68.62 million human and 57.73 million livestock population will also be threatened by increased water scarcity and agriculture and forest productivity.

Extent of degradation is such that about two third of the forest subtypes present in Rajasthan show below average standing biomass and carbon storage. Likewise forests of Ajmer, Bikaner, Churu, Sriganganagar, Jaisalmer, Jodhpur, Nagaur, Banswara, Bundi, Dausa, Jhalawar, Kota, Sawaimadhopur and Tonk districts show below average carbon density. Similar conditions are also for the pasturelands. Decrease in soil organic carbon and live biomass density and increase in soil inorganic carbon in the ecosystem is also an indicator of land degradation in Rajasthan.

The problem associated with such degradation appears to be the negligence by the local people and vice-versa in managing common resources together with forests. There is a need to think upon means and ways by which local people, particularly the poors, could be involved and work to reverse the process of land degradation and improve their livelihoods.

Plate 2.1 A desert view in Thar indicating linear dunes with isolated vegetation (left) and village Chetrodi in Shiv tehsil of Barmer district in Rajasthan (right).

Plate 2.2 A pastureland of *Lasiurus scindicus* in remote area of Jaisalmer (left) and severly degraded grazing land (right).

Plate 2.3 Riverin species in Mahi river area (left) and *Mitragyna parviflora* along a water body.

Annexure 2.1. Forest sub types and their probable locations in Rajasthan based on different studies

S No.	Sub-group type	Type name	Forest type availability in area or forest blocks		
			Champion & Seth (1968)	**ICFRE (2013)**	**Singh (2014b)**
1	5/1S1	Dry tropical riverain forest	Mahi river in Banswara	Chittorgarh	Sambhupura in Banswara, Karundia in Chitorgarh, Damoh in Dholpur, Damaria-1 in Dungarpur, Lakhaba-A in Kota, Amba pani in Pratapgarh and Makodia and Nalmokhi in Udaipur.
2	5/1S2	*Acacia catechu* Forest	-	-	Sariska Tiger Reserve in Alwar, Sambhupura in Banswara, Kasbathana-A in Baran, Badi in Chitorgarh, Borabas in Kota and Bansa in Rajsamand.
3	5/2S1	Secondary dry deciduous forest	Pratapgarh and Salamgarh Range in Banswara	Pratapgarh (Banswara) Salamgarh Range	Keoladev N. Park in Bharatpur, Ghatoli and Arera in Jhalawar, Gandher Radi in Pratapgarh and Haldi Ghati in Rajsamand.
4	5/2S2	Secondary Mixed dry Deciduous Forest	-	-	Kalyan Sagar in Baran and Gomukh area of Mt Abu in Sirohi.
5	5/DS1	Tropical Dry Deciduous scrub	Banswara	Abu Road (Sirohi)	Throughout Aravalli range of Rajasthan.
6	5/DS2	Tropical Dry Savannah forest	Not defined place Only species composition		Kharddia and Beed Hurdda in Bhilwara and Subara subari and Falasiya in Udaipur.
7	5/DS4	Tropical Dry Grassland	Only species composition	Kishangarh (Ajmer)	Para and Ganglas Chhapli in Bhilwara, and Karah Jod, Sudhasari and IGNP plantation 220RD in Jaisalmer.
8	5/E1	Anogeissus pendula forest	Ajmer, Chittorgarh fort, Dungarpur and Badnor in Udaipur	Bharatpur, Karauli, Bundi, S. Madhopur and Bajna, Indragarh, Falodi, Bassi and Borav Range in Chittorgarh.	Throughout semi-arid region and Aravalli range of Rajasthan and most of the arid district.
9	5/E1/DS1	*Anogeissus* pendula scrub	Not defined place Only species composition	Khetri in Jhunjhunu, Barmer, Bayana in Bharatpur,	Maakadwali, Baadamala, Bheelabat Dungra and Rajgarh in Ajmer, Bala dahra, Khera Mangal Singh, Godbag and Chimrauli in Alwar, Nahara Parvat in Bharatpur, Amargarh, Ulalabeed-A and Andheri in

S No.	Sub-group type	Type name	Forest type availability in area or forest blocks		
			Champion & Seth (1968)	ICFRE (2013)	Singh (2014b)
				Bundi and Bassi, Piplud, Indragarh Range in Chittorgarh.	Bhilwara, Rashmi, Gandraf and Kherdi in Chittorgarh, Dolia, Mavasa khera and Budkalas in Kota, Dhanachay and Lotana in Sirohi, and Baneta and Mata ji ki dungari in Tonk.
10	5/E2	*Boswellia* forest	Sarwan Deri block in Banswara and Baghana in Udaipur	-	Hokra and Srinagar in Ajmer, Agar village and Sariska T.R. in Alwar, Khareri in Bharatpur, Naya Nagar, Bhojaji ka Beed, Bairath, and Shohanpura in Bhilwara, Berupura in Bundi, Falihor in Dungarpur, Jamwa Ramgarh, Raisar, Virat Nagar, Khonagoriana and Bhuchara in Jaipur, Chakghas Malkhet-II in Jhunjhunu, Jawaher Sagar-1 in Kota, Bhagawadd in Rajsamand, Kuagaw in Sawai Madhopur, Dokan in Sikar, Bhakar in Sirohi and Sarvani ven, Padrada (Lawo ka Mathara), Shivadia and Jhamri-A in Udaipur.
11	5/E3	Babul forest	-	-	Chandpur in Alwar, Bheempura in Banswara, Shahpura in Jaipur and Tokar in Udaipur.
12	5/E5	*Butea* forest	Chittorgarh	Keladevi in Karauli and Begun, Bassi and Borav Range in Chittorgarh Forest division	Machadi, Amka, Lapada and Neemli in Alwar, Chitathala, Bhaverkote, Kotdi Bagaycha and Kalmi-A in Banswara, Bhavergarh, Basthuni-B, Raatae and Saarthal-B in Baran, Saimal and Basota ki Dhar in Bhilwara, Dabi phalka-B, Gopalpura and Lamba Khoa in Bundi, Sadi, Nahargarh and Jhhanjhi Rampura in Dausa, Bhuchara in Jaipur, Lotiyajhar, Molkiya, Richwa, Chandipur, Chamargarh kotda and Badgawvilas in Jhalawar, Amarvan in Karauli, Darra Sanctury in Kota, Nana-A in Pali, Jhamda Jogi and Jawaharnagar in Pratapgarh, Bhaisasingh and Forest Chotila in Sirohi, and Sagwada, Piapalbara, Bhuri dheper, Meerpur and Panund in Udaipur division.
13	5/E6	*Agle marmelos* type	Semalpur forest (Chittorgarh)	-	Samli Pathar in Chittorgarh and Borimlan, Jawsar Singatwara B, Jhunthari and Samar-A in Udaipur
14	5/E8a	Phoenix savannah forest	-	-	Tijara and Sariska Tiger Reserve in Alwar, Karundia in Chittorgarh and Dhar in Pratapgarh and some depression area in Udaipur and Dungarpur division.

S No.	Sub-group type	Type name	Forest type availability in area or forest blocks		
			Champion & Seth (1968)	**ICFRE (2013)**	**Singh (2014b)**
15	5/E8b	Babul Savannah forest	-	-	Jhakara and Dagdaga in Alwar, Keoladev N. Park in Bharatpur and Champapur Beed in Chittorgarh division.
16	5/E9	Dry bamboo brakes	Banswara	-	Sariska T.R. in Alwar, Sarvanderi-B and Satbidia in Banswara, Kungiswas in Baran, Kundal hill top in Barmer, Jaswantpura, Janagarh, Arampura and Chitarimata in Pratapgarh, Bagor B in Rajsamand, Mt.Abu in Sirohi and Khokaria Ki Nal and Majawad in Udaipur division.
17	5A/C1a	Very dry teak forest	Chittorgarh, Banswara, Udaipur	Banswara and Pratapgarh	-
18	5A/C1b	Dry teak forest	Banswara,	Chittorgarh	Naal Dabri, Bara Nandra Kho, Anandsagar, Talimakhia, Talavda, Tapada, Galdhar, Balachana Khajura, Kotharia, Jagmer jogimal-29 and Bhagtol-A in Banswara, Nayagaon ranwasa, Godiya chharan and Govindpura Beed Ghas in Baran, Rani Jhula, Pipallekh (Kavla Pipal)-1, Dungar Saran, Charwada, Charwada A and Marg Talab-1 in Dungarpur, Dhanoda in Jhalawar, Poona Pathar, Huda Bap Ji, Gamargarh Panadia, Sagwadi Bhootkhora, Chiklad, Bera, Jhaunda Kerwas, Panchkuda and Sitamata Sanctuary in Pratapgarh, and Manpura, Jhanjhari, Sun kala and Sageti in Udaipur.
19	5A/C3	Southern Tropical Dry Deciduous Forest	-	-	Padajhar and Jawada in Chittorgarh, Jaitaran ka Magra and Kumbhalgarh in Rajsamand, and Table tank and Mt. Abu in Sirohi.
20	5B/C2	Northern Tropical Dry Mixed Deciduous Forest	Chittorgarh, Udaipur	Kelwada in Rajsamand, Shahbad in Baran and Begun and Bassi range in Chittorgarh	Nahargarh, Jaitpura, Telani-B, Mundyari-A, KundaKotda-B, Mandisamar singh, Blendi, Jaipalla, and Modhpur Kunda in Baran, Kundal in Barmer, Marera in Bharatpur, Doliduma and Baanka in Bhilwara, Lavadia, Banseria, Dhawda Kuri and Bassi (Jalerwar) in Chitorgarh, Pipallekh (Kavla Pipal) and Nara Magra-2 in Dungarpur, Jaipur, Khokunda, Malatota, Mankund, Mandawar, Taraj and Surajpura in Jhalawar, Siyakheri in Pratapgarh, Tejo ka Gudda and Bagor C in Rajsamand, Jibraj ki Dhani and Arnua Compartment-5 & 8 in Sirohi, and Dholagarh, Ajbara, Dingri, Jhabla, Chanawad, Rishabhadev C, Paba A,

S No.	Sub-group type	Type name	Forest type availability in area or forest blocks		
			Champion & Seth (1968)	**ICFRE (2013)**	**Singh (2014b)**
					Marwad Alsigarh, Bari naka, Jhameri, Sar, Kodharmal, Adiwali Barwadi A and Naua in Udaipur division.
21	6/1S1	Desert dune scrub	Southern Rajasthan, Jhunjhunu	Kishangarh, Ajmer Saradhna, Naka, Sarwaad Range	Boravas, Goyana, Bhatala and Bheemthal in Barmer, 2 DL, 6DLM, 5AWM (Awaminor), 14 DKD, 5 KKM, 2BRWM, 43 KJD,1 HWM-II,7 BLD, 5 MTM, 2LKD plantation in Bikaner, 34 RD Sangita Block and 2ANM in SriGanganagar, Dav, Khuri, Faledi and Ghantiyali in Jaisalmer, Bhatkoria, Bawadi, Bagoriya-II, Osian III, Osian II, Bhari nagar II, Balarva II, Rajasni, Mathania , Chirai, Khichan, Falodi I, Falodi IV, Khirva, Baap II, Bap b, Naya Gaovn, Khakhori, Dholiya, Takra and Jamla in Jodhpur and Rinyan Badi in Nagaur.
22	6/2S2	*Prosopis juliflora* scrub	-	-	Throughout and all district of Rajasthan except in Pratapgarh didvision.
23	6/E1	*Euphorbia* scrub	Kailana and Mandor area, Jodhpur, Jaipur hills, Western Rajasthan and Deogarh area in Udaipur division	Siwana Range in Barmer and division of Ajmer	Hasla in Alwar, Kiradu hill in Barmer, Baddach and Karnipura in Bhilwara, Amner and Sunarkuddi in Rajsamand and Kaler in Udaipur division.
24	6/E2	*Acacia senegal* forest	Galta area in Jaipur division	Rajasthan	Somalpur, Madaar Pahar, Leelasewadi, Savitri, Saalarmala, Bhinay and Kotda in Ajmer, Vishala hill, Kuship-B, Bherupura ki Dhar, Beed Vanedda, Pili Magara, Aamesar, Shivpur, Lonedi and Amba ki Babri in Bhilwara, GLI Area in Bikaner, Chattargang in Bundi, Beed Ratannagar, Shyampadya and Dungra Athuda in Churu, Dausa Pahaar in Dausa, Pawata, Chhatarpur Piplud and Bichchun in Jaipur, Rama (Hill) and Badgoan hill in Jalor, Khetri area and Kankaria in Jhunjhunu, Keru-II, Naarva, Melana-II, Sawaniya, Osian VII, Bhari nagar I, Nandiya Kalan, Balarva I, Kharda Mavasar, Bhikamkor and Salawas in Jodhpur, Jhalra-A, Manglana, Biratia khurd, Borwad and Deepawas in Pali, Udansari, Rewasa jeenmata, Balwar-3, Kalakhera-3,

S No.	Sub-group type	Type name	Forest type availability in area or forest blocks		
			Champion & Seth (1968)	**ICFRE (2013)**	**Singh (2014b)**
					Meerpur and Balda in Sirohi and Kali Ghati (Kewda) block in Udaipur.
25	6/E3	Run saline thorn forest	-	-	Bagundi and Jhakarda in Barmer, RSM1 in Bikaner, Talchapar sanctuary in Churu, PPM 3 in SriGanganagar and Bhavatra forest block in Jalor division.
26	6/E4	*Salvadora* scrub	Jaipur.	-	Doonbas and Chhachhaka in Alwar, Bhimgora, Dedusar and Sihania in Barmer, Punchhri in Bharatpur, Shakhu, Ramdeora, Chhod I and Devicoat in Jaisalmer, Dorda, Sarnau and Kuri Sariyana in Jalor, Beed Forest in Jhunjhunu, Osian IV, Udat and Daipada in Jodhpur, Guda Endala in Pali and Khandela in Sikar.
27	6/E4/DS1	*Cassia auriculata* scrub	No defined place. Only species composition	-	Baretha in Jalor and Jod Sindarlai in Pali division. Moreover some of the community lands also shows such type of vegetation.
28	6A/C1	Southern thorn forest	-	Hanuman-garh, Barmer, Jalor, Jodhpur, Dholpur	-
29	6B/C1	Desert thorn forest	Joharbir in Bikaner and Bassi area in Jaipur	-	Bardod in Alwar, Bhaislana in Jaipur and most of the area of Arid districts of Rajasthan.
30	6B/C2	Ravine thorn forest	Gurla forest, (Chittorgarh)	-	Karawali in Bharatpur, Plantation 1957 Bandikue in Dausa, Sikharra in Dholpur, Acharol in Jaipur, Gudla and Paucholi in Karauli and Dabrikala, Geti, Nonera, Khatauli-A, Gordhanpura, Baalopa, Gopalpura, Barod, Mandaabra-A, Madanpura and Narsinghpura in Kota.
31	6B/DS1	*Zizyphus* scrub	Western Rajasthan, Jodhpur	-	Amdasar in Baran, Lohawat and Kolu Pabuji in Jodhpur and Sakatpura, Buddhkhan beed and Barapaate in Kota.
32	6B/DS2	Tropical Euphorbia scrub	Kailana and Mandor area in Jodhpur, Jaipur Hills area, Western Rajasthan, and Deogarh in Udaipur	Sivana Range, Ajmer	Ismilepur in Alwar, Kumpawas and Junapatrasar in Barmer, Jhalamali and Beedd Gorkhiya in Bhilwara, Naarkhurra, Kundal and Bilochi in Jaipur, Navi Hill in Jalor, Motisara, Wasteland and Beriganga in Jodhpur, Manglana B in Nagaur, Biratia Khurd and Manpura Bhakhri in Pali, Kantia dantila and Bhudoli in Sikar and Chandsen (R.F.) in Tonk forest division.

S No.	Sub-group type	Type name	Forest type availability in area or forest blocks		
			Champion & Seth (1968)	ICFRE (2013)	Singh (2014b)
33	8A/C3	Central Indian sub-tropical hill forest	Mt. Abu	-	-

Annexure 2.2A. Trees species with their families and local names in Rajasthan.

SNo	Botanical Name	Local Name	Family
1.	*Acacia auriculiformis* A. Cunn. ex Benth.	Australian babul	Fabaceae
2.	*Acacia catechu* Willd.	Khair	Mimosaceae
3.	*Acacia concinna* (willd.) Dc.	Shikakai	Fabaceae
4.	*Acacia farnesiana* (L.) Willd.	Hirkia Balia or Gandh Babool	Fabaceae
5.	*Acacia ferruginea* DC.	Safed khair, Kaigar khair	Mimosaceae
6.	*Acacia leucophloea* (Roxb.) Willd.	Arunj, Reunja	Mimosaceae
7.	*Acacia nilotica* (L.) Willd.	Babul, Deshibaval	Mimosaceae
8.	*Acacia nilotica* var. *Cupressiformis* (J. L. Stewart) Ali & Faruqi	Kabuli Kikar,Soolia babool, Ramkanti	Fabaceae
9.	*Acacia senegal* (L.)Willd.	Kumtha	Mimosaceae
10.	*Acacia tortilis* (Forssk.) Hayne	Israeli babul, Baawali	Fabaceae
11.	*Adansonia digitata* L.	Kalpvriksh	Bombacaceae
12.	*Adina cordifolia* (Roxb.) Brandis	Haldu, Hed	Rubiaceae
13.	*Aegle marmelos* (Linn.) Corr.	Beel, Bel	Rutaceae
14.	*Ailanthus excelsa* Roxb.	Ardu, Aduso	Simaroubaceae
15.	*Alangium salvifolium* Linn.f.	Ankol	Cornaceae
16.	*Albezzia lebbeck* (L.) Benth	Siris (Kala)	Fabaceae
17.	*Albizia odoratissima* (L.f.) Benth	Chichwa, kala siris	Mimosoideae
18.	*Albizia procera* (Roxb.) Benth.	Siris (Safed)	Fabaceae
19.	*Alstonia scholaris* (L.) R.Br.	Saptaparni, Shaitan ka jhar	Apocynaceae
20.	*Anogeissus latifolia* (DC.) Wallich ex Guill. & Perr.	Safed Dhawra	Combretaceae
21.	*Anogeissus pendula* Edgew.	Kala Dhonk	Combretaceae
22.	*Anogeissus sericea* ssp. *nummularia* Brandis	Indroka	Combretaceae
23.	*Anthocephalus cadamba* (Roxb.) Miq.	Kadam	Rubiaceae
24.	*Azadirachta indica* A. Juss.	Neem	Meliaceae
25.	*Balanites aegyptiaca* (Linn.) Del.	Hingot, Hingoria	Simaroubaceae
26.	*Bauhinia racemosa* Lam.	Jhinjha, Asundro, Asitro	Caesalpiniaceae
27.	*Bauhinia variegata* Linn	Kachanar	Caesalpiniaceae
28	*Bombox ceiba* L.	Semal	Bombacaceae
29	*Borassus flabellifer* Linn.	Tad	Arecaceae
30	*Boswellia serrata* Roxb. ex Colebr.	Salar	Burseraceae
31	*Bridelia retusa* (L.) Spreng.	Asan, Dantelo	Euphorbiaceae

SNo	Botanical Name	Local Name	Family
32	*Buchanania lanzan* Spreng	Chiraunji, Achar	Anacardiaceae
33	*Butea monosperma* (Lamk.) Taub.	Palas, Chheela, Khakhara	Fabaceae
34	*Capparis decidua* (Forsk.) Edgew.	Ker, Kerro, Karil	Capparaceae
35	*Capparis grandis* Linn.	Pandan Bor	Capparaceae
36	*Casearia elliptica* Willd.	Mojaal	Lecythidaceae
37	*Cassia fistula* Linn.	Amaltas, Garmala, Karmela	Caesalpiniaceae
38	*Cassia siamea* Lam.	Kasod	Fabaceae
39	*Citrus medica* linn	Nimboo	Rutaceae
40	*Clausena pentaphylla* D.C.	Ratanjot	Rutaceae
41	*Cochlospermum religiosum* (L.) Alston.	Ganiara	Bixaceae
42	*Cordia dichotoma* G. Forst.	Gunda, Lasoda	Boraginaceae
43	*Cordia gharaf* (Forssk.) Ehrenb. ex Asch.	Gundi	Boraginaceae
44	*Cordia myxa* L.	Gunda	Boraginaceae
45	*Crataeva nurvala* Buch. Ham.	Barna	Capparaceae
46	*Dalbergia paniculata* Roxb.	Pai, Dhoban	Fabaceae
47	*Dalbergia sissoo* roxb.	Shisham	Fabaceae
48	*Delonix elata* (Linn.) Gamble	Sandesro, White gulmohar	Caesalpiniaceae
49	*Delonix regia* Raf.	Gulmohar	Caesalpiniaceae
50	*Diospryos tomentosa* Roxb.	-	Ebenaceae
51	*Diospyros montana* Roxb.	Chikon	Ebenaceae
52	*Diospyros cordifolia* Roxb.	Bishtendu	Ebenaceae
53	*Diospyros melanoxylon* Roxb.	Timru, Tendu	Ebenaceae
54	*Dolichandrone falcata* (Wall.ex DC.) Seem	Medhshingi, Padol, Geuli, Tentu	Bignoniaceae
55	*Ehretia aspera* Willd.	Tambolia, Chanror	Boraginaceae
56	*Ehretia laevis* Roxb.	Tambolia	Boraginaceae
57	*Elaeodendron glaucum* Pers.	Jamrasi, Alan	Celastraceae
58	*Emblica officinalis* Gaertn.	Aonla	Euphorbiaceae
59	*Eriolaena hookeriana* Wight & Arn.	Giyari	Malvaceae
60	*Erythrina suberosa* Roxb.	Gadha Palas, Bhongaro, Paldua	Fabaceae
61	*Eucalyptus camaldulensis* Dehn	Safeda	Myrtaceae
62	*Feronia limonia* (linn) swingle	Kaith, Kotbari	Rutaceae
63	*Ficus arnottiana* (Miq.) Miq.	Pipal, Indian Rock Fig	Moraceae
64	*Ficus bengalensis* Linn.	Bargad, Bar	Moraceae
65	*Ficus carica* L.	Anjir	Moraceae
66	*Ficus cordifolia* Roxb	Paras Pipal	Moraceae
67	*Ficus glomerata* Roxb	Gular	Moraceae
68	*Ficus hispida* Linn.	Khatumar (kumbhi)	Moraceae
69	*Ficus infectoria* Roxb.	Pakar	Moraceae
70	*Ficus macrophylla*	Pipal	Moraceae
71	*Ficus palmata* Forsk	Jangli-Anjir	Moraceae
72	*Ficus religiosa* Linn.	Pipal	Moraceae

SNo	Botanical Name	Local Name	Family
73	*Ficus tomentosa* Herb.Madr. ex Wall.	kathphari, Kathpeepal	Moraceae
74	*Garuga pinnata* Roxb.	Karpata	Burseraceae
75	*Gmelina arborea* Roxb.	Shevan, Gamhar, White teak	Verbenaceae
76	*Grevillea robusta* A.Cunn. ex R.Br.	Silver Oak	Proteaceae
77	*Grewia asiatica* L.	Phalsa, Shukri	Tiliaceae
78	*Grewia elastica* Royle	Dhaman	Tiliaceae
79	*Grewia tiliifolia* Vahl	Dhaman	Tiliaceae
80	*Guazuma ulmifolia* Lam.	Rudrakshi	Sterculiaceae
81	*Hardwickia binata* Roxb.	Anjan	Caesalpiniaceae
82	*Holarrhina antidysenterica* Wall. Ex A. DC.	Dudhi, Karwala	Apocynaceae
83	*Holoptelea integrifolia* Roxb.	Kanji, Papri, Churel	Ulmaceae
84	*Kigelia pinnata* (Jacq.) DC	Balam khira	Bignoniaceae
85	*Lagerstroemia parviflora* Roxb.	Kalsadaria, Bakli, Sida	Lythraceae
86	*Lannea coromandelica* (Houtt.) Merr.	Gondal, Gurjan	Anacardiaceae
87	*Lawsonia inermis* Linn.	Mehndi	Lytharaceae
88	*Leucaena leucocephala* (Lam.) De Wit.	Subabool	Mimosaceae
89	*Limonia crenulata* Roxb.	Naopatti	Rutaceae
90	*Madhuca indica* J.Gmelin	Mahuwa	Sapotaceae
91	*Mallotus philiphinensis* Muell	Kamala, Rohani	Euphorbiaceae
92	*Mangifera indica* Linn.	Aam	Anacardiaceae
93	*Manilkara hexandra* (Roxb.) Dubard	Khirni	Sapotaceae
94	*Maytenus emarginata* (Willd.)	Kankera	Celastraceae
95	*Melia azedarach* Linn.	Bakain neem, Vilayati neem	Meliaceae
96	*Michelia champaca* Linn.	Champa	Magnoliaceae
97	*Miliusa tomentosa* (Roxb.) J. Sinclair	Umbia	Anonaceae
98	*Millingtonia hortensis* Linn.	AakashNeem, Neem chameli	Bignoniaceae
99	*Mimusops elengi* Linn.	Maulsiri	Sapotaceae
100	*Mitragyna parviflora* (Roxb.) Korth	Kadam, Kalam	Rubiaceae
101	*Morinda tinctoria* Roxb.	Aal, Aledi	Rubiaceae
102	*Moringa concanensis* nimmo ex Dalz. & Gibson	Sargora	Moringaceae
103	*Moringa oleifera* Lam.	Sainjana	Caesalpiniaceae
104	*Morus alba* Linn.	Shahtoot	Moraceae
105	*Murraya koenigii* (L.) Sprengel	Mitha Neem	Rutaceae
106	*Oroxylum indicum* (L.) Benth. ex Kurz	Tetu, Bhut-vriksha	Bignoniaceae
107	*Ougeinia oojeinesis* (Roxb.)Hochreut	Sandan, Tanas	Fabaceae
108	*Pandanus tectorius* Sol. ex.Rark.	Kewra	Pandanaceae
109	*Parkinsonia aculeata* linn	Bukhan	Caesalpinioideae
110	*Phoenix dactylifera* L.	Khajur	Arecaceae
111	*Phoenix sylvestris* Roxb.	Khajur	Arecaceae
112	*Pithecellobium dulce* (Roxb.) Benth.	Jangal Jalebi, Pardeshi amli	Mimosaceae

SNo	Botanical Name	Local Name	Family
113	*Polyalthia longifolia* (Sonn.) Thwaites	Ashok	Annonaceae
114	*Pongamia pinnata* (L.) Pierre.	Karanj	Fabaceae
115	*Prosopis cineraria* (L.) Druce.	Khejri, Sami	Mimosaceae
116	*Prosopis juliflora* (Sw) dc	Vilayati Babool	Fabaceae
117	*Pterocarpus marsupium* Roxb.	Bijasal, Biyo	Fabaceae
118	*Putranjiva roxburghii* Wall.	Jaiputha	Putranjivaceae
119	*Randia dumetorum* (Retz.) Poiret	Mindhal	Rubiaceae
120	*Riccinus communis* Linn.	Arundi	Euphorbiacae
121	*Salvadora oleoides* Decne.	Pilu, Mitha jal	Salvadoraceae
122	*Salvadora persica* Linn.	Kharajal	Salvadoraceae
123	*Santalum album* Linn.	Chandan	Santalaceae
124	*Sapindus emarginatus* Vahl.	Aritha	Sapindaceae
125	*Schleichera oleosa* (Lour.) Qken	Kusum	Sapindaceae
126	*Sericostoma pauciflorum* Stocks ex Wight	Lagria	Boraginaceae
127	*Soymida febrifuga* (Roxb.) A.Juss.	Rohan, Rohin	Meliaceae
128	*Sterculia urens* Roxb.	Katria, Gum Kadaya	Sterculiaceae
129	*Stereospermum suavedens* Roxb.	Padal, Patala	Bignoniaceae
130	*Syzygium cumini* (L.) Skeets	Jamun	Myrtaceae
131	*Syzygium jambos* (L.) Alston	Jamnai	Myrtaceae
132	*Tamarindus indica* Linn.	Emli, Imli	Caesalpiniaceae
133	*Tamarix aphylla* (L.) H. Karst.	Farash	Tamaricaceae
134	*Tecomella undulata* (smith) Seem	Rohida	Bignoniaceae
135	*Tectona grandis* L.f.	Sagwan	Verbenaceae
136	*Terminalia catappa* L.	Kadwa Badam	Combretaceae
137	*Terminalia tomentosa* Roxb. (ex DC)	Sadad, Saj, Sain	Combretaceae
138	*Terminallia arjuna* (DC.) Wight & Arn	Arjuna, Kohra	Combretaceae
139	*Terminallia bellerica* (Gaertn.) Roxb.	Baheda, Bahedo	Combretaceae
140	*Thespesia populnea* Linn	Paaras pipal	Malvaceae
141	*Toona ciliata* M. Roem	Toon	Meliaceae
142	*Trema orientalis* (L.) Blume	Indian charcoal-tree	Cannabaceae
143	*Vachellia farnesiana* (L.) Wight et Arn.	Gandhi babool	Mimosaceae
144	*Wrightia tinctoria* (Roxb.) R. Br.	Khirni, Dudhi	Apocynaceae
145	*Wrightia tomentosa* Roem. & Schult.	Dudhi, Kalo kudo, Kath-khirni	Apocynaceae
146	*Ziziphus xylopyrus* (Retz.) Willd.	Gathbor	Rhamnaceae
147	*Ziziphus mauritiana* Lam.	Ber, Bordi	Rhamnaceae

Annexure 2.2B. Shrubs and undershrubs species with their families and local names in Rajasthan.

SNo.	Botanical Name	Local Name	Family
1.	*Abutilon indicum* (Linn.) Sweet	Tara-kanchi, Kanghi	Malvaceae
2.	*Abutilon ramosum* Guill & Perr.	Pihari	Malvaceae
3.	*Acacia jacquemontii* Benth	Bhoo banwali	Mimosaceae
4.	*Adhatoda vasica* Nees	Adusa	Acanthaceae
5.	*Aerva persica* (Burm. f.) Merrill. in Philipp.	Bui	Amaranthaceae
6.	*Aerva pseudotomenosa* Blatt. & Hallb	Bui	Amaranthaceae
7.	*Agave americana* Linn.	Rambans	Agavaceae
8.	*Alhagi maurorum* Medik.	Jawasa	Fabaceae
9.	*Annona squamosa* L.	Sitaphal	Annonaceae
10.	*Argemone mexicana* Linn	Satyanasi	Papaveraceae
11.	*Barleria acanthoides* Vahl	Bajardanti, Chapari	Acanthaceae
12.	*Barleria cristata* Linn.	Bajardanti	Acanthaceae
13.	*Barleria prionitis* L.	Pili Kanteli	Acanthaceae
14.	*Cadaba fruticosa* (L.) Druce	Dabi	Capparaceae
15.	*Caesalpinia bonduc* (L.) Roxb.	Kantkaranj	Caesalpiniaceae
16.	*Calligonum polygonoides* Linn	Phog	Polygonaceae
17.	*Calotropis gigantea* R. Br.	Moto Aak, Madar	Asclepiadaceae
18.	*Calotropis procera* (Ait.) Ait.f	Aak	Asclepiadaceae
19.	*Capparis sepiaria* Linn	Kanther, Jaal	Capparidaceae
20.	*Carissa carandus* Linn.	Karaunda	Apocynaceae
21.	*Cassia angustifolia* Vahl	Sanay	Caesalpinaceae
22.	*Cassia auriculata* L.	Anwal, Tarwar	Caesalpiniaceae
23.	*Cassia occidentalis* Linn.	Kesudo	Fabaceae
24.	*Cassia sophera* Linn.	Kasaundi	Caesalpiniaceae
25.	*Citrullus colocynthis* schrad	Indrayan	Cucurbitaceae
26.	*Clerodendron phlomoides* Linn f.	Ami	Verbinaceae
27.	*Commiphora wightii* (Am) Bhand,	Gugal	Burseraceae
28	*Crotalaria burhia* Buch.Ham.	Senia, kharshna	Fabaceae
29	*Cryptostegia grandiflora* R. Br.	Vilayti akro	Periplocaceae
30	*Datura metel* Linn	Datura	Solanaceae
31	*Dendrophthoe falcata* (Linn. f.)	Banda (Apiphyte)	Loranthaceae
32	*Dichrostachys cinerea* (L.) Wight & Arn	Kamlai, Emna, Goyakhair	Fabaceae
33	*Dodonaea viscosa* Jacq	Kherata, Nevali, Nivoy	Sapindaceae
34	*Dyerophytum indicum* Kuntze		Plumbaginaceae
35	*Ephedra foliata* Boiss. & Kotschy ex Boiss.	Andho Khimp, Suo-phogaro, Sanbhar-bel	Gnetaceae

SNo.	Botanical Name	Local Name	Family
36	*Euphorbia caducifolia* Haines	Thor, Danda-thor	Euphorbiaceae
37	*Euphorbia neriifolia* L.	DandaThor, Patton-ki-send,Sehund, Sij	Euphorbiaceae
38	*Flacortia indica* (Burm. f.)	Kanker, Kakon, Kakoon	Flacourtiaceae
39	*Flemingia strobilifera* (L.) W.T.Aiton	Kanphuta, Kasraut	Fabaceae
40	*Grewia damine* Gaertn.	Gangaran	Tiliaceae
41	*Grewia flavescens* Juss.	Frangan, Kali Siyali	Tiliaceae
42	*Grewia tenax* (Forsk.) Fiori.	Gangan, Gangerun	Tiliaceae
43	*Grewia villosa* Willd.	Dholekan, Ban-phalsa	Tiliaceae
44	*Gymnosporia montana* (Roth) Bemth	Bekal	Celeastraceae
45	*Gynandropsis gynandra* (linn.) briq.	Arakpush	Capparaceae
46	*Haloxylon salicornicum* (Moq.) Bunge ex Boiss	Lana, Khar	Chenopodiaceae
47	*Hamiltonia suaveolens* (Roxb.) Roxb.	Padera, Padwa, Mahabal, Barcha, Ban champa	Rubiaceae
48	*Helecteres isora* Linn.	Maror-phali, Atedi	Sterculiaceae
49	*Indigofera anabaptista* stend	Bekario	Fabaceae.
50	*Indigofera argentea* Burm.f.	Neel, Jheel	Fabaceae.
51	*Indigofera oblongifolia* forsk	Jhil	Fabaceae.
52	*Ipomoea carnea* Facq.	Besharm	Convolvulaceae
53	*Jatropha gossipifoliia* L.	Choti Ratanjot	Euphorbiaceae
55	*Jatropha curcus* L.	Ratanjot	Euphorbiaceae
56	*Kirganelia reticulata* (Pior.) Baill	Khamboi, Neelbari	Euphorbiaceae
57	*Lantana camara* L.	Lantana, Dhanidaria	Verbenaceae
58	*Leptadenia pyrotechnica* (Forsk.)Decne.	Khimp	Asclepiadaceae
59	*Lycium barbarum* L.	Murali	Solanaceae
60	*Maerua oblongifolia* (Forssk.) A. Rich.	Orapa	Capparaceae
61	*Martynia annua* Linn	Bagh-nakhi, Bichchu	Martyniaceae
62	*Melhania futteyporensis* Munro ex Mast.	Basni	Sterculiaceae
63	*Mimosa hamata* Willd.	Jhinjani	Mimosaceae
64	*Nerium odoratum* Lam	Kaner	Apocynaceae
65	*Nyctanthes arbortristis* L.	Harsinghar, Sihari	Oleaceae
66	*Opuntia dillenii* (Ker-Gawl) Haw.	Nag Phni, Nagnithor	Cactaceae
67	*Papaver somniferum* linn.	Tijara	Papaveraceae
68	*Plumbago zeylanica* Linn.	Chittrak	Plumbaginaceae
69	*Punica granatum* Linn.	Anar	Punicaceae
70	*Punica granatum* Linn.	Anar	Punicaceae
71	*Rhus mysorensis* G.Don	Dansan	Anacardiaceae
72	*Sarcostemma acidum* (Roxb.) Voigt	Khir khimp, Kursanni, Tanta, Somlata	Apocynaceae

SNo.	Botanical Name	Local Name	Family
73	*Securinega virosa* (Roxb ex willd) Pax & Hottm	Selpi, Helpi	Euphorbiaceae
74	*Senna alata* (L.) Roxb.	-	Caesalpinaceae
75	*Senna uniflora* (Mill.) H.S.Irwin & Barneby	-	Caesalpiniaceae
76	*Solanum albicaule* Kotschy ex Dunal	Nar kanta	Solanaceae
77	*Solanum incanum* Linn.	Dholi Ringni	Solanaceae
78	*Solanum indicum* Linn.	-	Solanaceae
79	*Tamarix dioica* Linn	Jhau	Tamaricaceae
80	*Tephrosia falciformis* Ramaswami	Rati Biyani	Fabaceae
81	*Tephrosia hookeriana* W & A	Basuni	Fabaceae
82	*Tephrosia villosa* (L.) Pers	Beuna	Fabaceae
83	*Verbesina encelioides* (Cav.) Benth.& Hook.f.A.	Wild sunflower	Asteraceae
84	*Vernonia cinerascens* Schultz.-Bip.	Tadtadiya	Asteraceae
85	*Vitex negundo* Linn	Nirgundi	Lamiaceae
86	*Waltheria indica* L.	Khardudhi	Malvaceae
87	*Woodfordia fruticosa* Kurz	Dawi, Santha, Dhaura, Dhawri	Lythraceae
88	*Xanthium strumarium* Linn	Adhashishi, Chota dhatura	Asteraceae
89	*Ziziphus oenoplia* (L.) Mill.	Makoh, Jackal Jujube	Rhamnaceae
90	*Ziziphus nummularia* (Burm. f.) Wight et Arn.	Jharber	Rhamnaceae

Annexure 2.2C. Climbers with their families and local names in Rajasthan.

SNo	Botanical Name	Local Name	Family
1	*Abrus precatorius* Linn.	Chirmi, Ratti	Fabaceae
2	*Acacia pinnata* (L.)Willd.	Agla bel, Biswal	Fabaceae
3	*Asparagus racemosus* Willd	Narkanta	Asparagaceae
4	*Argyreia nervosa* (Burm. f.) Bojer	Samundrashodh	Convolvulaceae
5	*Ampelocissus latifolia* (Roxb.) Planch.	khata Limbu, Jungli angoor	Vitaceae
6	*Bryonia laciniosa* (Linn.) Naud.	Shivlingi	Cucurbitaceac
7	*Butea superba* Roxb.	Palash bel	Papilionaceae
8	*Cajanus scarabaeoides* (L.) Thouars	Kalkiya-bel	Fabaceae
9	*Canavalia ensiformis* DC.	Badi sem, Mahasimbi	Fabaceae
10	*Cardiospermum halicacabum* L.	Kanphuti, Kapal-phori	Sapindaceae
11	*Cayratia carnosa* gagnep	Katamba	Vitaceae
12	*Celastrus paniculata* Willd.	Malkangini	Celastraceae
13	*Cissampelos pareira* Linn	Padi, Paharbel	Menispermaceae

SNo	Botanical Name	Local Name	Family
14	*Citrullus colocynthis* (L.) Schard.	Tumba	Cucurbitaceae
15	*Clematis roylei* Rehder	Nal Chinkni	Ranunculaceae
16	*Cocculus hirsutus* (Linn) Diels	Bajar-bel	Menispermaceae
17	*Cocculus pendulus* (Forest) Diels	Pilwari bel, Pilwan	Menispermaceae
18	*Cryptolepis buchanani* Roem & Schult	Kala bel,nagbel, medhasingi	Asclepiadaceae
19	*Cuscuta reflexa* Roxb.	Amarbel.	Cuscutaceae
20	*Dactyliandra welwitschii* Hook.f.	-	Cucurbitaceae
21	*Hemidesmus indicus* R. Br.	Anantamul, Bakri Khaluda	Asclepiadaceae
22	*Hiptage benghalensis* (L.) Kurz.	Madhavi Lata, Helicopter Flower	Malpighiaceae
23	*Ichnocarpus frutescens* R. Br.	Dudhi (Kalibel)	Apocyanaceae
24	*Ipomea indica* (Burm.F.) Merr.	Blue dawn flower	Convolvulaceae
25	*Ipomea nil* (L.) Roth	Kaladana, neelkalmi	Convolvulaceae
26	*Ipomoea eriocarpa* R. Br.	Tiny morning glory	Convolvulaceae
27	*Ipomoea pesti-gridis* L.	Panchpatia	Convolvulaceae
28	*Momordica dioica* Roxb. ex Willd	Kakora, Janglikarela, ankarela	Cucurbitaceae
29	*Mucuna pruriens* Baker	Kauch, kevach	Papilionaceae
30	*Pergularia daemia* (Forsk.) Chiov	Gadariari bel, Menda singi, Akadi	Asclepiadaceae
31	*Rhynchosia minima* (L.) DC.	Chiri-motio, Kalta	Fabaceae
32	*Rivea hypocrateriformis* (Desr.) Choisy	Phang, Rota-bel	convolvulaceae
33	*Tinospora cordifolia* (Willd.) Miers	Neem gilody	Menispermaceae
34	*Vallaris solanacea* (Roth) O. Ktze.	Dudhi Ki bel	Apocynaceae
35	*Wattakaka volubilis* (L.f.) Stapf	Padal bel, Akad bel	Asclepiadaceae

Annexure 2.2d. Herbaceous species with their families and local names in Rajasthan.

SNo.	Botanical Name	Local Name	Family
1	*Abelmoschus manihot* (L.) Medik	Muskdana, bhindi	Malvaceae
2	*Abutilon asiaticum* G. Don	Kanghi	Malvaceae
3	*Acalypha ciliata* Forssk.	Cat tail	Euphorbiaceae
4	*Acalypha indica* L.	Khokali, Khokla, Khokli, Muktajhurui	Euphorbiaceae
	Acanthospermum hispidum D.C.	Bristlu starbur	Asteraceae
5	*Achyranthas aspera* L.	Latzeera;Ounga; Chirchitta, Andhijhara, Apamarga	Amaranthaceae
6	*Actiniopteris radiata* (J. Koenig ex Sw.) Link	–	Pteridaceae
7	*Adiantum lunulatum* Burm f.	Hansapadi	Pteridaceae

SNo.	Botanical Name	Local Name	Family
8	*Aerva lanata* (L.) Juss. ex Schult.	Bui, Kapuri-jhari	Amaranthaceae
9	*Ageratum conyzoides* L.	Unchti	Asteraceae
10	*Alternanthera paronychioides* ASt.-Hil.	–	Amaranthaceae
11	*Alternanthera pungens* Kunth	Kunth	Amaranthaceae
12	*Alysicarpus bupleurifolius* L.	Paatha	Fabaceae
13	*Alysicarpus monlifer* (L.) DC.	Paatha	Fabaceae
14	*Alysicarpus rugosus* (Willd.) DC.	Paatha	Fabaceae
15	*Alysicarpus vaginalis* (L.) DC.	Bela	Fabaceae
16	*Amaranthus spinosus* L.	Kantio-chandelo	Amaranthaceae
17	*Amaranthus virdis* L.	Chauraiya, Jangali chaulai	Amaranthaceae
18	*Ammannia auriculata* Willd.	–	Lythraceae
19	*Andrographis echioides* L. Nees	Goondlu, Kalmegh	Acanthaceae
20	*Anisochilus carnosus* (L.f.) Wall.	doddapatre or karpuravalli	Lamiaceae
21	*Anisomeles indica* (L.) Kuntze	kala bhangra	Lamiaceae
22	*Anisomeles indica* (L.) Kuntze	Rantil	Lamiaceae
23	*Argemone maxicana* Linn.	Satyanashi	Papaveraceae
24	*Aristolochia bracteolata* Lamk.	Hukkabel, Aulosa, Kabar	Aristolochiaceae
25	*Arnebia hispidissima* (Lehm.) DC.	Ram-bui, Rambus	Boraginaceae
26	*Barleria acanthoides* Vahl	Bajradanti	Acanthaceae
27	*Barleria cristata* L.	Bajradanti	Acanthaceae
28	*Barleria prionitis* L.	Bajradanti	Acanthaceae
29	*Bidens biternata* (Lour.) Merr. & Sherff	–	Asteraceae
30	*Bidens pilosa* L.	–	Asteraceae
31	*Biophytum sensitivum* (L.) DC	–	Oxalidaceae
32	*Blainvillea acmella* (L.) Philipson	–	Asteraceae
33	*Blepharis maderaspatensis* (L.) Roth	–	Acanthaceae
34	*Blepharis repens* (L.) Roth	–	Acanthaceae
35	*Blepharis sindica* Stocks ex. Anders	Bhongri, Billi-khoja (Bikaner), Utangan	Acanthaceae
36	*Blumea eriantha* DC		Asteraceae
37	*Boerhavia diffusa* L.	Punarnova, Sathan, Seanti	Nyctaginaceae
38	*Boerhavia erecta* L.		Nyctaginaceae
39	*Borreria articularis* (L. f.)F. N. Williams	Bagrakote jungle, Satgathia	Rubiaceae
40	*Borreria pusilla* (Wall.) DC.	Safed phooli	Rubiaceae
41	*Cannabis sativa* linn	Bhanng, Hashish	Cannabaceae
42	*Cassia absus* L.	Caksu, Chaksu	Fabaceae
43	*Cassia angustifolia* M. Vahl	Sanay, Senna	Caesalpiniaceae
44	*Cassia italica* (Mill.) Spreng.	Bhinda-anwal, Medi-anwal, Goranwal	Caesalpiniaceae
45	*Cassia pumila* Lamk.		Caesalpiniaceae
46	*Cassia tora* L.	Ponwaar, Panwar, Fawad, Chakvad	Fabaceae

SNo.	Botanical Name	Local Name	Family
47	*Catheranthus pusilus* (Murray) G. Don	Sadaabahar	Apocynaceae
48	*Celosia argentea* L.	Sufaid murgha	Amaranthaceae
49	*Centella asiatica* (L.) Urban	Brahmi	Mackinlayaceae
50	*Chenopodium album* L.	Chilaro	Amaranthaceae
51	*Chenopodium murale* L.	Goyalo, Kharbathua	Amaranthaceae
52	*Chrozophora tinctoria* (L.) Raf.	Shadevi	Euphorbiaceae
53	*Cistanche tubulosa* (Schrenk.) Hook.f.	Beaphor, Lonki-ka-mula	Orobanchaceae
54	*Cleome gynandra* Linn.	Bagroo, Ajagandha	Cleomaceae
55	*Cleome simplicifolia* Hook.f. & Thomson		Capparaceae
56	*Cleome viscosa* (L.)DC.	Pili-hulhul	Capparaceae
57	*Coldenia procumbens* Linn.		Boraginaceae
58	*Commelina benghalensis* L. jio	Bokhna, Kankua	Commelinaceae
59	*Commelina erecta* L.	-	Commelinaceae
60	*Convolvulus arvensis* L.	-	Convolvulaceae
61	*Conyza bonariensis* (L.) Cronq.	-	Asteraceae
62	*Conyza stricta* Willd.	-	Asteraceae
63	*Corchorus aestuans* Linn.	-	Tiliaceae
64	*Corchorus depressus* Linn.	Cham-ghas, Munderi, Bahupali	Tiliaceae
65	*Corchorus olitorius* Linn.	-	Tiliaceae
66	*Corchorus tridens* Linn.	Kagnasha	Tiliaceae
67	*Corchorus trilocularis* L.	-	Tiliaceae
68	*Craterostigma plantagineum* Hochst.	-	Scrophulariaceae
69	*Cressa cretica* Linn.	Rudanti	Convolvulaceae
70	*Crotalaria medicaginea* Lam	Jhojru	Papilionaceae
71	*Crotalaria mysorensis* Roth	-	Fabaceae
72	*Crotalaria prostrata* Rottl.	Chhunchhuni	Fabaceae
73	*Crotalaria retusa* L.	-	Fabaceae
74	*Croton bonplandianum* Baill.	kalabhangre	Euphorbiaceae
75	*Cucumis callosus* (Rottler) Cogn.	Kachri	Cucurbitaceae
76	*Cucumis melo* L. subsp. agrestis (Naudin)	Kachari, kachariya	Cucurbitaceae
77	*Cyanotis cristata* (Linnaeus) D. Don	-	Commelinaceae
78	*Desmodium dichotomum* (Willd.) DC.	Shaalparni	Fabaceae
79	*Desmodium procumbens* (Mill.) Hitch.	Shaalparni	Fabaceae
80	*Desmodium triflorum* (L) DC.	-	Fabaceae
81	*Digera muricata* (L.) Mart.	Lolaru, Lulur	Amaranthaceae
82	*Dioscorea bulbifera* L.	Ratalu	Dioscoreaceae
83	*Dipteracanthus patulas* (Jacq) nees	Haadjud	Acantheaceae
84	*Echinops echinatus* Roxb.	Unt-kantalo, Bhangro	Asteraceae
85	*Eclipta alba* L.	Bhrangraj	Asteraceae

SNo.	Botanical Name	Local Name	Family
86	*Elytraria acaulis* (L.f.) Lindau	patharchattaa	Acanthaceae
87	*Emilia sonchifolia* (L.) DC.	-	Asteraceae
88	*Enicostema axillare* (Lam.) A. Raynal.	-	Gentianaceae
89	*Euphorbia indica* Lam.	Barki-sehund, Konpal	Euphorbiaceae
90	*Euphorbia chamaesyce* L.	Dudhi	Euphorbiaceae
91	*Euphorbia granularis*	Dudhi	Euphorbiaceae
92	*Euphorbia hirta* Linn	Dudhi	Euphorbiaceae
93	*Euphorbia pulcherrima* Willd. ex Klotzsch	-	Euphorbiaceae
94	*Euphorbia thymifolia* L.	-	Euphorbiaceae
95	*Evolvulus elsinoides* L.	Phooli	Convolvulaceae
96	*Fagonia indica* Burm.f	Dhamasa, Shoka	Zygophyllaceae
97	*Fagonia schweinfurthii* Hadidi	Dhamaso	Zygophyllaceae
98	*Fumaria indica* (Hausskn.) Pugsley.	Pit papra	Papaveraceae
99	*Gisekia pharnacioides* Linn	Sareli, Morang	Molluginaceae
100	*Glinus lotoides* Linn.	Satialeti, Matter, Bakada, Hata, Dholakani	Molluginaceae
101	*Glossocardia bosvallea* (L.f.) DC.	-	Amaranthaceae
102	*Gnaphalium purpureum* L.	-	Asteraceae
103	*Gymnema sylvestre* R.Br	Gudmar	Asclepiadaceae
104	*Haplanthodes verticillatus* (Roxb.) R.B.Majumdar	Kastula	Acanthaceae
105	*Hedyotis corymbosa* (L.) Link.	Pitpapra	Rubiaceae
106	*Heliotropium curassavicum* Linn.	-	Boraginaceae
107	*Heliotropium marifolium* Retzius	Choti-santari	Boraginaceae
108	*Heliotropium subulatum* Hochst.ex DC	Kali bui	Boraginaceae
109	*Hemigraphis latebrosa* (Heyne ex. Roth) Nees	-	Acanthaceae
110	*Hibiscus ovalifolius* (Forssk.) Vahl.	Chiramulti	Malvaceae
111	*Hybanthus enneaspermus* (L.) Muell.	-	Violaceae
112	*Hygrophila auriculata* (Schumach.) Heine	Ikshura	Acanthaceae
113	*Hypodematium crenatum* (Forssk.) Kuhn	Jadi Buti	Dryopteridaceae
114	*Hyptis suaveolens* (L.) Poit	Wilayati tulsi	Lamiaceae
115	*Impatiens balsamina* L.	-	Balsaminaceae
116	*Indigofera astragalina* DC.	-	Fabaceae
117	*Indigofera cordifolia* B. Heyne ex Roth	Bekariya	Fabaceae
118	*Indigofera hochstetteri* Baker	Dhakadi	Fabaceae
119	*Indigofera linifolia* (L.f.) Retz.	Bekari	Fabaceae
120	*Indigofera linnaei* Ali.	Latahai, leel	Fabaceae
121	*Indigofera tinctoriaI* Linn.	Neel	Fabaceae
122	*Ipomea dichroa* Hochst. ex Choisy	-	Convolvulaceae

SNo.	Botanical Name	Local Name	Family
123	*Justicia diffusa* Willd.	-	Acantahceae
124	*Justicia procumbens* L.	Pitpapada	Acantahceae
125	*Justicia quinqueangularis* K.D.Koenig ex Roxb.	-	Acantahceae
126	*Launaea procumbens* (Roxb.)	Van-gobi, Jangli gobi	Asteraceae
127	*Launaea resedifolia* (Linn.)O.kuntze	Dud phad, Dhantar, Phulavalo-Unt-kantalo	Asteraceae
128	*Lavandula bipinnata* (Roth) Kuntze	-	Lamiaceae
129	*Lepidagathis cristata* Willd.	-	Acantahceae
130	*Lepidagathis trinervis* Nees.	Unt Kantalo, Siyalbethna	Acantahceae
131	*Leucas aspera* (Willd.) Link	Gumma, Gomo, Munda-Patti	Lamiaceae
132	*Leucas cephalotes* (Roth) Spreng.	Dronpushpi	Lamiaceae
133	*Leucas martinicensis* (Jacq.) R. Br.	-	Lamiaceae
134	*Leucas suffruticosa* Benth.	-	Lamiaceae
135	*Lindenbergia muraria* (Roxburgh ex D. Don)	Pindru, Pili buti	Scrophulariaceae
136	*Lindernia ciliata* (Colsm.) Pennell	-	Scrophulariaceae
137	*Lindernia crustacea* (Linn.) F. Muell.	Chotibui	Scrophulariaceae
138	*Ludwigia octovalvis* (Jacq.) Raven	-	Onagraceae
139	*Macrotyloma uniflorum* (Lam.) Verdc.	Horse gram, kulath	Fabaceae
140	*Melhania oblongifolia* F. Muell.	-	Malvaceae
141	*Melochia corchorifolia* L.	Chunch, Bilpat	Malvaceae
142	*Metreola petiolata* (J.F. Gmel.) T.&G.	-	Loganiaceae
143	*Mollugo cerviana* (L.) Ser.	Chirio ka dhaniya, Taph-jhad	Molluginaceae
144	*Mollugo nudicaulis* Lam.	-	Molluginaceae
145	*Monsonia senegalensis* Guill. & Perr.	-	Geraniaceae
146	*Murdania spirata* L.	-	Commelinaceae
147	*Murdannia nudiflora* (L.) Brenan	Doveweed	Commelinaceae
148	*Neuracanthus sphaerostachys* Dalzell	-	Acanthaceae
149	*Ocimum americanum* L.	Bapchi, Ban Tulsi	Lamiaceae
150	*Ocimum basilicum* L.	Sweet basil	Lamiaceae
151	*Ocimum sanctum* L.	Holy basil, or tulasi,	Lamiaceae
152	*Oligochaeta ramosa* (Roxb.) Wagenitz	Unt-kantalo	Asteraceae
153	*Orthosiphon* spp.	-	Lamiaceae
154	*Oxalis corniculata* L.	Tripatti	Oxalidaceae
155	*Pavonia odorata* Willd	Chach-kamdi, Sugandhabala	Malvaceae
156	*Pedalium murex* Linn	Bara Gokharu	Pedaliaceae
157	*Peganum harmala* Linn.	Harmal, Gandhiyo	Zygophyllaceae
158	*Pentanema indicum* (L.) Y. Ling.	Bichhloo	Asteraceae
159	*Peristrophe paniculata* (Forsk.) Burm.f.	-	Acanthaceae
160	*Phyla nodiflora* Linn.	matsyagandha, Jalpapli	Verbenaceae
161	*Phyllanthus amarus* Schum. & Thonn.	Bhui Aanwla	Euphorbiaceae

SNo.	Botanical Name	Local Name	Family
162	*Phyllanthus maderaspatensis* L.	Khejario Khad	Euphorbiaceae
163	*Phyllanthus virgatus* G.Forst.	Sarnapati	Euphorbiaceae
164	*Physalis minima* L.	Pipat	Solanaceae
165	*Polygala arvensis* Willd.	Golbel	Polygalaceae
166	*Polygala erioptera* DC.	Sarbha Golia	Polygalaceae
167	*Portulaca pilosa* L.	Lunia	Portulacaceae
168	*Proboscidea louisiana* (Mill.)Wooton & Standley	-	Martyniaceae
169	*Pulicaria crispa* (Cass.) Benth. &Hook.f. Gen.	Dhola lizru	Asteraceae
170	*Pulicaria wightiana* (DC)Clarke	Sonela	Asteraceae
171	*Pupalia lappacea* (Linn.) Juss.	Undio bhurat	Amaranthaceae
172	*Rhynchosia schimperi* Hochst. ex Boiss	-	Fabaceae
173	*Rungia pectinata* (L.) Nees.	Kharmor	Acanthaceae
174	*Salvia aegyptiaca* Linn.	-	Lamiaceae
175	*Salvia plebeia* R. Brown	Kamrkash, Samundarsok	Lamiaceae
176	*Salvia santolinaefolia* Boiss.	-	Lamiaceae
177	*Scoparia dulcis* Linn.	Mithi patti, Ghoda tulsi	Scrophulariaceae
178	*Sesbania sesban* (Jacq.) W. Wight	Jayanti	Fabaceae
179	*Sida acuta* Burm.f.	Bal	Malvaceae
180	*Sida alba* L.	Kantio bal	Malvaceae
181	*Sida cordata* (Burm. f.) Borss.	Dhamni	Malvaceae
182	*Sida cordifolia* L.	Kharenti, Bal	Malvaceae
183	*Sida rhombifolia* L.	-	Malvaceae
184	*Solanum nigrum* Linn	Makoy	Solanaceae
185	*Solanum xanthocarpum* Schrad & Wendl.	Bhurangini, Adkuntali, Ringani	Solanaceae
186	*Sonchus arvensis* L.	-	Asteraceae
187	*Sonchus asper* Hill.	Kali-jibi	Asteraceae
188	*Sonchus oleraceus* Linn.	Aakadiyo	Asteraceae
189	*Sopubia delphinifolia* G. Don.	Dhudhali	Scrophulariaceae
190	*Striga densiflora* (Benth.) Benth.	-	Scrophulariaceae
191	*Striga gesnerioides* (Willd.) Vatke	Missi	Scrophulariaceae
192	*Suaeda fruticosa* (L.) Forrssk	Lunki, Lunak	Amaranthaceae
193	*Tephrosia apollinea* (Delile) DC.	-	Papilionaceae
194	*Tephrosia pumila* (Lam.) Pers.	-	Fabaceae
195	*Tephrosia purpurea* (Linn.) Pers.	Biyani, ban-nil, ghodakan	Fabaceae
196	*Tephrosia strigosa* (Dalz.) Sant. & Mahesh.	Jhino-Biyono	Fabaceae
197	*Tephrosia uniflora* Pers. Subsp. *Petrosa*(Blatt. & Hallb.) Gillett. & Ali	Bhaker Biyani	Fabaceae
198	*Tephrosia villosa* (L.) Pers.	Ruvali-biyani, Kharaio	Fabaceae
199	*Teramnus labialis* (L. f.) Spreng	-	Fabaceae

SNo.	Botanical Name	Local Name	Family
200	*Teramnus mollis* Benth.	-	Fabaceae
201	*Thespesia lampas* Dalz and Gibs	Ban-kapas	Malvaceae
202	*Tribulus pentandrus* Forssk	Gokhru	Zygophyllaceae
203	*Tribulus terrestris* Linn.	Gokhru, Kanti	Zygophillaceae
204	*Trichodesma indicum* (Linn.) R. Br.	Sal-Konta, Chota-Kulpha	Boraginaceae
205	*Trichosanthes tricuspidata* Roxb	-	Cucurbitaceae
206	*Tridax procumbens* L.	Kali menhdi	Asteraceae
207	*Triumfetta pentandra* A.Rich.	Mandli	Malvaceae
208	*Triumfetta rhomboidea* Jacq.	Laapta	Malvaceae
209	*Typha elephantina* Roxb.	Aira, Pataer	Typhaceae
210	*Urena lobata* L.	Bachitaa, Chirchatta	Malvaceae
211	*Urginea indica* roxb.	Koli kanda	Liliaceae
212	*Vernonia cinerea* (L.) Less.	Sandri, Sahadevi	Asteraceae
213	*Vigna aconitifolia* (Jacq.) Marechal	Moth	Fabaceae
214	*Vigna mungo* (L.) Hepper	Kali daal, urad daal	Fabaceae
215	*Vigna radiata* (L.) R. Wilczek	Mung	Fabaceae
216	*Vigna trilobata* (L.) Verd.	Jangli moth	Fabaceae
217	*Viola cinerea* L.	-	Violaceae
218	*Viscum articulatum* Burm. f.	Vaayhakal, Budu, Banda	Viscaceae
219	*Withania somnifera* (L.) Dunal	Ashwagandha	Solanaceae
220	*Xanthium strumarium* L.	Anadhasishi	Asteraceae
221	*Zaleya pentandra* (L.) C. Jeffrey	Wasanh/Waaho	Aizoaceae
222	*Zinnia peruviana* (L.) L.	-	Asteraceae
223	*Zornia gibbosa* Span.	Gewani	Fabaceae
224	*Zygophyllum simplex* Linn.	Lunwo, Lonk, Alethi	Zygophyllaceae

Annexure 2.2E. Grass and sedges species with their families and local names in Rajasthan.

SNo.	Botanical Name	Local Name	Family
1	*Acrachne racemosa* (B.Heyne ex Roth) Ohwi	-	Poaceae
2	*Alloteropsis cimisina* L.	-	Poaceae
3	*Andropogon pumilus* Roxb.	Masudi, Masuri	Poaceae
4	*Apluda mutica* L.	Tamtabheda, Bhangti	Poaceae
5	*Aristida adscensionis* L.	Lamp	Poaceae
6	*Aristida depressa* Retz.	Lapla	Poaceae
7	*Aristida funiculata* Trin. & Rupr	Rampla	Poaceae
8	*Aristida hystrix* Linn. f.	Lapla. (safed)	Poaceae
9	*Aristida mutabilis* Trin. & Rupr	Bada lapla	Poaceae
10	*Arthraxon ciliaris* P. Beauv.	-	Poaceae
11	*Arthraxon lancifolius* (Trin.) Hochst.	-	Poaceae
12	*Arundo donax* Linn.	Narkul	Poaceae

SNo.	Botanical Name	Local Name	Family
13	*Bothrichloa pertusa* (Linn.) A Camus.	Karad, Chhoti Jarga	Poaceae
14	*Brachiaria deflexa* (Schumach.) Robyns.	-	Poaceae
15	*Brachiaria ramosa* L.	Murut, Kuri(kora chinki)	Poaceae
16	*Brachiaria reptans* (Lien) C.A. Gardn. C.E. Hubb.	Kalia	Poaceae
17	*Cenchrus barbatus* Schum. (C.cathaticus, Del.).	Bharut	Poaceae
18	*Cenchrus biflorus* Linn	Bhurat	Poaceae
19	*Cenchrus ciliaris* Linn	Dhaman	Poaceae
20	*Cenchrus setigerus* Vahl. (C.biflorus, Roxb)	Anjan (Kala), Bhwat, Neenjna	Poaceae
21	*Chloris barbata* (SW.)	Kali-charkali	Poaceae
22	*Chloris dactylifera*	-	Poaceae
23	*Chloris dolichostachya* Lagas.	Bamna	Poaceae
24	*Chloris inflata* Link. (C.barbata (Linn) S.W.)	Chirkali (Kali)	Poaceae
25	*Chloris roxburghiana*, Schutt.	Chinkali, Kevai	Poaceae
26	*Chloris virgata* Sw.	Gharniya ghas	Poaceae
27	*Chrysopogon fulvus* (Spreng.) Chiov.	Goria Sedua, Seran, Sedva	Poaceae
28	*Chrysopogon serrulatus* Trin.	Kurdi	Poaceae
29	*Coix gigantea* Koen ex Roxb. (*C. lachmymajobi* Stapf, ex. Hook. f.)	Garalu	Poaceae
30	*Cymbopogon jwarancusa* Boiss.	Hathipaga, Kanchen, Burh	Poaceae
31	*Cymbopogon martinii* (Roxb.) Watson	Raicha, Rosha, Rooiva (Rois), Motia grass	Poaceae
32	*Cynodon dectylon* (L.) Pers.	Dub	Cyperaceae
33	*Cyperus arenarius* Retz.	Motha	Cyperaceae
34	*Cyperus iria* L.	Motha	Cyperaceae
35	*Cyperus rotundus* Linn.	Naagarmotha	Cyperaceae
36	*Cyprus diformis* L.	-	Cyperaceae
37	*Digitaria adscendens* (HBK) Henr.	Kudi	Poaceae
38	*Digitaria cruciata* (Nees) A. Camus.	Kudi	Poaceae
39	*Dactyloctenium aegyptium* (L.) Willd.	Jharnia, Makra	Poaceae
40	*Dactyloctenium sindicun* Boiss.	Ganthia (Jarnia)	Poaceae
41	*Dendrocalamus strictus*	Bans	Poaceae
42	*Desmostachya bipinnata* (Linn.) Stapf.	Dab, Kush	Poaceae
43	*Dicanthium annulatum* (For sk) Stapf.	Karad, Jarga, Karar	Poaceae
44	*Dicanthium caricosum* (Linn.) A camus.	Badi	Poaceae
45	*Dichanthium foveolatum* (Del.) Roberty	Buhari	Poaceae
46	*Dichanthium huegelii* (Hack.) S.K.Jain & Deshp.	-	Poaceae

SNo.	Botanical Name	Local Name	Family
47	*Digitaria bicornis* (Link), Roem ex Schult.	Kudi	Poaceae
48	*Digitaria ciliaris* (Retz.) Koel.	Jharnia ghas	Poaceae
49	*Dinebra retroflexa*	Khariu	Poaceae
50	*Echinochloa colona* (L.) Link	Sawank	Poaceae
51	*Echinochloa colonum* (Linn.) Link.	Sawan	Poaceae
52	*Eleusine compressa* (For sk)	Tantia, Ghoda dub	Poaceae
53	*Eragrostielia bifaria* (Vahl) Wight ex Steud.	Jondli	Poaceae
54	*Eragrostis cilianensis* (All.) Lut. ex Janchen.	-	Poaceae
55	*Eragrostis ciliaris* (Linn.) R.Br.	Under-puncha (chota)	Poaceae
56	*Eragrostis minor* Host.	-	Poaceae
57	*Eragrostis tenella* (Linn.) P Beauv	-	Poaceae
58	*Eragrostis unioloides* (Retz.) Nees ex Steud.	-	Poaceae
59	*Eragrostis* spps.	Chiri-bajra.	Poaceae
60	*Eremopogon foveolatus* (Deb) Stapf.	Buhari, Gandhel	Poaceae
61	*Erianthus munja* (Roxb) Jaswiet. (Saceharum munja, Roxb.)	Munt	Poaceae
62	*Hackelochloa granularis* (L.) Ktze.	-	Poaceae
63	*Heteropogon contortus* (L.) P. Beauv	Scorwala Kali Lamp., Laapdi, Sukhala	Poaceae
64	*Iseilema laxum* Hack.	Gandhel	Poaceae
65	*Kyllinga bulbosa*	Nirvishi	Cypreaceae
66	*Lasiurus sindicus* Henz.	Sevan	Poaceae
67	*Melanocenchris jacquemontii* Jaub.& Spach	-	Poaceae
68	*Melinis* spp.	-	Poaceae
69	*Oplismenus burmannii* (Retz.) P.Beauv.	Sanwa/Phorda	Poaceae
70	*Oropetium thomaeum* (L.f.)	Susa-chunti	Poaceae
71	*Panicum antidotale* Retz.	Gunera, Graamna	Poaceae
72	*Paspalum serebiculatum* Linn.	Kodra	Poaceae
73	*Pennisetum typhoides* (Burn.) S & Hubb.	Bajra	Poaceae
74	*Perotis indica* (L.) Kuntze	Under-puncha (Bara)	Poaceae
75	*Rottboellia exaltata*	-	Poaceae
76	*Saccharum munja*	Moonjh	Poaceae
77	*Saccharum spontaneum* Linn.	Kans	Poaceae
78	*Sehima nervosum* (Rottl.) Stapf.	Sien, Seran, havan	Poaceae
79	*Setaria glauca* (L.) P.Beauv.	Bindar	Poaceae
80	*Setaria pumila* (Poir) Puem & Schult	-	Poaceae
81	*Sorghum halepense* (Linn.) Pers.	Baru	Poaceae
82	*Sporbolns marginatus* Hochst, ex. A. Rich.	Uaari, Chirion ka chawalia	Poaceae
83	*Sporobolus diander* (Retz.) P.Beauv.	-	Poaceae

SNo.	Botanical Name	Local Name	Family
84	*Tetrapogon tenellus* (Roxb.) Chiov.	Kagio, Chinki	Poaceae
85	*Themeda quadrivalvis* (L.) Kuntze.	Rataide, Ratarda	Poaceae
86	*Tragus roxburghii* Panigr.	Indian bur grass	Poaceae
87	*Urochloa panicoides* P. Beauv.	Kuri	Poaceae
88	*Vetiveria zizanioides* (L.) Nash.	Khus	Poaceae

3

DESERTIFICATION: LANDS DEGRADATION IN DRYLANDS

Desertification ranks high among the greatest environmental challenges throughout the world. Though its occurrence is a continuous phenomenon, but it was highlighted after 1969-1973 droughts, which struck the Sahel in Africa and the other regions of the world. Severe drought and repeated crop failures in Africa forced the international community to call upon the UN Conference on Desertification (UNCOD) in Nairobi 1977. In this conference desertification was considered as a problem of global significance. Desertification was defined in UN Convention on Combating Desertification (UNCCD) in 1992 as the land degradation in drylands, which include arid, semi-arid and dry sub-humid regions, and caused by both climatic variations and human impacts. Over exploitation of resources, vegetation removal and a decline in forest species richness and tree density under increased human economic activities has accelerated land degradation in all climatic zones and drylands in particular. UNCCD is more strongly based on socioeconomic aspects by recognizing desertification as a problem of unsustainable development and closely interlinked with poverty, food insecurity, and environmental degradation. The severity of desertification is more in developing countries where the people are dependent on the surrounding environments for their livelihood, and resources are inadequate for restoring the over-exploited dry land ecosystems. Thus desertification, land degradation and drought are not only serious threats to the ecosystem's health and humans living within the region, but it also affects areas far away from the dry lands.

1. INTRODUCTION

Arid lands, dry lands or deserts are the areas where water availability is relatively poor to the plants for a long period. The most prominent characteristic of deserts is aridity (a Latin word '*arere*' means to be dry) and this implies deficiency of rainfall and absence of a shallow groundwater table (Verheye, 2006). Based on the aridity index, which is a measure of the ratio between average annual precipitation and total annual potential evapo-transpiration; there are six climatic zones throughout the world. These are arid, semi-arid, dry subhumid, moist subumid, humid and perhumid regions. The term "drylands," as used by the Convention to combat Desertification (CCD) and discussed by United Nations Environment Programme (UNEP) in 1997, encompasses the hyper-arid deserts (aridity index <0.05), arid (aridity index 0.05–

0.20), semi-arid (aridity index 0.20-0.50), and dry sub-humid (aridity index 0.50–0.65) excluding polar and sub-polar regions (Table 3.1). Thus tropical and temperate areas with an aridity index of less than 0.65 are considered drylands. By definition dryland is the area with scarcity of water. The evaporation of the water from the soil is higher than the water that comes into the system by precipitation. Drylands include cultivated lands, scrublands, shrub lands, grasslands, savannas, semi-deserts and true deserts. They are the zones where precipitation is counterbalanced by evaporation from soil surfaces and transpiration by plants (i.e., evapotranspiration). Among these, hyper-arid lands are deserts, although a number of the world's deserts include both hyper arid and arid zones. Thus dry lands refer to arid, semi-arid and dry sub-humid areas, but exclude deserts when referred to in the context of sustainable development.

Table 3.1 Global figures of drylands (Modified from Safriel and Adeel, 2005).

Climatic zone	Aridity index*	Global area		Population	
		m km^2	%	(x10^3) number	%
Hyper-arid	<0.05	9.8	6.6	101,336	1.7
Arid	0.05–0.20	15.7	10.6	242,780	4.1
Semi-arid	0.20–0.50	22.6	15.2	855,333	14.4
Sub-humid	0.50–0.65	12.8	8.7	909,972	15.3
Total	-	60.9	41.3	2,109,421	35.5

*The ratio of precipitation to potential evapo-transpiration.

In these, arid ecosystems are annual grasslands suitable mainly for grazing animals, except the area which is interrupted by rivers, lakes or any water body. Semi-arid ecosystems are thorny savannahs with annual and perennial grass species, which may be cleared for farming and livestock and carry the highest population densities of the lands in these categories. Dry sub-humid ecosystems are broad-leaved savannah woodlands with higher and denser tree canopies and perennial grasses. Because of some large irrigated areas along some perennial rivers in dry lands, the farming activities are relatively intense. Almost all drylands experience high rainfall variability within seasons, between years and in longer-term cycles. Combined with low average rainfall, this variability is a high risk to non-irrigated or rainfed agricultural activities (Bantilan and Anupam, 2006; CGIAR, 2012).

About 35.5 percent of the total world's population resides in drylands, where the share of hyper arid and arid regions is 5.8 per cent of the global population (Table 2.1). Expansions of global dryland will further increase the population affected by water scarcity and land degradations, whereas at the same time water scarcity will increase with an increase in the aridity (Milesi et al., 2010). For basic well-being, each person requires a minimum of 2,000 cubic meters of water per year. People in the drylands have access to 1,300 cubic meters only, whereas the availability is projected to decrease. Today, water scarcity affects between 1-2 billion people, and most of them are in the drylands. Under the climate change scenario, nearly half of the world's population in 2030 will be living in areas of high water stress. In some arid and semi-arid areas, it will displace up to between 24 million and 700 million people.

Worlds land utilization pattern indicate that about 65% of the global drylands fall under rangeland, which decreased with increase in the aridity index (Table 3.2). In contrast crop land area has increased with increase in aridity index and constitutes about 25% of the global drylands. The remaining 10% drylands are utilized in other uses including urban areas (UNEP, 2011).

Table 3.2 Land uses and degradation in the world's drylands.

Climatic zone	**Land use (%)**			**% degradation**
	Range land	**Cropland**	**Other (including urban areas)**	
Hyper-arid	97	0.6	3	5
Arid	87	7	6	
Semi-arid	54	35	10	9
Sub-humid	34	47	20	8
Total	65	25	10	22

2. SERVICES OF DRY LAND ECOSYSTEMS

Drylands play a vital role in local as well as global climate regulation. Land use change results in releases of greenhouse gases into the atmosphere, while soil improvement is essentially the reverse process. It is sucking excess atmospheric carbon into the soil. Drylands store approximately 46% of the global carbon share. About 53% of global soil carbon and 14% of the global biotic carbon are in drylands (UNEP, 2011). Land rehabilitation practices such as mulching, composting, manuring and mixed cropping and reforesting, which increase carbon stocks in the soil, contributing directly to soil carbon sequestration. These techniques are also part of the technology toolbox known as sustainable land management. Multiple benefits are supplied by dry land ecosystems as a result of their structure and function; the conditions and processes through which nature sustains human life on earth (Daily, 1995) and the life support systems, without which we cannot live (Table 3.3).

Table 3.3 Varying types of services of an ecosystem.

SNo	**Services**	**Function**
1	Provisioning	Goods provided by the ecosystem are food, fiber, forage, fuel wood, biochemicals, fresh water etc.
2	Regulating	Obtained from the regulation of ecosystem processes like water regulation, pollination and seed dispersal, climate regulation (local through vegetation cover and global through carbon sequestration).
3	Supporting	That maintain the conditions of life on earth like soil development (conservation/formation), primary production, nutrient cycling etc.
4	Cultural	Nonmaterial benefits obtained from the ecosystem like recreation and tourism, cultural identity and diversity, cultural landscapes and heritage values, indigenous knowledge systems, and spiritual, aesthetic, and inspirational services

Source: MEA (2005).

Millennium Ecosystem Assessment (MEA, 2005) has classified these services into four broad categories like provisioning, regulating, cultural and supporting. Ecosystem services are also classified according to their geographical scale (local, regional, global), value to society (direct and indirect), or the type of natural ecosystems providing the service, such as forest, coral reef or wetlands (WRI, 2009). A recent report of UNEP (2011) highlights the problems and importance of dry lands of the world, a summary of which is provided in Box 3.1.

BOX 3.1

Area and human population

- Drylands cover approximately 40% of the world's land area.
- It supports two billion people, 90% of whom live in developing countries.
- Around one billion people rely directly on dryland ecosystem services for their daily survival, whether through rain-fed or irrigated farming, or through widespread pastoralism.

Human well-being at risk

- Unsustainable land and water use and the impacts of climate change are driving the degradation of dry lands.
- Approximately 6 million km^2 of dry lands (about 10%) bear a legacy of land degradation.

Cost of dryland degradation

- Dryland degradation costs developing countries an estimated 4–8% of their national gross domestic product (GDP) each year.
- About 1–6% of dryland human populations live in desertified areas, while a much larger number is under threat from further desertification.

Opportunities for local populations and regional and global benefits of drylands

- The biodiversity of drylands provides ecosystem services which benefit local communities.
- With specialized adaptations to unstable, but resilient, ecological conditions, the increasing and urbanizing human populations of drylands can help to generate significant regional benefits.
- Drylands can have major global climate benefits: carbon storage (mainly in the form of soil carbon) accounts for more than one third of the global stock.
- The potential local, regional and global benefits of drylands have not been fully utilized because of myths, market failures, a lack of public goods, weak incentives, high investment costs and gender inequalities.

Pay off of drylands

- Investments in drylands pay off if configured to the short and long-term variability of these human-ecological systems.
- Many drylands in developing countries have become centre of investments and sustained higher levels of investment can support enhanced productivity and better incomes.
- Opportunities for increased investments in drylands are coupled with global and regional trends.
- Opportunities for investment in drylands exist for the public sector, the private large-scale commercial sector, the community sector, and the household or small-scale private sector.
- The UN system is uniquely positioned to promote increased investments in drylands.
- With its global reach and large range of activities and expertise, a coherent and holistic UN-wide response can help catalyze a transition towards increased investments in drylands.

3. DEFINING DESERTIFICATION

Healthy Lands - Healthy People is very much relevant in present scenario of environmental degradation. Desertification is a phenomenon that ranks among the greatest environmental challenges at present throughout the globe. Desertification began long before the 1969-1973 droughts, which struck the Sahel in Africa and the other regions of the world. But it was Stebbing (1937a, 1937b), who alarmed over the speedy deforestation of the Sahelian and Sudanian regions in Africa and considered forest degradation in West Africa as desertification that lead to erosion and ultimately end up with a barren sandy lands or rocks. That process was speeded up by wind-blown sand from the Sahara being deposited on the deforested land. The latter activity was referred to the 'encroaching Sahara' (Stebbing, 1938). This concept proved so attractive to researchers and field practitioners on desertification that it now represents a common view on the subject-desertification (Cloudsley-Thompson, 1974). Encroachment of moving sand dunes on desert oases, roads, railway lines and water bodies is an aspect of desertification. Though it is of small in aerial extent but is locally important and highly visible. Similar warnings for the Sahel were also sounded by other researchers throughout the world.

In fact desertification is not the natural expansion of existing deserts, but the degradation of land in dry (arid, semi-arid, and dry sub-humid) areas (Grainger et al., 2000). The term ‘Desertification’ was coined first by the French Scientist Lavauden, (1927) to describe the impoverishment of plant cover in the Sahara desert and latter by French forester Aubreville (1949) working in sub-humid Africa in early 1900 in his report “Climats, forêts et désertification de l´Afrique tropicale”. The concept however, was discussed earlier in terms of increased sand movements, desiccation, desert and Sahara encroachment as well as manmade deserts (Bovill, 1921; Coching, 1926; Stebbing, 1938; Lowdermilk, 1935; Jones, 1938). In early 1990, desertification meant the spreading of deserts or desert-like conditions. But the indication of this phenomenon was often related to sand movement and encroachment into oasis and desert margins. Formation of real deserts in the 700-1500 mm annual rainfall areas has also been acclaimed during this period (Aubreville, 1949). One school of thoughts supported the idea of a postglacial climate change (i.e., desiccation and gradual increase in aridity) as a major driving force causing desertification, whereas the others schools of thoughts stressed the significance of human impact. The latter was expressed in terms of poor land management that included over cutting, overgrazing, over cultivation and misuse of water leading to salinity development. The American “Desert Bowl” forced millions of people to leave their farms in the American Great Plains in the 1930´s. The drought and land degradation catastrophe had an important impact on the western scientific community for a long time initiating research and development efforts in soil erosion and soil conservation techniques (Thomas and Middleton, 1994). Since then, different concepts of desertification have developed and been discussed over and over again by scientists, politicians and the international society.

Droughts and repeated crop failures in the Sahelian zone in Africa during 1970s and 1980s compelled international community to call upon the UN Conference on Desertification (UNCOD) in Nairobi 1977, where desertification was considered as a problem of global significance (Thomas and Middleton, 1994). Subsequently the UN Conference on Environment and Development (UNCED) in Rio de Janeiro 1992 was followed up by the UN Convention to Combat Desertification (UNCCD) adopted in 1994 and entered into force in 1996. Desertification experts have proposed more than 100 formal definitions because of its multidimensional interpretation. These definitions cover a number of issues which are cross-cutting in nature and differ in their emphasis on three distinct dimensions, i.e. ecological, meteorological, and human (Reynolds, 2001). The definitions presented in the UNCOD documentation (Mainguet, 1991; Helldén, 1991; Thomas and Middleton, 1994) were implicitly understood that leads to “long lasting” and possibly “irreversible” desert-like conditions. However, decrease in the productivity was the key process included implicitly or explicitly in most of the definitions. Desertification was commonly considered to affect arid, semi-arid and sub-humid ecosystems by the combined impact of droughts and human activities. The relative role of climate, droughts and human impact are discussed in general and the key problems identified as a chronic process inducing land degradation. Drought is rather seen as a catalyst which exposes the effects of the long-term degradation caused by people (Thomas and Middleton 1994), but the most important causes of desertification reported during the first decades of the century i.e., over cutting, overgrazing, over cultivation and misuse of water remained the same. UNCOD formulated and adopted the Plan of Action to Combat Desertification (PACD), endorsed by the UN General Assembly in 1977, whereas the responsibility for follow up action and coordinating the plan was given to the UN Environment Programme (UNEP). The countries prone to desertification were requested to develop National Plans of Action to Combat Desertification. Though this was seen as a fundamental instrument for the implementation of the PACD recommendations, but only few, if any, have ever been financed and implemented despite of several national plans have been written. The UNEP´s concept of desertification was seriously challenged by groups of scientists during the 1980´s and at the beginning of the 1990´s (Helldén, 1991; Thomas and Middleton, 1994) that contributed to a UNEP led initiative to modify the prevailing concept of desertification in 1990. In this, desertification is land degradation in arid, semi-arid and dry sub-humid areas resulting mainly from adverse human impact. Desertification was neatly defined in the text of the United Nations Convention to Combat Desertification (UNCCD, 1994; Thomas, 1997) as:

"Land degradation in arid, semi-arid and dry sub-humid regions resulting from various factors, including climatic variations and human activities."

The UNCCD is now more strongly based on socioeconomic aspects as compared to the other environmental agreements (Wolfrum and Nele, 2003) because it recognizes desertification primarily as a problem of insustainable development and closely interlinked with poverty, food insecurity, and environmental degradation. However, due to comprehensive coverage of a number of cross-cutting developmental issues, the implementation of the UNCCD remains as major challenge particularly for poor countries (Kannan, 2014). Several initiatives were taken to provide clear direction to facilitate effective implementation of the UNCCD within the context of resource constraints and the ability of developing nations to undertake such challenging activities. In this direction, a brokering institute called Global

Mechanism (GM) under Article 21(4) of the UNCCD was established that promotes actions leading to the mobilisation and channeling of substantial financial resources to affected developing countries, though this mechanism did not conceive to raise or administer funds. Latter on Global Environment Facility (GEF) was designated in 2003 as a financial mechanism to assist developing countries in implementing the Convention (GEF, 2003). Subsequently, the GEF decided to designate land degradation as its fifth focal area and to establish the GEF as a financial mechanism of the UNCCD (Rechkemmer, 2004).

Drought is another natural phenomenon accelerating desertification and land degradation (Fig 3.1). Due to drought and desertification about 12 million hectares of land is lost (i.e., 23 hectares/minute) each year where 20 million tons of grain could have been grown (UNCCD, 2014). The effects of drought can be classified as short term and long term. Short-term effects of drought lead to decline in the cropped area and agricultural activity; and in the long run, it leads to the migration of people to other areas. The consequence of drought in the short run adversely affects the food grain production which can lead to drop in employment and income, and in the long run, it leads to distress sale of assets and migration out of the village (Pandey, 2007). Another short–term effect of drought is decline in the food stock that leads to the increase in food grain prices, and thus, there is reduction in the intake of food, and in the long run, it affects the health of people and leads to starvation. The Hadley Center for Climate Prediction and Research has forecasted an increase in the global area expected to experience severe drought from 10% of the world‘s land surface in 2005 to 40% in the future for a given global warming of 3°C to 4°C (Stern, 2006). While an increase of 20% in drought frequency is expected in East Africa and Central America, an increase in drought frequency is also anticipated in southeastern and southern Asia (Webster et al., 2008). The countries heavily depending on rainfed agriculture and having low risk bearing ability will be severely affected by drought because of predicted high economic loss and human suffering. The combined effects of desertification, land degradation and drought (DLDD) affects 1.5 billion people depending upon degrading areas, where 42% of the very poor lives, compared with 32% of the moderately poor and 15% of the nonpoor globally (Nachtergaele et al., 2010). There is loss of 12 million ha area each year due to drought and desertification, where 20 million tons of grain could have been grown. The 5th international conferences on DLDD (2014) held at Ben-Gurion University of the Negev, Israel concluded that existing knowledge has to be further assessed for detecting existing adaptations to projected climate conditions, an effort that explores newly proposed indicators for specifically monitoring land-based climate adaptations, and establishing a science-policy mechanism in this direction.

Reduced water availability and corresponding biological activity in drylands also affects biogeochemical cycles (Schwinning and Sala, 2004). The increase in aridity predicted for the twenty-first century in the drylands (Feng and Fu, 2013) may therefore threaten the balance between biogeochemical cycles, differentially affecting the availability of essential nutrients (Dai, 2013). Aridity negatively affects the concentration of soil organic carbon and total nitrogen, but has positive effects on the concentration of inorganic phosphorus. Reduction in plant cover with increase in aridity favour the dominance of physical processes such as rock weathering, a major source of phosphorus to ecosystems, over biological processes that provide more carbon and nitrogen, such as litter decomposition (Walker and Syers, 1976). Thus predicted increase in aridity with climate change will probably reduce the concentrations of nitrogen and carbon in drylands, but will increase the concentration of phosphorus. These changes would uncouple the C, N and P cycles in drylands and could negatively affect the provision of key services provided by these ecosystems (Delgado-Baquerizo et al., 2013).

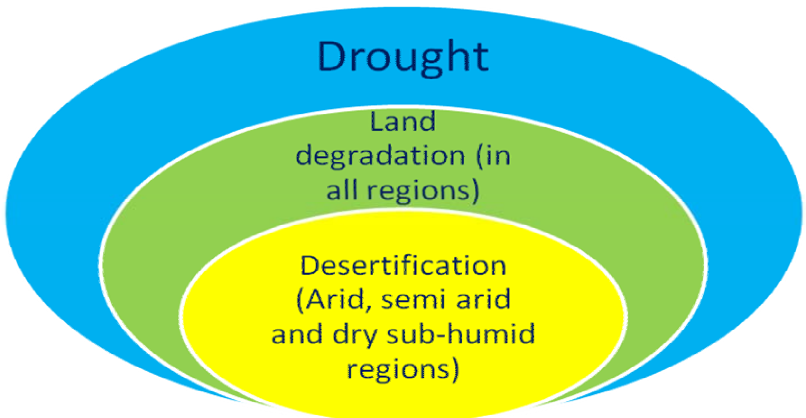


Figure 3.1 Desertification, land degradation and drought (DLDD)

Factors like forest type, climate, and soil properties that affect soil organic carbon (SOC) mineralization influence SOC stocks. The conversion of forest to agricultural land destroys the soils aggregate structure, which enhances organic matter mineralization and CO_2 emissions to the atmosphere. The SOC turnover rate constant increases with the mean annual precipitation and temperature after the conversion of forests to agricultural land (Wei et al., 2014). In general, SOC stocks decrease rapidly and then stabilize after a land-use change. The percent decrease in SOC stocks and the turnover rate both vary according to forest type and cultivation stage. The largest decrease in SOC stocks is in temperate regions (52% decrease), followed by tropical regions (41% decrease) and boreal regions (31% decrease).

The degraded area is also associated with lower levels of socio-economic development including policy-controlled indices such as infrastructure development index. Relatively less developed region is also related to lower levels of development and less access to public infrastructure (Pani and Carling, 2013). Severity of desertification is a multiple sum of various environmental and social factors, whereas occurrence of desertification is more sensitive towards albedo change followed by land use land cover (LU/LC) change and USLE; whereas population pressure has least contribution (Khire and Agarwadkar, 2014). This can be described by the equation:

$$\text{Desertification Severity} = (17.5 \times \text{NDVI}) + (16.2 \times \text{LULC}) + (13.7 \times \text{Albedo}) + (13.5 \times \text{USLE}) + (10.5 \times \text{Meteorological Drought}) + (9.2 \times \text{Wind Erosion}) + (9.1 \times \text{DMAI}) + (6.2 \times \text{Ground Water Depletion}) + (4.1 \times \text{PPI})$$

Here NDVI is Normalised Differential Vegetation Index; LULC is land use land cover change; USLE is soil erosion estimated using USLE model; PPI is Population Pressure Index and DAMI is De Martonne‟s Aridity Index (Khire and Agarwadkar, 2014).

4. CAUSES OF DESERTIFICATION

There is no linear cause-effect process that leads to land degradation in the drylands. However, the drivers, which interact in complex ways leading to desertification (Ritter, 2006; Varghese, 2013) can be divided into two categories, i.e. direct and indirect which change over time and vary by location. Direct drivers are: (i) climatic, i.e. rainfall, moisture etc affecting rural production system, and (ii) human activities like overgrazing, cultivating marginal lands or steep slope areas, deforestation without reforestation and inappropriate use of water for irrigation. Indirect drivers are mostly human derived and include (i) population pressure and increased urbanization, (ii) poverty, (iii) inequitable sharing of resources, (iv) technology used, (v) global and local market trends, (vi) sociopolitical dynamics, and (vii) globalization and new economic policies (NAPCD, 2001).

The proximate causes of desertification are dominated by agricultural intensification and land use changes (Reynolds et al., 2007). The consequences of *Green Revolution*, begun in the 1970s have been massive. Overgrazing, mono-cropping, excessive tillage, deforestation, salt buildup of irrigated lands, over-extraction of ground water and utilization of lands unsuitable for arable cropping are the additional factors. Each practice has contributed to widespread desertification of drylands and even large amounts of previously forested area. It is also caused by a combination of social, political, economic, and natural factors which vary from region to region. Policies that can lead to an unsustainable use of resources and lack of infrastructures are major contributors to the land degradation. Intensive agriculture and mono-cropping are significant causes of desertification. Policies favouring sedentary farming over nomadic herding in regions more suited to grazing can also contribute to desertification. Trade liberalization, economic reforms, and export-oriented produc-tion in drylands are promoting desertification. These factors lead to degradation of 24% land globally, but the technological intervention and improvement in environmental conditions in many areas of the world has also resulted in a land recovery at 16% (Table 3.4). It is estimated that the land lost annually to desertifi-cation could produce 20 million tons of grain. Desertification and degradation represents an income loss of about US$ 42 billion annually.

Table 3.4 Extent of degrading and recovering lands globally and corresponding economic loss.

	Degrading land	Recovering land	Loss per year
Rainfed			US$ 8.2 billion
Cropland	20%	18%	US$ 10.8 billon
Rangeland	20-25%	43%	US$ 23.3 billion
Forests	42%	23%	
Global	24%	16%	US$42.3 billion

A study conducted in western Rajasthan indicate that Jhunjhunu and Sikar districts with high developmental indicators have also high desertification indicators showing linkages between development and desertification indicating direct relationships between population and desertification (Table 3.5). The highest number of wells increases irrigation potential, but simultaneously put forward protection from vulnerability because of ground water depletion. Nagaur, Jodhpur, Jhunjhunu and Sikar enlist highest tractor density (no. of tractors/1000 ha) – an indicator of intensive tillage, making the region more fragile. Further, greater livestock population than the human population in Jodhpur and Nagaur districts are putting pressure on fodder security (Varghese, 2013). Thus human activities destroy surface vegetation, degrade soil structure and fertility, impede water infiltration, and cause soil drying promoting desertification.

Table 3.5 Composite indices and ranks according to development and desertification indicators (Source: Varghese, 2013).

SNo.	District	Development		Desertification	
		Criteria & Indicator	Rank	CI	Rank
1	Barmer	0.76	9	0.50	3
2	Bikaner	0.37	3	0.35	1
3	Churu	0.39	4	0.55	4
4	Jaisalmer	0.68	8	0.48	2
5	Jalore	0.67	7	0.67	5
6	Jhunjhunu	0.30	1	0.71	8
7	Jodhpur	0.42	6	0.70	7
8	Nagaur	0.42	5	0.72	9
9	Sikar	0.34	2	0.68	6

This is especially true for the fragile transition zone between arid and semiarid land where human activities have stretched the ecosystem to its limit causing expansion of deserts particularly in desert margins. Study of Liu et al. (2003) along the Great Wall in northern *Shaanxi* Province- vulnerable to desertification due to its fragile ecosystem and intensive human activities reveals that desertification is both a natural and anthropogenic processes. The study reveals that the overall severity of land degradation has worsened during the last two decades with severely, highly and moderately degraded land accounting for 84.2% of the total area in 1998. While the area affected by desertification has increased, the rate of desertification has also accelerated from 0.74 to 0.87%. Kirui and Mirzabaev (2014) reviewed the studies on the causes of land degradation in eastern Africa, where major causes leading to land degradation included non-sustainable agricultural practices, overgrazing and overexploitation of forest and woodland resources. The major underlying causes are believed to be population pressure, poverty and market and institutional failures.

Global population has grown up from 1 billion in 1800 to 7 billion in 2012 and expected to reach 10.8 billion by the end of 21st century (Snider and Brimlow, 2013; Myeni, 2016). This is accelerating the demand for natural resources and placing more pressures on the integrity of the land. While the induced innovation theory (Boserup, 1965; Hayami and Ruttan, 1970; Jayne et al., 2014) has predicted that farmers will intensify their land investment with increases in the population, other studies have suggested more land degradation in areas with greater population density (Cleaver and Schreiber, 1994; Von-Braun et al., 2012). Forest cutting for fuel wood has deforested large tracks of land in Africa and Asia encouraging desertification. For example overexploitation of forests and corresponding washing of forest floor leads to destroying of topsoil, decrease in water tables and contamination of water (Sibaud, 2012). Over use of forestlands leads to crusting of the exposed topsoil by rain and sunshine that increases runoff, water erosion and terrain deformation or bare rocks. Overgrazing has several effects that causes a decline in pasture vegetation and palatable grass species, replaces perennials with short-lived annual species that do not hold soil against erosion, compacts soil under trampling hoofs, and destabilizes dunes when crest vegetation is destroyed. Soil drying promotes wind erosion and encroachment of sand dunes on arable land. However, the extent to which erosion actually reduces crop yields depends on the types of crops, indicating that the crop management system can have an influence on crop yields and the effects of land degradation (Jolejole-Foreman et al., 2012). In the long run and in instances of severe degradation, the effects of land degradation might lead to temporary or permanent neglect of the area and to a conversion of land to lower-value uses (Scherr and Yadav, 1996). All these mechanisms are very closely interlinked and have spiral feedbacks on land productivity (Fig 3.2). According to Bossio et al. (2010) there is a strong link between land and water productivity also as there is reduced water efficiency due to land degradation, which leads to a greater demand for agricultural water. Water quality and storage may also be reduced under desertification. Change in land use is one of three anthropogenic activities that have contributed to increase in atmospheric CO_2, the other two being fossil fuel combustion and cement manufacturing (IPCC, 2000). While deforestation directly leads to lower rainfall and higher temperatures, growing too many crops, year after year on the same piece of land damages the soil structure and reduces the soil fertility. However, in order to understand desertification processes, it is necessary to know the geomorphic processes under natural set-up and acceleration to the processes through anthropogenic activities (Kakad, 2012). The factors leading to desertification are extremely evident in the many parts of India in general and Rajasthan in particular.

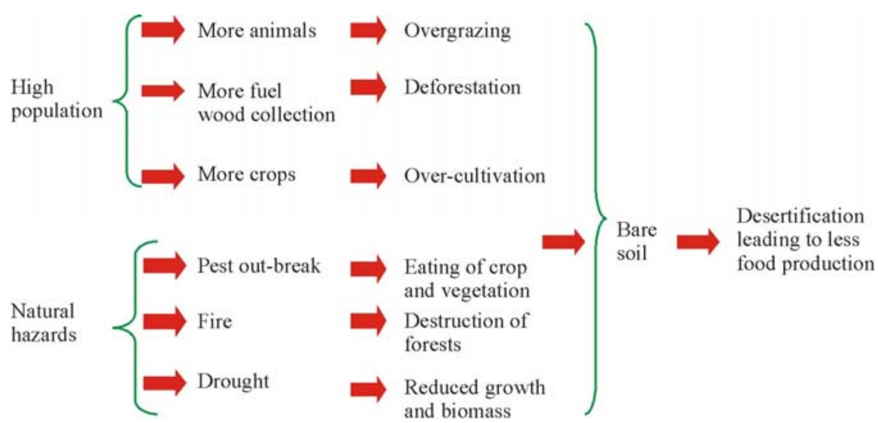


Figure 3.2 Causes and the process of desertification

4.1 Wind erosion of soils

Wind erosion is one of the most dominant problems particularly in western Rajasthan, where the sandy terrain is dominated by sparse natural vegetation cover. Strong wind regimes build up along with the increasing temperature which reaches to 15 to 18 km h^{-1}. Wind erosion is a major contributor to land degradation and it affects about 15.20 million ha land. Highly affected districts by wind erosion in Rajasthan are Jaisalmer, Bikaner, Barmer, Churu and Jodhpur. Indeed, there is clear evidence that the Thar Desert is expanding in eastward as well as northeast direction (Goswami and Ramesh, 2008; Ajai et al., 2009). Low and erratic rainfall, intense solar radiations, high evaporation, low relative humidity, poor edaphic conditions, high biotic pressure and high wind speed are responsible for the spatial variability in sand reactivation pattern and dune movement and hamper vegetation growth, reduce air quality and enhance economic loss (Fig 3.3). Furthermore the introduction of the tractor for deep ploughing, instead of the traditional animal-driven wooden plough, has increased the sand load manifold for the aeolian processes in large parts of the desert, and accelerated the mobility of sand-leading to wind erosion. Increased destruction of the natural land cover in grazing lands for fuel and fodder and enlarging the frontiers of cultivation to less suitable sandy areas are also the responsible factors exacerbating wind erosion. About 75% areas of western Rajasthan are affected by wind erosion/deposition alone. About 21% area is affected by desertification of severe intensity, and 40% by moderate intensity, especially due to high human and animal pressures. Windblown dust adversely affects respiratory and cardiovascular systems of desert dwellers as well as on other health parameters (Santra and Mertia, 2006). Field measurements at Jaisalmer and Chandan reveal that PM10 (particulate matter of 10 micron size) and PM2.5 (particulate matter of 2.5 micron size) load are on an average 20.0% and 15.5% of the total mass transport, respectively. The PM2.5 load in eroded sediment is slightly higher at Chandan (16.6%) than at Jaisalmer (13.9%) and is due to higher percentage of silt (<0.02 mm) and clay (<0.002 mm) in parent soil material at the respective place. Most of the windblown sand/dust is deposited in adjoining areas that results in economic loss due to decreased land production and expenditure involved in removal of soil/silt from roads, canal or water bodies.

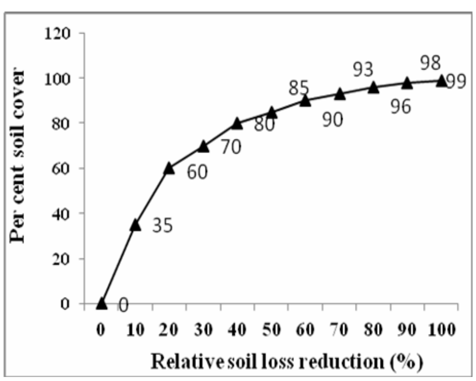


Figure 3.3 Effects of soil cover on relative soil loss reduction (left) and economic loss in road maintenance of road encroached by a shifting dune (right)

Severe wind erosions are observed in the extreme western regions of India and have been found related negatively to vegetation cover and positively to wind velocity. It is reported that the removal and deposition of sand during a 100-day period from April to June ranges between 1449 and 5560 tons per ha (Singh et al., 1990). The latest estimates show that area affected by wind erosion is 17.5 million ha (5.34 of the total geographical area as compared to the 4.1% estimated earlier). A study in Rajasthan indicates the loss of soil during sand storm with a mean wind speed of 20 km hr^{-1} is 273.7 kg per ha per day from a bare sandy soil at Bikaner, 76.7 kg per ha per day from a grass cover sandy soil at Chandan near Jaisalmer and 15.6 kg per ha per day from a loamy sand soil with clod formation at Jodhpur (Gupta, 1993). Such types of sand induced land degradation forces people to look for other income source and livelihood alternatives in western Rajasthan. Raina and Joshi (1994) have estimated nutrient losses by wind erosion in the sandy terrain of Jodhpur district covering the cultivated lands, the culturable wastes (pasture lands), and the permanent pastures (locally called the *orans*) and have observed 58% and 37% losses of available P and K in the wind-degraded cultivated fields, while the loss of organic carbon has been highest (up to 50%) from the degraded orans or sacred groves.

4.2 Water Erosion

Soil erosion through fluvial processes affect large areas along the eastern margin of the Thar Desert where the average annual rainfall varies from 350 to 500 mm. In the foothills of the Aravali hill ranges cultivation activities also lead to accelerated water erosion, as manifested through the formation of rills and gullies. Water erosion in the form of sheet, rill and gully is usually a problem in the areas of average annual rainfall exceeding 350 mm, but high rainfall intensity together with moderate to steep slope and shallow soils add to the problem, i.e. formations of ravines like that in south-eastern region of Rajasthan (Plat 3.1). Sharma (1968) has defined ravines as a channel of ephemeral flow, denuded and guided essentially by the process of rejuvenated streams, and having steep sides and head scarps with a width and depth always greater than a gully. Largest incidence of ravines is observed in Madhya Pradesh, Uttar Pradesh and parts of Rajasthan covering an estimated area of 3.67 million hectares and occurs along the banks of Beas in Punjab, Chambal in Madhya Pradesh, Rajasthan and Uttar Pradesh, Kalisind, Banas, Morel and Gambhir in Rajasthan, Yamuna in Uttar Pradesh, and Mahi, Sabarmati, Narmada and Tapti in Gujarat. The ravines of Chambal have originated from tectonic activity, but continued deforestation exposes the nutrient deficient soil, which exacerbates ravine expansion. Extreme climatic events can speed up erosion and development of ravines during the last 15 years affecting production system (Pani and Mohapatra, 2013).

Washing away of the deposited sand along the hill slopes in western Rajasthan by running water during rainfall period also leads to the formation of gullies and ravines in the region. Flash floods also lead to localized high erosion and sedimentation across the desert, and thus changes in land productivity. For example, high-intensity rainfall for three days in Barmer-Jaisalmer tract in August 2006 not only resulted in yearlong flooding in Kawas and Malba village areas of Barmer Rajasthan, but also led to erosion of topsoil and nutrients from the upper catchment and their deposition in the lower catchment. The stream network, revived after more than half a century, however, did not deviate from the simulated channel courses for the area (Kar et al., 2007; Singh et al., 2008). It has been observed that the shallow sandy channels of the desert are hardly able to accommodate much of the run-off generated during the long spells of high intensity monsoon rainfall, and leads in general to flooding in lower catchment areas. The floodwater often gushes out along some old and abandoned channels. It is only when such old courses are under human use systems and sand deposition that obstruct the free passage of floodwater.

4.3 Mining activities and mined-wastelands

Mineral extraction from the earth has been increased from 7 to almost 60 billion tons in the last century itself (UNEP, 2012). Rajasthan province of India is very rich in the mineral production, where 79 varieties of minerals are available. Out of this 58 minerals are extracted. In 2013-14, out of the total 5,30,232.93 ha under mining in India, 1,16,009.93 ha is in Rajasthan alone, which is the largest area under mining leases granted by any state. This is followed by Orissa with 74,990.98 ha under mining and Andhra Pradesh 69,607.07 ha (Singh, 2014). Likewise, the number of leases granted by the state is 3,403 (for major minerals) which are followed by Andhra Pradesh with 2,031 leases and Gujarat with 1,162 mining leases over 29,430.04 ha. In addition about 11861 leases have been granted for the minor minerals in the state (Table 3.6). Though these mining activities are providing employment of about 2.82 lakhs, but a lot of these leases are accorded in the forest areas, which may be hazardous to forests and the environment because of a close linkage between the mining activity and the environment. For example, in the Bijolia region of Rajasthan sandstone quarrying covering only an area of about 0.84 km^2 in 1971 has increased to 12.04 km^2 in 1984 and to 30.83 km^2 in 1991. Forest area and the quality of forest habitat in the region have also decreased proportionally during the same period (Sinha et al., 2000). The small entrepreneurs hardly take up any posit mining management of the mined pits and waste dumps largely practice open cast mining (Saxena et al., 1997).

Table 3.6 Number of leases, area, production and employment in extraction of major and minor minerals in Rajasthan (Source: GoR, 2014).

Mineral type	Number of leases	Area (ha)	Production (million tons)	Revenue (million Rs.)	Employment (Nos.)
Major minerals	3403	98529.98	94.90	15946.87	34993
Minor minerals	11861	86101.74	251.82	12706.23	246434
Total	15264	814631.72	346.72	28653.10	281427

The area occupied by the mines is increasing, which is about 0.05 per cent of Jaisalmer district and 1.15 per cent of Jhunjhunu district (Kakad, 2012). Mining on agricultural land, either surface or underground, reduces the productivity of land by way of excavation, disposal of debris and tailing. Mineral processing like grinding of limestone for cement industry and calcite and soapstone for ceramic industry have three-fold adverse effects on environment (Plate 3.2). Quarrying activities in the catchment areas of small watersheds reduce water inflow to the ponds. Due to very poor plant nutrients and high pH and exchangeable sodium, magnesium, sulfur and phosphorus in the overburden/mine dump, their rehabilitation is a difficult proposition (Saxena and Chatterji, 1995), but achievable (Kumar et al., 1998; Kumar et al., 2004). In mining activities fine dust released into the atmosphere leads to surface scaling of the adjacent land after it settles down, consequently the infiltration rate reduces and the run-off increases. The mined materials such as limestone, china clay, fuller's earth, badarpur, calcite and gypsum generate fine particles, which are washed down the slopes with runoff and get deposited in the adjoining cultivated fields, restricts the sub-surface movement of water. With the removal of vegetation, the rate of evapotranspiration reduces; as a result, there is a change in the hydrological balance in the area. Due to this change, the perched water table rises and causes salinity in the affected area. Further, the mining debris of ball clay, china clay, Fuller's earth, bentonite and gypsum are dumped on the sandy plain resulting in development of a semi-impermeable surface layer leading to water-logging and salinity building-up. Sodium salt mining increases the surface salt concentration and causes total loss of vegetation.

4.4 Vegetation/forests degradation

The cause of destruction of the vegetation cover is its overuse by households, mainly for fuel wood collection. To cover vital energy needs, most households gather biomass, including crop residues and animal dung but most of all, fuel wood. Annual use of wood always exceeds the sustainable yield of forest or wooded areas leading to gradual loss of forests and woodlands. This in turn triggers or accelerates soil erosion and loss of productivity in the region. The common grazing lands around the villages are severely degraded sites and have been encroached upon for agriculture or housing. Overgrazing was not as large of a problem long ago because of the movement of livestock in response to rainfall and the sizes of herds were also less. Increased livestock and use of fences to keep the animals at one place cause overgrazing. Destruction of plants and cutting down of trees for fuel wood are putting soil prone to erosion. Overgrazing converts tree into scrub, i.e. spreading over the soil surface like *P. cineraria*, *A. senega*l, *B. aegiptiaca*, *Lycium barbarum* and *Anogiesus pendula*. In absence of readily available intensification and diversified income generation techniques, particularly for small ruminants that are appropriate for socio economic and ecological situation, these factors exacerbate by the attitude to mistrust between pastoralists and protected area managers. On an average the area with good grass species in the less than 300 mm average annual rainfall zone has declined from about 7% to 1% now, while in the more than 300 mm average annual rainfall zone the decline in tree and shrub cover is from 8% to 1-2% (Mertia, 1996). As the plant stands become more isolated, it gradually leads to a more heterogeneous distribution of soil fertility, which provokes further degradation (Schlesinger et al., 1990).

Reduced vegetation cover affects biodiversity in relation to the composition of pastures, livestock, tree and crop systems, the soil biota and the hydrological systems (Venkateswarlu, 2012). Most of the common lands (gauchar, Oran, Agor, Nadi etc) are severely degraded, exploited, neglected and encroached upon (Singh, 2014a). Over-exploitation and habitat loss of some of the vegetation like *Calligonum polygonoides* from sand dunes area, *Haloxylon recurvum* from saline depression for paddy cultivation, *Leptadenia pyrotechnica* for its utilization in break industries and *Lasiurus sindicus* for groundnut cultivation are some burning examples (Singh, 2011b).

A major casualty of natural vegetation degradation is a gradual replacement of the depleted useful species by the aggressive alien colonizers, which are the second most important cause of biodiversity loss (Shankar and Kumar, 1987; Kumar, 1997; Gibs and Salmon, 2015). Many introduced species establish, spread and subsequently invade and affect all environments including freshwater bodies, aboveground and in the soils services, and human physical and cultural health. Most of the ecosystems of Rajasthan are invaded by *Prosopis juliflora*, which has been reported in 36.7% forest block distributed in 32 districts, whereas *Lantana camara* has invaded in 7.2% forest block distributed in 15 districts in Rajasthan (Singh, 2014b). Drainage lines and wetlands are covered by many species like *Ipomoea carnea*, *Tamarix dioca, Fragmites australis* etc. (Table 3.7).

Table 3.7 Species under a decreasing population and some invasive species in Rajasthan.

Depleting species	Invasive species
Trees and shrubs	
Tecomella undulata, Calligonum polygonoides, Haloxylan salicornicum, H. recurvum, Calotropis procera, Commiphora wightii, Ephedra foliata	*Prosopis julifora, Lantana camara*
Herbs and grasses	
Lasiurus sindicus, Cenchrus ciliaris, Cenchrus priurei, Panicum antidotale	*Dyperigium gloucum, Cyperus rotundus, Eclipta erecta*
	**Wetlands invasive** *Typha angustata, Fragmites australis, Tamarix dioca* (in a drainage line at Ranakpur, side photo), *Saccharum spontaneum, Eichornia cressipes*

Decrease in forest cover particularly after 2001 is an indication of forest degradation affecting biomass and carbon stock of forest ecosystem of Rajasthan. Forest areas of more than 50 per cent of the districts of Rajasthan indicate below state average biomass and carbon stock (Singh, 2014b). Decrease in economic returns from crop cultivation, there has been an increase in harvesting of these products from the protected areas. Evidences suggest that the rate is strong enough to affect regeneration of the plants, as well as feed sources of wild animals. In a recently estimated ecosystem level available carbon stock in forests of Rajasthan indicates 305.19 Tg (million tons or terra gram) of carbon. Out of this, 142.6 Tg is soil inorganic carbon (SIC), 121.6 Tg is soil organic carbon (SOC), 1.24 Tg is as dead material, 0.77 Tg is in the form of herbaceous biomass and 38.98 Tg is in the form of standing tree and shrubs (both above-ground and below-ground) live biomass (Table 3.8). There is strong spatial variation also in carbon density, i.e. by 43.7-fold between forest sub types. Carbon density of shrubs, trees, bamboo and tree saplings combine has varied from 76.63 tons ha^{-1} in 5/2S2 type to 1.76 tons ha^{-1} in 5/E8b type forests (forest types in Annexure 2.1), whereas it varies from 2.05 tons ha^{-1} in Bikaner to 25.17 tons ha^{-1} in Rajsamand, when districts are considered (Singh, 2014b).

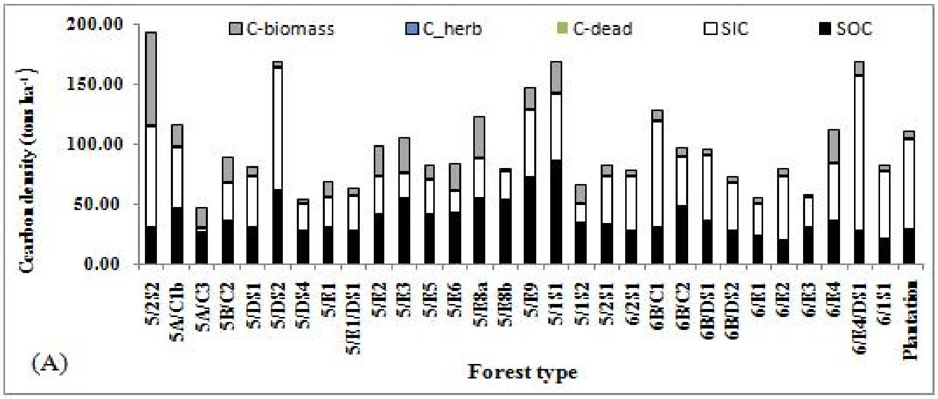
Table 3.8 Component-wise carbon stock in forests of Rajasthan (Source: Singh, 2014b). Values are in million tons (Tg).

Component	Above-ground	Below-ground	Total
Live biomass (tree, shrubs, tree sapling and bamboo)	27.30	11.68	38.98
Herbaceous	0.77	-	0.77
Dead material (litter and wood)	1.24	-	1.24
Soil inorganic carbon (SIC)	-	142.60	142.60
Soil organic carbon (SOC)	-	121.60	121.60
Total (million tons)	29.31	275.88	305.19

Forest types 5/DS1, 5/DS2, 5/DS4, 5/E1/DS1, 5/E8b, 5/2S1, 6/2S1, 6B/C1, 6B/C2, 6B/DS1, 6B/DS2, 6/E1, 6/E2, 6/E3, 6/1S1 and plantation show below average carbon density, whereas forest types 5/DS2, 5/DS4, 5/E1/DS1, 5/E8b, 6/2S1, 6B/DS1, 6B/DS2, 6/E1, 6/E2, 6/E3 and 6/1S1 show even lesser carbon density than plantation. Among districts, forests of Ajmer, Bikaner, Churu, Sriganganagar, Jaisalmer, Jodhpur, Nagaur, Banswara, Bundi, Dausa, Jhalawar, Kota, Sawaimadhopur and Tonk districts show low carbon density as compared to start average (Fig 3.4). Among all the districts, forests carbon density (live biomass, dead material carbon, herbaceous carbon and soil organic and inorganic carbon up to 1 m soil depth) range between 40.81 tons C ha^{-1} in Barmer and 180.63 tons C ha^{-1} in Pali districts. Order of SIC, SOC and live-biomass carbon (biomass_C) have been observed in following three categories in the forests of different districts of Rajasthan:

SIC>SOC>Biomass_C:	Ajmer, Bikaner, Ganganagar, Hanumangarh, Jalore, Jhunjhunu, Jodhpur, Nagaur, Pali, Baran, Bhilwara, Jhalawar, Karauli, Pratapgarh, Rajsamand, Sawaimadhopur and Tonk
SOC>SIC>biomass_C:	Barmer, Churu, Jaisalmer, Sikar, Banswara, Bundi, Chitaurgarh, Dausa, Dungarpur, Jaipur, Kota and Udaipur
SOC>Biomass_C>SIC:	Alwar, Bharatpur, Dholpur and Sirohi

In this decreased SOC and live biomass density and increased SIC in the forest ecosystem coupled with decreased dead materials indicate varying degree of forest degradation in Rajasthan.



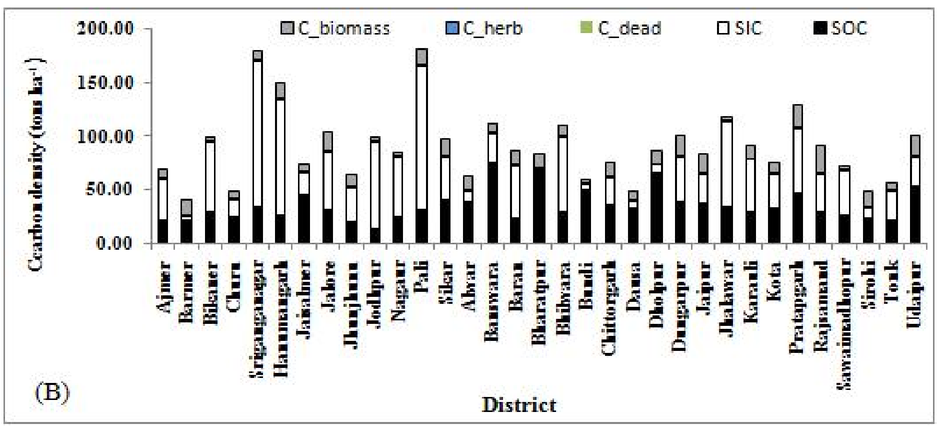


Figure 3.4 Spatial variation in carbon density in different components of forest ecosystems, i.e. standing biomass (C_biomass), herbaceous biomass (C_herb), dead material (C_dead), soil inorganic carbon (SIC) and soil organic carbon (SOC) under varying forest sub types (A), and districts of Rajasthan (B). Horizontal line indicates state average value.

4.5 Water logging and salinity

With the introduction of canal irrigation system water table in Indira Gandhi canal command areas is rising at an average rate of about 0.88 m yr^{-1}, while that in the Gang Canal command and Bhakra canal command it is 0.53 m per year and 0.66 m per year, respectively. As a result of this, large area has become water-logged and this area is increasing every year (Plate 3.3), and thus becoming is a serious problem particularly in deep black soils (Raina et al., 2009). Salinity and Alkalinity are profound problems in some parts of Rajasthan due to permanent high water table and/or faulty methods of irrigation. Sodicity is related to alkalinity but with high residual sodium carbonate content of irrigation water results in deterioration of the land quality. According to Minhas and Gupta (1992), about 84% groundwater in western Rajasthan is of poor quality. Irrigation with waters having EC >2.2 dS m^{-1} and up to 10 dS m^{-1} coupled with high RSC (up to 20 me L^{-1}) leads secondary salinization (Gupta et al., 2000). The problems of high soil pH (8.6-10.5) in the districts of Barmer, Jalore, Pali, Jodhpur and Sikar in western Rajasthan, unusual hardness, restricted water infiltration and decreased nutrient availability to plants in the soils irrigated with high RSC water are such that even after frequent ploughing and application of higher doses of farmyard/organic manure land productivity could not be restored (Raina et al., 1991; Raina, 1997). In the Malkosani, Pipar and Bhagasani soil series in the southern part of Jodhpur district, irrigation for at least 27 years with groundwater rich in carbonate and bicarbonate has increased the level of inorganic carbon in soil by 64, 44, 14 g m^{-2}, respectively, with simultaneous rise in pH by 0.2 to 0.4 units (Singh et al., 2009c).

4.6 Intensification of the agriculture and soil deterioration

Change from a fallow system to a reduced fallow, annual cropping and/or multi-cropping system that require a higher input of labour per area unit and dependence on external inputs such as seeds, chemical fertilizers, pesticides and herbicides is agricultural intensification (Szirmai, 1996). Population growth requires the extension of interference into new areas of lower resilience and higher sensitivity for which existing management practices may be inadequate leading to land degradation (Raut et al., 2010). Inadequate access to technological changes leads the growing poor rural populations to increasingly degrade and mine the natural resources to ensure their day-to-day survival. To overcome the problem of reduced soil fertility farmers use to increase the rate of irrigation and fertilization as well as cropping intensities, which result in land degradation such as salinization, water-logging and pollution by pesticides or fertilizers (Nambiro, 2008; Gregory et al., 2001). For example, total fertilizer consumption in India has increased from 16.19 million tons in 1997-98 to 27.74 million tons in 2011-12 with an average increase of 0.77 million tons per year, where use of nitrogenous fertilizer is relatively high. During 1997-98 to 2012-13 the production of total food grain has increased from 192.26 million tons to 250.14 million tons with an average increase of 3.62 million tons per year. Despite of shorter duration the consumption of fertilizer is 1.72-fold as compared to 1.31-fold increase in total food grain production (Fig 3.5).

The clearing of forestland, intensive cropping and imbalanced fertilizer application leads to depletion of soil organic carbon (SOC). In the central part of western Rajasthan the SOC was depleted between 1975 and 2002 by 10.4% and in the arid western Rajasthan as a whole, about 747 Tg (Terra gram, 10^{12} g), by 2002. Lands with very poor vegetation status and extensive fallow have been severely depleted of SOC. The mean emission of CO_2 from soil profiles (i.e., 0-100 cm deep soil column) in an area of 22850 km^2 is 11.2 Tg available phosphorus (during 1975-2002) by 21.9% and potassium by 17.6% (Singh et al., 2007a). The degraded soils have also registered a loss of silt by 39- 47%, and clay by 41-64%.

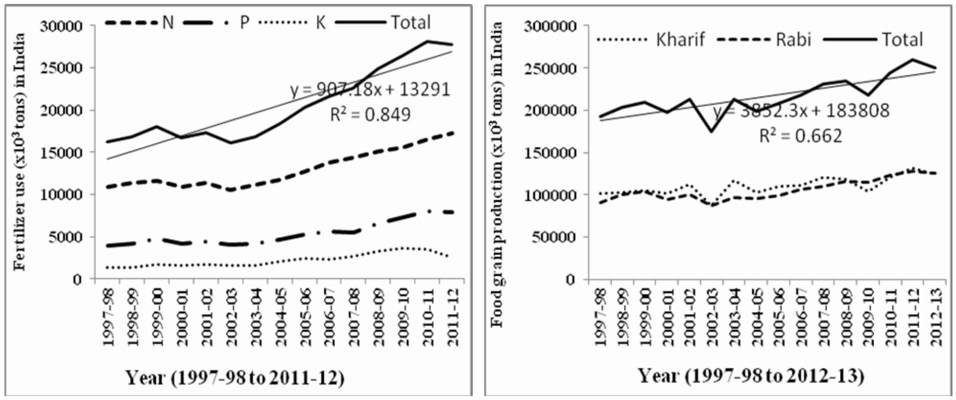


Figure 3.5 Figures showing fertilizer use (left) and food grain production (right) in India. Source: SIA (2012-13).

4.7 Increased industrialization and industrial wastes

Decreased agriculture production and lack of employment opportunities in rural area result in diversion of most of the agragarian population to the nearest city or town (Vogel, 1988). Growing population and simultaneous increases in day-to-day resource requirements support industrial growth and water use. Ultimately it produces wastewater from industrial and municipal activities and the occasional storm water during the rain, which if not properly disposed off accelerates the process of environmental degradation. The effluent discharge into different rivers and drainage lines contaminates lands and the related production system (Singh and Ram, 1997; Singh et al., 2009b). A reservoir constructed at Nehda, about 50 km downstream of Pali on the Bandi River to conserve water for drinking and minor irrigation now collects the polluted water from Pali and transmits the pollutants further downstream. On an average the effluent waters have pH >6, RSC of about 25 me L^{-1}, and sodium absorption ratio (SAR) exceeding 22 (Rathore et al., 2014). Recent studies by Centre for Science and Education, New Delhi, and our own observations have revealed that despite the establishment of common effluent treatment plants (CETP) in these areas, there are problems of lower capacity of the plants than the total discharge resulting in bypassing of the CETP to channelize untreated effluents to the river. The concentrations of arsenic, copper, lead and zinc in the groundwater in village wells downstream of Pali are alarmingly high and pose health hazard (CSE, 2006, 2007).

4.8 Groundwater depletion

Groundwater has been used in western Rajasthan in a most reckless manner during the last two and a half decade (from 1984 to 2009) to increase land productivity (Kumar et al. 2013a; Yadeo, 2014). According to Kumar et al. (2013a) the withdrawal of groundwater for irrigation is worsening water balance in the state, resulting in the ever increasing numbers of blocks under the categories of over-exploited, whereas under over-exploited category has gone up to around 70 percent that were only 36 percent in 1984. As electricity became available across the desert and Green Revolution technologies spread from the mid-1970s, irrigated winter cropping became the most sought after farming practice, with no regulation on water use. Farmers are cultivating groundnut, caster and in some areas cotton too using ground water after clearing the land of natural vegetation. Since there is much less recharging of the aquifers, the over-use of groundwater has ultimately resulted in a gradual decline of the aquifers. Ground water level monitoring data of pre-monsoon 2013 compared with decadal mean of pre-monsoon (2003-2012) indicates that half of the monitoring well have shown a declining trend in Rajasthan which leads to increase in salinity of the groundwater also (Maheshwari et al., 2012; MoWR, 2013). A recent satellite-based study on temporal changes in micro-gravity has re-confirmed the acute stage of groundwater use in western region of Rajasthan (Rodell et al., 2009). As more fresh water is being exploited from the aquifers, there is increasing danger of saline and toxic water incursion, affecting human health and soil quality. Moreover, depletion of groundwater is forcing farmers to shift back to rain-fed cropping in the sandy terrain, with adverse socio-cultural consequences.

5. DESERTIFICATION ASSESSMENT AND MAPPING

Natural and anthropogenic processes that lead to degradation or loss of the land’s productivity and complexity are also desertification. To assess the desertification status, integrated set of indicators have been identified that provide synthetic information on threshold levels, status and evolution of relevant physical, chemical, biological and anthropogenic processes. Multi-criteria decision-making (MCDM) is a collection of methodologies used to compare, select, or rank multiple alternatives that involve incommensurate attributes. Technique for order preference by similarity to ideal solution (TOPSIS) method is a multiple criteria method to identify solutions from a finite set (Sepehr and Zucca, 2012).

The first major global assessment of soil degradation was done by World Soil Information Center between 1987 and 1995 popularly known as the Global Assessment of Human-Induced Land Degradation (GLASOD). By 1990, GLASOD developed a world map of human-induced soil degradation defining soil degradation as “human-induced phenomena, which lower the current and/or future capacity of the soil to support human life” (Oldeman et al., 1991). Mapping of the soil degradation was based on the types and country using the degradation attributes like soil erosion by wind and water, chemical soil deterioration and physical soil deterioration and was produced for the United Nations Conference on Environment and Development (UNCED) in 1992 (Thomas and Middleton, 1994). Soil degradations were further categorized into light, moderate, severe, and very severe categories (Oldeman et al., 1991). According to this study 38% of the global land area was lightly degraded, 46% was moderately degraded and 15% was strongly degraded. Water erosion is the most important cause of soil degradation, followed by wind erosion, both of which accounted for about 84% of land area under degradation. The most degraded area was Europe (25%), followed by Asia (18%) and Africa (16%), whereas North America had smallest degraded area. Global news report (GNR, November 28, 2011) acclaimed that 25 per cent of the world's land is highly degraded by soil erosion, water quality degradation and biodiversity loss. Another 8 per cent is moderately degraded, while 36 per cent is stable or slightly degraded and 10 per cent is ranked as "improving." The rest of the Earth's surface is either bare or covered by inland water bodies. The productivity of some lands has declined by 50% due to soil erosion and desertification mostly in drylands but other regions are not untouched (GNR, November 28, 2011).

Land Degradation Assessment in Drylands (LADA) assessed the causes, status, and impact of land degradation in drylands (arid, semi-arid and dry subhumid) based on existing maps and databases added with GIS and remote-sensing technologies. The Global Land Degradation Assessment (GLADA) was built on LADA and assessed both land degradation and improvement by including humid and subhumid areas also over drylands defining land degradation as a "long-term decline in ecosystem function and productivity" (Bai et al., 2008). Here net primary productivity (NPP) or the rate of carbon dioxide fixation by vegetation minus losses through respiration was used to measure ecosystem productivity. The indicators monitored with remote-sensing imagery were NPP, rainfall use efficiency (RUE), aridity index (AI), and rainfall variability and erosion. However, the assessed high percentage of degraded area in the humid region was criticized because RUE is a poor indicator in humid areas (Wessels, 2009). The Millennium Ecosystem Assessment (MEA) was conducted during 2001 to 2005 to assess current trends in ecosystems and human well-being. It used GLASOD, the Convention on Biological Diversity and other available data and studies to assess land degradation. According to MEA the drivers of changes in ecosystem services are multiple and are related in a complex and interactive manner. These drivers of changes mediate and lead to trade-offs and synergetic associations. One such is conversion of land use types to agriculture, related to the loss of biodiversity. Regardless of some shortcomings there are quite good improvements in monitoring systems, but the key points need to be taken care of establishing a clear monitoring mechanism of the impacts of all programmes and schemes underway in improving the livelihood status and socio-economic conditions of the people as well as improvement of the ecosystem in the affected regions. On contrary that the hyper-arid areas are also populated and have substantial land-based economic activities (Singh et al., 2008), GLASOD assessment excluded the hyper-arid regions (~8% of the global land area) from the desertification assessment considering that the hyper-arid areas are irreversibly desertified (UNCOD, 1977). While Hellden and Tottrup (2008) have reported general changes in NDVI changes in dryland areas based on some regional studies but have cautioned also against using the result for interpretation as systematic desertification trend. Likewise, Sivakumar (2007) has suggested dramatic changes in agricultural practices during the last several decades as a major driver of desertification.

6. EXTENT OF DESERTIFICATION

6.1 Desertification in World

Desertification is the expansion of dry lands because of poor agricultural practices (e.g. overgrazing and soil fertility degradation and structure), improper soil moisture management, salinization and erosion, forest removal, and most importantly the climate change. The extent of distribution is highest in Asia (Table 3.9). Dry lands cover about 41.3% of the world's land area and covers area of about 15% of Latin America, 66% of Africa, 40% of Asia and 24% of Europe. Worldwide there is a significantly greater proportion of drylands in developing countries (72%), and the proportion increases with aridity as almost 100% of all hyper arid lands are in the developing world. There are six countries with at least 99% of their area classified as drylands. These are Botswana, Burkina Faso, Iraq, Kazakhstan, the Republic of Moldova, and Turkmenistan. Hyper arid region, which covers about 8% of global lands when included into drylands the total goes up to about 48% of the total global area (Table 3.9). However, these are barely productive and provide a meager existence to small populations, usually nomadic, who depend upon water sources in oases and wells. Hyper-arid regions include the Sahara-Arabian deserts and the Gobi desert. The other types are arid, semi and dry sub-humid regions, which are in the danger of becoming desertified (Plat 3.4).

Table 3.9 Extent and distribution of dry lands (million ha) in different continent of the world (Source: NAPCD, 2001).

Continent	Hyper arid	Arid	Semiarid	Dry subhumid	Total area (million ha)	% of total cropped area
Africa	809.9	505.2	507.3	280.8	1293.3	70.0
Asia	274.4	606.4	764.9	455.8	1837.1	44.0
Australia & Oceania	-	348.8	353.2	99.6	801.6	89.0
Europe	-	0.5	37.3	96.1	133.9	24.0
Americas & Caribbean	26.8	120.1	711.3	455.6	1287.0	31.0
World	1111.0	1591.0	2374.0	1387.9	5352.9	48.0
Per cent of total area	8.0	12.0	18.0	10.0	48.0	

About 22 per cent of the drylands are under desertification globally. However, there is a considerable extent of difference between them in terms of nature and processes of degradation with highest percentage of desertification in semi-arid followed by dry-sub humid region. Desertification and land degradation starts with wind and water erosion that may occur naturally and/or triggered by human activity. It refers to deterioration in the physical, chemical, and biological characteristics of soil, and the long-term loss of natural vegetation (UNEP, 1992). Its main manifestation includes decrease in land productivity, decline in land output potential, loss of land resources, and emergence of surface conditions unfavourable for production (Zhu, 1994). The degradation process may be everlasting, gradual, continual, or localized depending upon the prevailing climatic conditions and the interactive intensity of the people in the region (Liu et al., 1997). The United Nations Conference on Desertification ranks desertification hazard on the basis of a drop in agricultural productivity into four categories like none, moderate, high and very high depending upon the percentage loss in agriculture production (Table 3.10). It is prevalent along the margins of semiarid and arid lands in Asia, central Australia, portions of North and South America, and Africa (Plate 3.4). Desertification of the worlds and lands has been proceeding for more than thousand years though with varying pace. It has caused untold misery among those most directly affected, yet environmental destruction continues. After analyzing the data for 1948–2008 and climate model simulations for 1948–2100, Feng and Fu (2013) linked enhancing GHGs with desertification and observed that global drylands have expanded in the last sixty years. It was expected that by the end of the 21st century, the world's drylands may increase by 5.8×10^6 km^2 (or 10 %) than in the 1961–1990 under a high greenhouse gas emission scenario. The major expansion have been expected in the arid regions of southwest North America, the northern fringe of Africa, southern Africa, and Australia; and in semiarid regions of northern area of Mediterranean, southern Africa, and North and South America. There have been chances of increasing aridity over the global land between 60°N and 60°S latitude except India, northern China, eastern equatorial Africa and the southern Saharan regions.

Table 3.10 Desertification hazards ranked on the basis of decrease in agriculture productivity. (Source: Ritter, 2006).

SNo.	Desertification hazard	Loss in agriculture productivity
1	None	less than 10%
2	Moderate	10% to 25 %
3	High	25% to 50%
4	Very high	more than 50%

About three quarters of Africa's agricultural drylands are already degraded to some degree. The impact of desertification on the greatest number of people occurs in Asia. Degraded regions include the sand dunes of Syria, the eroded mountain slopes of Nepal, and the deforested and overgrazed highlands of Laos. The northern Mediterranean region is the cradle of civilization and has borne the effects of poor agricultural practices. Salinized, infertile soils are the result of natural hazards e.g. droughts, floods and forest fire, as well as over-tilling and overgrazing. Soil degradation is high through much of Central and Eastern Europe and very high in some areas, for example along the coast of the Adriatic Sea. Poor irrigation practices and the unsustainable exploitation of water resources are contributing to chemical pollution, soil salinization and aquifer depletion. Nearly a quarter of the inhabitants of Latin America and the Caribbean live below the poverty line fueling practices that lead to land degradation. Erosion and water shortages are further intensifying in many East Caribbean islands.

6.2 Desertification in India

After the first UN Conference on Desertification (UNCOD) at Nairobi in 1977, first attempt was made to map the processes of desertification in arid western Rajasthan (Singh et al., 1978). Since then many attempts have been made to assess the extent of land degradation at regional and country level. Most of these were based on a compilation of the different kinds of low-yielding or waste/barren lands that are mentioned in the land revenue records of the villages. Based on these, Ministry of Agriculture (MOA), Govt. of India, suggested 107.6 million ha area of the country under varying degradation processes in 1994 (32.7% of the total area), while a previous assessment mentioned in the said compilation had suggested 173.6 million ha (Anon., 1994). The assessment by the National Bureau of Soil Survey and Land Use Planning (2004) showed 146.8 million ha, i.e., 44.7% of total area of the country as degraded (Samra and Sharma, 2005). National Remote Sensing Agency (NRSA; now NRSC), released a wasteland atlas in 2005 that suggested 55.27 million ha of the country's land as wastelands (17.45% of country's area). These exercises reveal wide variations between the kinds of assessment. This indicates that individual perceptions, methods of assessment and attempts to exaggerate the effects of local droughts often played their role in the land degradation estimation and mapping at country level (Kar, 1996). To minimize the discrepancies in the data reported from different assessing agencies, Indian Council of Agricultural Research (ICAR) and the Department of Space (DOS), Government of India have tried to harmonize the existing data through a dialogue process among the major institutions (Table 3.11). The emphasis was always to identify the physical status of degradation for taking up remedial land development activities, rather than to take a holistic view, including the driving forces and the pressure variables. Inclusion of ravine areas under water erosion, non-inclusion of flooding/submerged area and shifting cultivation and mining activities in forest area illegally are some examples for the differences.

Table 3.11 Types and extent of land degradation (million ha) assessed by various agencies in India. Areas are in million ha.

Degradation category	Ministry of agriculture (1994)	NBSS&LUP (2004)	NRSA-Wastelands (2005)	ICAR-DOS harmonized*		
				Arable land	Open forest	Total
Water erosion	57.155	93.68	-	73.27	9.30	82.57
Ravines	2.678	-	4.32	-		
Flooding	-	0.21	-	-		
Wind erosion	11.160	9.27	-	12.40	-	12.40
Water logging	3.197	14.30	0.89	0.88	-	0.88
Salt-affected	6.323	5.94	3.90	6.64	0.1	6.74
Soil acidity	-	16.03	-	10.82	7.13	17.95
Mining/industrial wastes	0.425	-	-	0.19	-	0.19
Shifting cultivation	2.378	-	2.40	-	-	-
Degraded forests	24.897	-	-	-	-	-
Complex/special problem	0.089	7.381	-	-	-	
Total	108.30	146.81	11.51	104.2	16.53	120.71

Source: Kar et al. (2009); *ICAR (2010).

Out of 328 million hectare total geographical area (TGA) of India, about 228 mha (i.e., 69% of TGA) is under dry lands. In this arid, semi-arid and dry sub-humid areas cover 50.8 million ha (15.8%), 123.4 million ha (37.6%) and 54.1 million ha (16.5%), respectively (MoEF, 2011). While total area where the process of land degradation in India is estimated at 105.48 million ha (32.07% of TGA), area undergoing desertification is 81.45 million ha (24.78% of TGA), i.e. land degradation in drylands (Table 3.12). Largest area (22.97 million ha) under land degradation has been observed in Rajasthan that accounts for 21.77% of the total geographical area of India (Plat 3.5). It is followed by Jammu & Kashmir (12.79%), Gujarat (12.72%) and Maharashtra (12.66%). In Rajasthan, wind and water erosions account for 85.54% and 15.64 % of the total degradation type in Indian drylands, respectively. However, Sharda et al. (2013) have assessed 34.18 million ha area of Rajasthan under varying degree of erosion. Out of this about 59% (20.14 million ha) area falls under tolerance limits ranging from soil loss of 2.5 tons $ha^{-1}y^{-1}$ to 12.5 tons ha^{-1} y^{-1} (Sharda et al., 2013). However, in its recent report on desertification and land degradation in India, Space Application Centre, Ahmadabad (ISRO) has estimated 96.40 million ha and 82.64 million ha under land degradation and desertification, respectively in the year 2011-2013 as compared to the respective value of 94.53 million ha and 81.48 million ha the years 2003-2005 (SPA, 2016). This indicates an additional loss of 1.87 million ha land due to land degradation/desertification during this period.

Table 3.12 Current status of desertification (million ha) in the arid, semi-arid and dry sub-humid regions of India.

Type of degradation	India				Rajasthan	
	Arid	Semiarid	Dry sub-humid	Total	Rajasthan	% of total
Water erosion	3.67	17.67	4.87	26.21	3.84	14.65
Wind erosion	16.16	1.60	0.01	17.77	15.20	85.54
Vegetation degradation	1.97	8.43	7.23	17.63	2.14	12.14
Salinity/alkalinity	3.03	0.71	0.23	3.97	0.37	9.32
Water logging	0.00	0.07	0.59	0.66	0.004	0.61
Barren/Rocky	0.00	1.16	0.00	1.16	1.38	99.22
Man-made (mining, etc.)	0.00	0.08	0.03	0.11	0.03	27.27
Mass movement	3.66	0.50	0.30	4.46	-	-
Frost shattering	6.39	1.77	1.31	9.47	-	-
Frost heaving	0.01	0.00	0.00	0.01	-	-
Total	34.89	31.99	14.57	81.45	22.97	28.20

Except few pockets of Mt Abu whole Rajasthan is under drylands. This assessment indicates that 22.97 million hectares area in Rajasthan is degraded land, out of which 15.20 million hectare land is affected by wind erosion, whereas 3.84 million hectare is affected by water erosion. Degradation under vegetation removal covers about 2.14 million hectare. About 3.18 million hectare area of Rajasthan falls under Rocky and barren categories. While wind erosion and sand deposition is prevalent in arid region, the effects of sand deposition on land productivity are increasingly becoming more common in humid region too. For example sand deposits in paddy fields in Assam has significantly affected paddy yields, where productivity losses have ranged between 92 and 246 kg of paddy per hectare with an average presence of 54% sand in the soil (Das, 2012). Further, many of the area of western Rajasthan are affected by frost shattering affecting not only the crops but other vegetation (*Calotropis procera*, *P. juliflora*, *Acacia niliotica* etc.) and plantation like *Azadirachta indica*, *Dalbergia sissoo* and *Acacia nilotica* also.

Among the different districts of Rajasthan, Jaisalmer is highly degraded with 2,772 thousand ha, followed by Bikaner (2,120 thousand ha), Barmer (1,922 thousand ha), Churu (1,381 thousand ha), Jodhpur (1,241 thousand ha) and Udaipur (1,014 thousand ha). Wind erosion is a major contributor to land degradation; it affects 11,419 thousand ha (Fig 3.10 right). Highly affected districts are Jaisalmer (2,753 thousand ha), Bikaner (2,119 thousand ha), Barmer (1,908 thousand ha), Churu (1,346 thousand ha) and Jodhpur (1,235 thousand ha). Water erosion is very prominent in Udaipur (986 thousand ha), Chittorgarh (633 thousand ha), Bhilwara (571 thousand ha), Baran (564 thousand ha) and Bundi (539 thousand ha). Saline soils (82 thousand ha) are mostly found in Bhilwara, Bharatpur, Alwar, Ajmer, Tonk and Jaipur, and sodic soils are in Alwar, Ajmer, Chittorgarh, Dungarpur, Udaipur and Ganganagar. Saline soils cover an area of 82 thousand ha, mostly confined to Hanumangarh, Nagaur, Jaipur and Jaisalmer districts of the state. Sodic soils account 181 thousand ha and the districts affected by sodicity are Ganganagar, Alwar and Udaipur.

6.3 Forest degradation

Decrease in rainfall and increase in extreme weather conditions as predicted by the Intergovernmental Panel on Climate Change will lead to severe water scarcity and are likely to cause a vicious cycle of land and forest degradation and unsustainable livelihoods (Pearce, 2001). Forests of dryland has been trapped in a spiral of deforestation, fragmentation, degradation and desertification, driven by adverse land-use policies and subsidies, poor governance, and a general lack of understanding of the importance and vulnerability of these ecosystems. This is coupled with a lack of investment for their sustainable management and restoration. Climate change is another gargantuan and growing concern in drylands. Growing evidence shows that forests in dry areas have been declining with very high rates in many places, suggesting a need for a better understanding of the processes and causes of dryland forest degradation (de Waroux and Lambin, 2012). Forests in drylands account for about 6 per cent of the world’s forests (Malagnoux et al., 2007). They include most of North African and Sahelian forests and woodlands, parts of the Miombo woodlands and bushlands in Central and Southern Africa, the Dry Chaco, Caatinga and Mediterranean ecosystems in South America, the Brigalow Belt in Australia, as well as parts of Mexico, the United States and Central and South Asia. Most definitions describe de-forestation as long-term or permanent conversion of land from forest to non-forest lands. In the Marrakesh Accord, deforestation is defined as ‘the direct human-induced conversion of forested land to non-forested land’ (Ravindranath et al., 2012). The Food and Agriculture Organization defines deforestations as ‘the conversion of forest to another land use or the long-term reduction of the tree canopy cover below the minimum 10% threshold’ (Puyraud et al., 2010). Likewise a decline in forest density by 44.5% during 1997-2007 in woodlands of semi-arid to arid Southwest Morocco, Africa has also been observed (De Waroux and Lambin, 2012). Increasing aridity and, to a lesser extent, fuel wood extraction have been observed related to forest decline, but no effect of grazing by local livestock has been found.

According to Ministry of Environment and Forest, Government of India (1999) there were depletion in forests at the rate of about 0.34 million ha annually during 1980 to 1990, while afforestation efforts covered about one million ha of area annually during the same period. Such shrinkage in forests in India have been observed as a result of pressures from varying user groups and the pressure is more in drylands particularly in arid and semi-arid areas (Plat 3.6). There has been an increase in total forest cover by 5.71 million ha during 1987 to 2013, where the increase in dense forests and open forest are 4.04 million ha and 1.41 million ha respectively, but in fact there is substantial decline in original forest cover, whereas it has been added from non-forest to the forests of varying categories. For example there is an increase in forest cover in 2013 as compared to 2011 by 5871 km^2 area wherein the increases in very dense forest and open forests are by 31 km^2 and 7831 km^2, respectively. In fact there is a decrease in very dense forest area by 0.03 million ha (converted to moderately dense and open forests) and in moderately dense forests by 1.79 million ha area has shifted to scrub or non forests (SFR, 2013). The study of Reddy et al. (2016) also indicates a decrease in forest cover from 869,012 km^2 in 1930 to 625,565 km^2 in 2013 showing a net loss of 243,447 km^2 (i.e., 28 %) in these eight decades (Plate 6.3 right). Thus the figure is significantly underestimated if forest area change only is used as a measure of degradation. Ravindranath et al. (2012) has also estimated the net annual forest loss or deforestation as 0.065 million ha during 2003-05, 0.047 million ha during 2005-07 and 0.043 million ha during 2007-09, even though the national total area estimates show a net gain. According to another estimate, if one subtracts plantation from total forest cover, India’s native forests were actually declining at the rate of 0.8% to 3.5% per year for 2000–05 (IPCC, 2003). There has been increase in cover of both dense forests and open forest by 1448 km^2 and 2160 km^2, respectively during 1987 to 2013, but there is significant decrease in per capita forest cover. Unfortunately, there has been significant decrease in dense forests cover (1826 km^2) and total forest cover by 281 km^2 during last 12 years (2001-2013) and increase in open forest cover by 1545 km^2 area (Table 3.13).

Table 3.13 Temporal changes in areas of different forests categories in India and Rajasthan. Data are extracted from States of Forest Reports, Forest Survey of India, Dehra Dun.

Year	India (million ha)				Rajasthan (sq. km)			
	Dense forest	Open forest	Total	Scrub	Dense forest	Open forest	Total	Scrub
1951	-	-	40.49		-	-	-	-
1987	36.54	27.66	64.20	7.68	3048	9430	12478	-
1989	38.27	25.74	64.01	5.89	2902	10064	12966	-
1991	38.50	25.42	63.92	5.96	3027	9808	12835	
1993	38.56	25.45	64.01	5.89	3581	9518	13099	6.75
1995	38.58	25.38	63.96	6.05	3684	9596	13280	6.89
1997	36.73	26.61	63.34	5.72	3690	9663	13353	6.78

1999	39.52	26.31	65.39	4.73	-	-	-	-
2001	41.68	25.87	67.55	4.03	6322	10045	16367	4925
2003	39.06	28.78	67.83	3.85	4496	11330	15826	4564
2005	40.35	28.68	69.02	3.85	4526	11486	16012	4356
2007	40.25	28.84	69.09	-	4522	11514	16036	4347
2009	40.42	28.78	69.20	-	4522	11514	16036	4347
2011	40.42	28.78	69.20	4.15	4520	11567	16087	4357
2013	40.23	29.57	69.79	4.14	4496	11590	16086	4211
2013-1987	+4.04	+1.41	+5.71	-	+1448	+2160	+3608	

7. CONCLUSIONS

Increasing potential evaporation and changes in precipitation patterns under a warming climate are leading to an increase in aridity in Rajasthan (Goyal, 2004) and global level as well resulting in the expansion of drylands. Increasingly high human and livestock populations are going to be affected by water scarcity, whereas extensive land use and other human activities will further amplify these changes (Reynolds et al., 2007).

Over exploitation of resources, vegetation removal and a decline in forest species richness and tree density under increased human economic activities have accelerated land degradation in all climatic zones and drylands in particular (Chen and Tang , 2005; Gonzalez, 2001).

The severity of desertification is more in developing countries where people depend more on the surrounding environments for their livelihood, and adequate resources are not available for restoring the over-exploited dry land ecosystems.

Desertification is not only a serious threat to the ecosystems health and human living within the region, but also affects areas far away the dry lands. The soils blown away by wind or washed away by rain remove soil organic carbon and nutrients from the soil and enhance cost of production; salt build up in the soil makes it harder for plant growth, the amount of food being made will decline, ecosystem services will decline leading to economic problems and starvation for growing population; desertification will reduce soil drainage and infiltration leading to flooding, poor water quality, dust storms, and pollution; reduction in soil quality and biomass production leads socioeconomic loss; and increase in salt content of previously fresh lakes, wetlands and the other water sources will deteriorate drinking water supply and will increase diseases etc.

Predicted climate change and increase in frequency of drought will further agravate the problems of desertification and people livelihood. It is indicated by increase in area under land degradation in India.

An adequate measure including scientific, socioeconomic and political views is needed to combat desertification and to make the production system more sustainable.

Plate 3.1 Ravine along Chambal river in Dholpur district of Rajasthan.

Plate 3.2 Sand stone mining a cause of health hazards and land degradation in outskirts of Jodhpur city.

Plate 3.3 Development of water logged area and salinity (salt encrustation) due to over-irrigation in some pockets of Rajasthan.

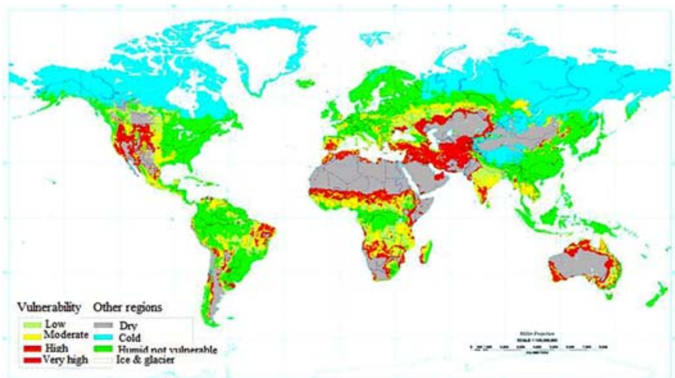


Plate 3.4 Desertification vulnerability (Courtesy NRCS).

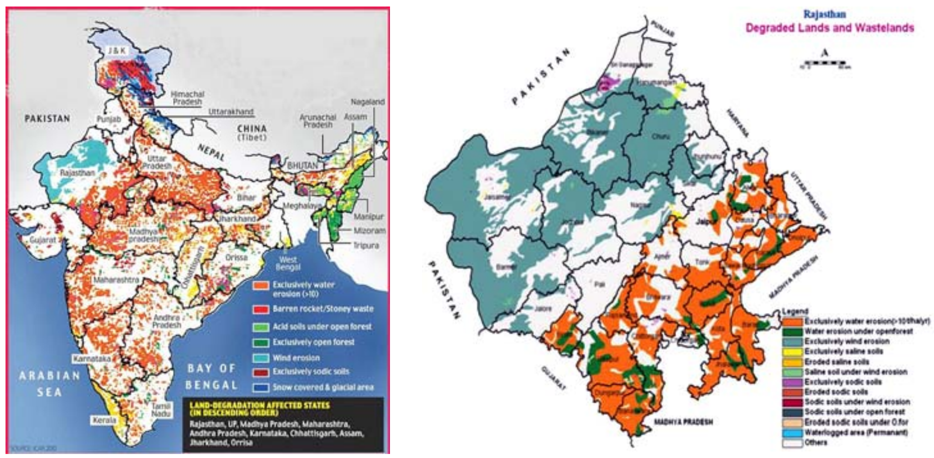


Plate 3.5 Land degradation status in India and Rajasthan

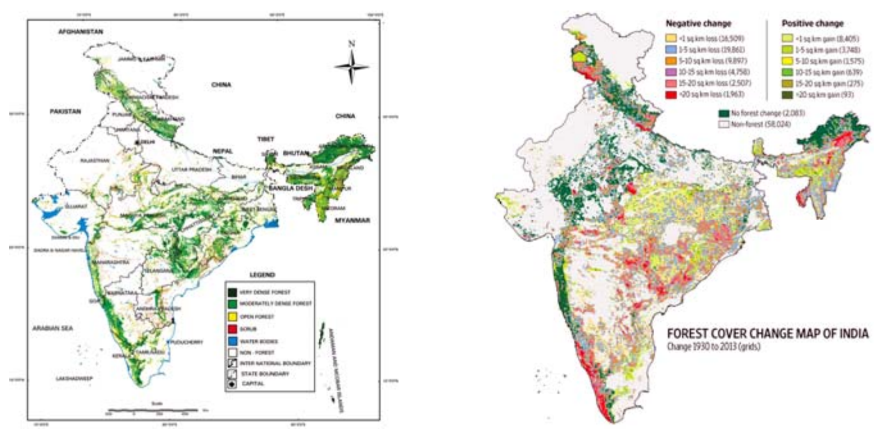


Plate 3.6 Status of forest in different states of India including Rajasthan (left, from SFR, 2015) and forest cover change during 1930 to 2013 (right, from Reddy et al., 2016).

4

THE ECONOMIC PERCEPTIONS OF LAND DEGRADATION

Unsustainable interaction of land and its users causes different kinds of land degradation and results in serious social problems because of change in soil constituents, the biotic component, landscapes and the climatic attributes all together. It has both onsite and offsite impacts. The onsite impacts reduce soil organic carbon, nutrients, biodiversity and biomass production. These factors also increase the production costs due to increasingly more inputs to address the negative physical impacts. The off-site impacts are deposition of large amounts of eroded soil in ponds, canals/streams, lakes, and other ecosystems reducing water storage capacity and raise the waterways, and make them more susceptible to overflowing and flooding and contaminate water bodies by various chemicals too. Land degradation has various economic impacts, which are direct (affecting the land users), indirect (affecting people at distant place), and economy-wide impacts (sum of the initial costs increased by the multiplier effect linked with other economic sectors). Different methods of economic valuation of land degradation includes (i) replacement cost approaches; (ii) nonmarket valuation techniques; (iii) productivity change approaches; (iv) aversive behaviour and damage costs approaches; and (v) benefit transfer approach. Each of these methods has its own merits and demerits, but there is clear indication that there are huge economic losses due to desertification, land degradation and drought. This chapter describes the pattern of losses due to land degradation, its various environmental, social and economic impacts, their economic evaluation and suggestive measures to cope with these challenges, which are going to aggravate in future.

1. INTRODUCTION

Recognizing the fact that land refers to more than just soil, the United Nations Convention to Combat Desertification (UNCCD) defines land as “the terrestrial bio-productive system that comprises soil, vegetation, other biota, and the ecological and hydrological processes that operate within the system” (UNCCD, 1996). Unless covered over by roads, buildings, etc., all soils sustain biomass production, whether it is natural vegetation or nurtured for agriculture and forestry. From the smallest herbaceous seedling to the largest tree, all land-based vegetation depends on soil for providing them the nutrients, water and root support. In turn these vegetation support animal life on the land. The productivity of soil depends upon its physical and chemical properties and on immediate environment. In general, the most productive soils are used for arable farming, whereas less productive soils are utilized for grassland, heath land and forest (Dupouey et al., 2002). A significant amount of world's total land area of 150 million km^2 is not suitable for agriculture. Arable land comprises 10% of the total, whereas permanent crops are 1%; meadows and pastures are 24% and forest and woodland are 31%. The remaining 34% land surface supports little or no vegetation, i.e. Antarctica, deserts, mine sites, urban areas. Most of the world's productive land is already exploited, whereas most of the unexploited land is too steep, wet, dry or cold for agriculture.

About 75% of land (>80% in Asia) is under food production at present; however increasing needs for food, fuel, fodder, urban development etc are competing for high quality agricultural land (Osakwe and Igwe, 2013). Land under farming was just 7 percent of the world's land in 1700 A.D.. According to Food and Agriculture Organization (FAO), total farmlands have been increased by 5 million hectares annually between 1992 and 2002 (Owen, 2005). At present about 38% of world's land is under agriculture, which has increased in area under cereal production by 9.29% during 2000-2002 to 2011-2013 with an average consumption of 141.3 kg fertilizer per hectare of arable lands (WB, 2014). However, during the last 40 years, more 30% of the total arable land of the world is lost by erosion and it continues to be lost at a rate of 10 million ha yr^{-1} (Pimental et al., 1995). In India, where about 18.5% of the total world's soil erosion occurs, about 5334 million tons of soil is lost annually (Dhruvanarayana and Ram Babu, 1983).

Interaction of natural processes, human activities, and social systems causes land degradation and increase the costs of land production (Safriel, 2007). For example, land and its user interactions, if unsustainable, lead different kinds of land degradation and result in serious social problems because of change of the ensemble of the soil constituents, the biotic component, landscapes and the climatic attributes (Vlek et al., 2010). Though early definitions of land degradation refer to a decline in "the current and/or potential capability of soils to produce (quantitatively and/or qualitatively) goods and services" (FAO, 1979), more recent definitions provided by UNCCD is "reduction or loss in arid, semiarid, and dry subhumid areas, of the biological or economic productivity and complexity of rainfed cropland, irrigated cropland, or range, pasture, forest, and woodlands resulting from land uses or from a process or combination of processes, including processes arising from human activities and habitation patterns". The later definition extends land degradation to spatial and time dimensions.

Degradation in soil conditions as a result of decreased efficiency of soil and water conservation and its amount and quality in dry areas is the main direct cause of desertification. Though climate and soil characteristics are very much related to land degradation, but it is deforestation and inappropriate use and management of the natural resources, soil and water, which are responsible for desertification. The main effects are decrease in water supply, a non sustainable agricultural and food production, and increased risks of catastrophic flooding, sedimentation, landslides, etc. In the medium or long term, the sign of global climatic changes may contribute to accelerate the processes of desertification. However, in a study Zhou et al. (2013) have observed climate change as dominant factor in desertification reversion, whereas human activities dominated the desertification expansion, though the relative roles of both climate change and human activities in desertification possess great spatial heterogeneity.

Land degradations are classified into physical, chemical, and biological types. These types do not necessarily occur individually; rather spiral feedbacks between processes are often present in the process (Katyal and Vlek 2000). Physical land degradation refers to erosion, loss of soil organic carbon, changes in the soil's physical structure, such as compaction or crusting and waterlogging. Chemical degradation, on the other hand, includes leaching, salinization, acidification, nutrient imbalances, and fertility depletion. Biological degradation includes rangeland degradation, deforestation, and loss in biodiversity, involving loss of soil organic matter or of flora and fauna populations or microbial species in the soil (Scherr, 1999).

2. IMPACTS OF LAND DEGRADATION

Degrading lands have both onsite and offsite impacts. On site impacts of land degradation include reduction in soil organic carbon and nutrients and the increase of production costs due to increasingly more inputs to address the negative physical impacts. As a consequence of erosion and land degradation there are income losses, as farmers are not able to pay for inputs and to invest in improved land management techniques (Bojö, 1996). Land degradation reduces the availability of biomass because of tree cutting and over-exploitation of vegetation, which in turn increases the labour input required for collecting fuel wood and fodder from distant places (Cooke et al., 2008; Singh and Sharma, 2010). Degraded land also lead to loss of biodiversity, which in turn leads to reduction in ecosystem services used by the local people (Table 4.1). Reduction in the water absorptive and storage capacity of soil due to erosion increases the demand for water. For example moderately eroded soils absorb about 7 - 44% less water per hectare per year from rainfall as compared to the erosion free soils (Murphee and McGregor, 1991). Increased demand for irrigation water implies higher production costs, low yields and plant biomass, and consequently lower overall species diversity in the farming system (Walsh and Rowe, 2001; Maitima et al., 2009; Majule, 2010). However, because of linkages across the sectors of the economy like supply and demand, production, demand, prices, and trade of all commodities are beyond the crops and are directly affected by soil loss. Lowering of production levels particularly in staple food crops leads food insecurity problems as the population is increasing day by day (Diao and Sarpong, 2007).

Off-site impacts of land degradation include the deposition of large amounts of eroded soil in ponds, canals/streams, lakes, and other ecosystems through Aeolian deposits or soil sediments that are transported in the surface water from eroded agricultural land into lake and river systems including the rivers of western India, i.e. Rajasthan and Gujarat (Table 4.2). These deposits reduce the water storage capacity and raise the waterways, and make them more susceptible to overflowing and flooding of the area. They also contaminate the water with soil particles containing fertilizer, nutrients or chemicals that include pesticides. However, there are beneficial off-site effects of soil erosion that include the deposition of alluvial soils in the valley plains or over/along the rocky surfaces, which forms fertile soils for cultivation and higher land productivity. For example, the alluvial soils in the deltas of rivers Nile, Ganges, Bramhaputra, Indus, Mississippi etc are results of long-term upstream soil erosion and are the main cultivable fertile lands for agricultural crop (Pimentel, 2006). Likewise Aeolian deposits on the rocky surface or along the rocky slopes provide an opportunity of cultivating these unused lands in many parts of the world including Thar Desert region. While the provision of fertile sediment on flood plains decreases crop yield upstream or at source site, there is an increase in yields in the silt deposited areas (Clark, 1996; Pimentel, 2006). The siltation of rivers and reservoirs reduces their water storage capacity that leads to decrease in water availability for irrigation and for uses in drinking, industry and hydroelectricity generation. It also damages equipment and reduces flood control structures and ultimately disrupting the stream ecology, decreases navigability of waterways and harbours, increases maintenance costs of dams and shortens the lifetime of the reservoirs and rainwater harvesting structures.

Table 4.1 Varying onsite and offsite effects of forest (land) degradation.

SNo.	Onsite effect	Offsite effect
1	Decrease in biomass production	Sedimentation in river, reservoirs etc.
2	Decrease in supply of timber and other forest products	Increase in labour and time in fodder and fuel wood collection
3	Increase in soil erosion	Decrease in water storage and supply
4	Decrease in soil depth	Decrease in power generation
5	Decrease in soil and its attributes like SOC, nutrients etc.	Eutrophication in reservoir and other water bodies
6	Decrease in biological diversity	Increase in flooding
7		Lowering of water quality
8		Increase in maintenance cost of infrastructure
9		Decrease in air quality

Table 4.2 Sediment load in the rivers of Rajasthan and Gujarat, India.

State	River	Location	Sediment (tons)
Rajasthan	Mahi	Kadana	16291968
	Mahi	Mouth	22100000
Gujarat	Banas	Dantowada	3009107
	Tawa	Tawa	6800000
	Narmada	Garudeshwar	69700000
	Narmada	Mouth	125000000
	Narmada	Mouth	61400000
	Tapti	Savkhoea	24700000
	Tapti	Ukai	70936500
	Tapti	Mouth	102000000

Source: Extracted from Sharma (2002).

According to Alfsen et al. (1996) there are significant production impacts of soil erosion, which also affects trade, labour, private consumption, and investment. Impacts of degradation under over-irrigation are development of salinity, dryland salinity, soil structure decline, and induced soil acidity, which affect agricultural output and profitability. A study in New South Wales, Australia (Gretton and Salma, 1997) indicates that agricultural output and profit depend on the type of degradation. The results suggest that the expansion of some farming systems, and the associated increased degradation due to salinity, provides a net increase in production and profit in the medium term, whereas soil structure decline and induce soil fertility leading to negative net effects. The study of Diao and Sarpong (2007) on the effects of soil loss on the economy and on poverty in Ghana indicates a decline in the national and rural poverty rates between 2006 and 2015 by 5.4% and 7.1%, respectively, when soil loss is taken into account.

Others off site effects are the environmental services provided by flora and fauna, which forms life supporting systems for the human beings and other organisms. These are recreation and the amenity value of water resources. Under a condition of biodiversity decrease, the lands become less resistant to droughts and require more time to recover in its productivity (Pimentel, 2006). The loss of keystone species may affect the survival of other species, as well as the biological cycle within the ecosystem. In case of increased population, more food will be needed and more will be produced even on marginal lands with low productivity, which has an effect on food security, farm income and poverty (Eswaran et al., 2001). As desertification decreases the natural productivity of the soil, it has the potential to decrease land production, or at least to increase the production costs. These two effects, in turn, raise food prices and increase food insecurity and poverty in the region. However, higher food prices also offer the potential for improved adoption of conservation measures in agriculture by increasing their profitability (Pender, 2009).

2.1 Impact on productivity

Land degradation is an important global issue because of its adverse impact on agricultural productivity, the environment, and its effect on food security and life quality (Eswaran et al., 2001; Lopez and Jiang, 2010). Productivity impact of land degradation is due to the decline in on site land quality where degradation (i.e., erosion) occurs and off site where sediment or sand is deposited. Rainfall failure leads to soil water stress that in turn lead to loss in agricultural production and other forms of social and economic hardship. Over 3.6 billion hectares of land is threatened worldwide by desertification and about 6 million hectares of productive land are lost every year due to land degradation since 1990 (Le et al., 2014). This includes forest ecosystems too, which is degrading and lost because of rapid population change and economic incentives that make forest conversion more profitable than forest conservation.

There is a decline in area of biomass productivity by 36 million km^2, i.e. 24% of global land area during 1980-2006 as a result of desertification (Le et al., 2014). The decline in NDVI (Normalized Difference Vegetation Index) has been observed in 25% of croplands and vegetation-crop mosaics, 29% of mosaics of forests with shrub- and grasslands, 25% of shrublands, and 33% of grasslands, as well as 23% of areas with sparse vegetation (Table 4.3). However, it is quite encouraging that about 2.7% of the global land mass has experienced significant improvement of biomass productivity over the last 25 years. Improvement in NDVI are located in the Sahelian belt in Africa, Central parts of India, western and eastern coasts of Australia, central Turkey, areas of North-Eastern Siberia in Russia, and north-western parts of Alaska in the US (Fig 4.1). However, the improving figure is significantly low than the extent of areas under degradation.

Table 4.3 Decline in area of NDVI during 1982-2006 and in percentages for the corresponding land cover.

SNo.	Category	World (km^2)	%
1	Cropland	289024	13
2	Mosaic vegetation-crop	25344	11
	Forested land	115392	31
4	Mosaic forest shrub/grass	448	22
5	Shrubland	25344	19
6	Grassland	17664	11
7	Sparse vegetation	0	0
	Total	473216	16

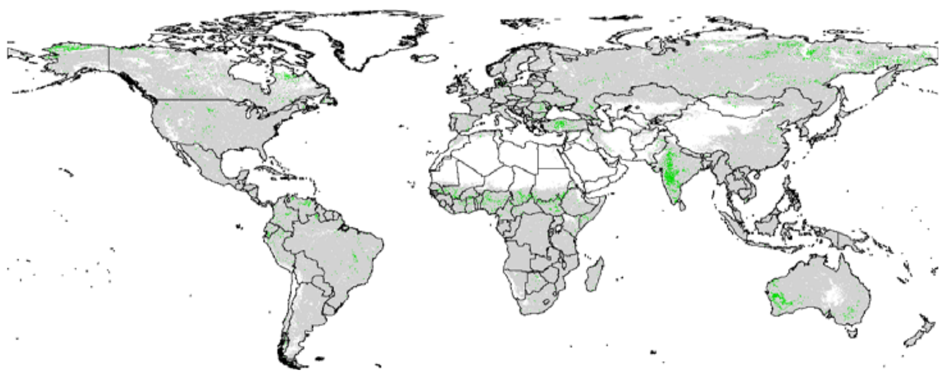


Figure 4.1 The areas of NDVI improvement, with slope of inter-annual mean NDVIs >= 10% over 25 year and 90% statistically significant, adjusted/corrected for RF and AF effects, LAI < 4. (Courtesy: Le et al. 2014).

2.2. Impact on socio-ecology

Livelihood of more than 3.2 billion people (35.5% of the total population), who reside currently in degrading areas, depends upon these lands. Of this about 0.6 billion people live in areas where land degradation is directly observed, whereas 1.2 billion people live in areas where land degradation is likely masked by rainfall dynamics and atmospheric fertilization effects. Another 1.3 billion people reside in areas where chemical fertilization may be masking soil and land degradation (Le et al., 2014). Because of increased human economic activities coupled with climate change and over-exploitation of ecosystem, desertification is accelerated in many parts of the world. The seriousness of desertification is more in developing countries where people are dependent on the surrounding environment or ecosystem for their livelihood, and resources are not available for restoring the over-exploited dry land ecosystem. A decline in forest species richness and tree density in the West African Sahel in the last half of the 20th century is a burning example (Gonzalez, 2001).

2.3 Impact on hydrology and air quality

As a result of desertification the world's drinking water supplies have decreased by almost two thirds since 1950, whereas about 12 million people die every year because of water shortages or drinking of contaminated water. Javed et al. (2012) have recorded a decrease in the area occupied by surface water resources owing to a decline in rainfall over the years. Decline of ground water table by 1 - 2 m on annual basis coupled with significant drawdown is leading to water scarcity in many parts of Rajasthan, India. A sharp decline of rainfall by 269 mm from 1977 to 2007 results in shifting in the cropping pattern under climatic change and decline in availability of water for irrigation. This results in land degradation and making rainfed agriculture more vulnerable. Dust storms from the Gobi desert have caused significant air quality and traffic problems in many Asian cities like Beijing, Seoul, and parts of Japan, and have even reached as far as the east coast of North America. Likewise dust storms from Sahara desert are affecting the air quality of Europe and have crossed even Atlantic or Arabian- Indian Ocean. About 135 million people have become homeless, whereas losses in income due to desertification are totaling USD 42 billion. An estimate on environmental degradation in India indicates a loss of about US $ 80 billion annually, i.e. equivalent to 5.7 per cent of gross domestic product in 2009 (Mani et al., 2012). The death of adults because of pollution and other environmental concerns costs Rs. 1,01,8 billion annually, while the loss of children will result in Rs. 13 billion per year. In addition, hospital admissions and restricted activity due to health problems will cause an annual cost of Rs. 1103 billion every year owing to mortality and morbidity.

3. APPROACHES AND METHODS

The economic impacts of desertification are categorized into direct (affect the land users that cause degradation); indirect (affect people far away from where the degradation occurs); and economy-wide impacts (sum of the initial costs increased by the "multiplier effect" owing to complex links with other economic sectors). Stern (2006) in his '*Review on the Economics of Climate Change*' has concluded that investing in the mitigation of greenhouse gas emissions makes more economic sense than facing the future costs of being unsuccessful to do so. The G8 initiated Potsdam Initiative (2007) has worked on the economics of biodiversity loss through the programme 'The Economics of Ecosystems and Biodiversity (TEEB) is similar to the climate change mentioned above (Balmford et al. 2008). The economic valuation is placing a monetary value on the various ecosystem services provided by the land, even when they are not marketed, so that recommendations regarding the economic efficiency of land management choices can be made. Desertification, land degradation and drought (DLDD) affects the provision of terrestrial ecosystem services. The economic values of these ecosystem services are necessary inputs for evaluating the costs of DLDD and its mitigation. Though there are considerable advances in the economic valuation of ecosystem services in recent years, there are still many gaps in such valuations including the economic valuation of specific ecosystem services and in the geographic coverage of such valuation, particularly in drylands, where DLDD is more prevalent. Though all ecological functions are related closely to economic functions, many important forest functions have no markets, hence no apparent economic value. Further, decreased contribution of forest in total economy of a country is also a cause of neglect. A decrease in the share of forestry sector to the total GDP in India has decreased sharply from 14.3% in 1950-51 to 1.4% in 2011-12) as compared to a decline in total agriculture share of 51.9% to 14.1% in same period (Fig 4.2). This justifies the use of forest land for other land uses.

Assigning economic values to non marketed benefits has the potential to change radically the way one look at forests and to make this swing back from a presumption in favour of forest conversion to more conservation and sustainable use (Pearce, 2001). Economic valuation and understanding show, how different components of forest ecosystem interact with the income and welfare of rural households is a key step towards sustainable use and management of forests. The economic valuation of this resource can enable decision-makers to include the impact of restoration activities in terms of cost-benefit analysis. Further, by valuing ecosystem services it is anticipated that the contribution of ecosystems, including soils, to human well-being will be better recognized and incorporated in societal decision making. A series of economic valuation techniques have emerged in an attempt to address the diverse nature of goods and services provided by ecosystems, and the various incentive for assigning them an economic value. The techniques rely on actual, surrogate or hypothetical markets to observe stated preferences for changes in ecosystem services (Samarasinghe et al., 2013).

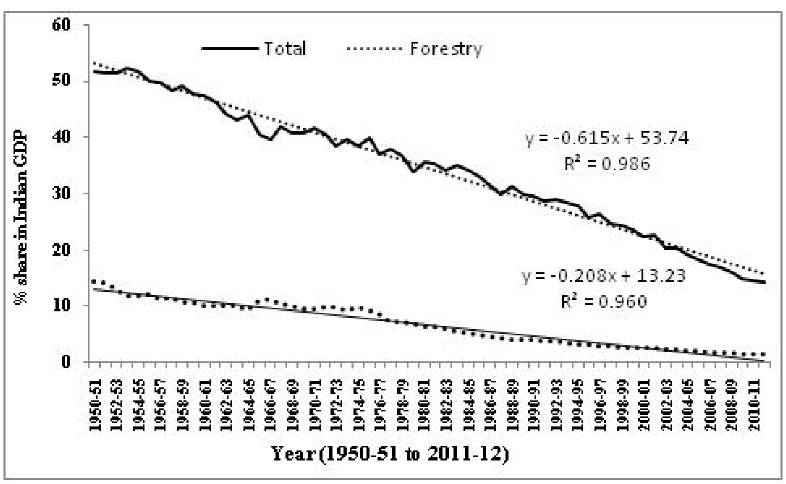


Figure 4.2 Per cent contribution of total agriculture (agriculture, forestry and fishery) and forestry to the total gross domestic product (GDP) of India.

Based on an economic theory, economic models present procedure for assessing the economic costs of land degradation centered on the both on-site and off-site effect (Telles et al., 2013). While the *direct method* determines the physical effects of variations in the environment on economic activities and measures the monetary value of the damaged ecological function; the *indirect method* assigns a monetary value to the physical damage caused by environmental degradation. However, the latter is not based on the behaviour of economic agents but assumes that environmental quality is a production factor and affects the prices of the products. There is clear relationship between land degradation and production, which are linked directly to income and costs. For example soil erosion affects the economy in two ways: (i) erosion of topsoil; and (ii) sedimentation of waterways (Table 4.4). Economic evaluation also includes the costs of action (the costs of mitigating land degradation) versus the costs of inaction (the costs induced by continued degradation). From an economic perspective, the current profits of adopting land-degrading practices are compared with the future benefits that derive from the adoption of land conservation practices. In most of the cases, however, the ecosystem services that result in lowering in the production levels are generally considered under economic evaluation, whereas those that do not become measurable in terms of lost production are generally neglected. Further, most studies apply discount rates ranging from 1 to 20 percent and time horizons from 5 to 100 years (Clark, 1996). The net present values (NPVs) and the internal rate of return (IRR) are common indicators used to compare alternative scenarios of adoption or no adoption of conservation measures. Cost–Benefit Analysis **(**CBA) is specified to assess the effectiveness of the adoption of conservation measures (Lutz et al., 1994), the type of crops and the choice of discount rate (Shiferaw and Holden, 2001) and the intensity of a conservation measure (Shively, 1999).

Table 4.4 Model approaches for valuation of the onsite and off-site effects of soil erosion.

SNo.	Onsite effect	Off site effect
1	Loss of nutrients	Sedimentation
2	Decrease in productivity	Flooding
3	Decrease in land value	Water treatment
4	Loss of biological system	Electric power generation
5		Repairing of public property
6		Global warming
7		Disaster
8		Increase in food price

Source: Modified from Telles et al. (2013)

Model based analysis of land degradation aims to maximize the net present value of the agricultural output in order to find the optimal rate of land degradation. These models are flexible and allow the integration of economic and biophysical conditions and feedbacks into the local economy and incorporate the impacts of various market imperfections (Shiferaw and Holden 2001; Holden et al., 2004), impacts of policies and subsidies (Börner, 2006) and combined impacts of land degradation, population growth, and market imperfections (Holden and Shiferaw, 2004). Literature on cost and benefit analysis of land degradation and land improvement mainly employ the approaches and activities that included crop yield with varying levels of fertilizer use, with and without conservation measures, crop sale and consumption, seasonal family labour, labour hiring, leisure, and livestock production and the activities to cover future negative impacts of soil erosion or forest degradation. Some of these methods are:

(i) Replacement cost approaches.

(ii) Nonmarket valuation techniques, such as hedonic pricing, contingent valuation, and choice experiments.

(iii) Productivity change approaches.

(iv) Avertive behaviour and damage costs approaches.

(v) Benefit transfer.

3.1 Replacement cost approach

In this approach, the costs of restoring land's capability to provide ecosystem services after land degradation is calculated in general (Drechsel and Gyiele, 1999). This approach was developed and subsequently utilized in estimating the nutrients budgets of all Sub-Saharan African countries (Stocking, 1986; Stoorvogel and Smaling, 1990). On-site replacement costs of nutrient mining were calculated on the basis of the nutrient balance model adjusted for nutrient availability by Drechsel and Gyiele (1999) which showed that nutrient depletion in Rwanda, Tanzania, Mozambique, and Niger accounts for 12% or more of the agricultural share in GDP, indicating nutrient mining as a significant factor for economic growth. The annual share of the average Sub Saharan African person engaged in agriculture on the nutrient deficit is about US$32. Pimentel et al. (1995) considered soil depth, biota, organic matter, and water resources in addition to wind and water erosion in their analysis and included costs related to the energy requirements to replace the lost water and the application of fertilizers. After scaling up the cost estimates for the United States Pimentel et al. (1995) estimated worldwide costs of soil erosion at $400 billion per year. Most studies used to cost the impacts of soil erosion particularly nutrient depletion, i.e. by calculating the costs associated with the application of chemical fertilizer to replace the already lost nutrients. This method however, is often criticized because of focusing mainly on soil erosion processes that excludes the damage caused by other aspects of soil characteristics, like organic matter content and physical structure of soils. Further, addition of chemical fertilizer is usually insufficient to fully restore soil functionalities, and thus soil nutrient reserves in particular are ignored. Thus inefficiencies of fertilizer due to leaching and vapourization should also need to be taken into account (Jayasuriya, 2003). There may be chances of negative off-site effects on actual replacement with artificial fertilizer. Therefore, all costs associated with replenishing nutrients, including transportation, labour, and energy costs need to be considered in calculating the replacement costs. A slight decrease in soil nutrients may have little effect on production, especially when other factors like rainfall appeared dominant production constraints (Lutz et al., 1994; Bojö, 1996). In absence of any established connection between soil nutrients and agricultural production the replacement cost approach is not helpful for the selection of the most appropriate conservation action. This method is also used for overestimating the values of soil nutrients.

3.2 Nonmarket approaches

3.2.1 Hedonic Pricing

Hedonic pricing uses realized market prices to conclude how much people value changes in the attributes of the produce sold. It can be used to estimate economic benefits or costs associated with: (i) environmental quality, including air pollution, water pollution, or noise; and (ii) environmental amenities, such as aesthetic views or proximity to recreational sites (Monson, 2009). The hedonic pricing method is most often used to value environmental amenities that affects the price of residential properties. In this method well-functioning land markets and the price of land are assumed to be equal to the sum of the appropriately discounted stream of net benefits derived from its use (Freeman, 2003). Further, Hedonic pricing assumes that differences in property values are attributable to controlling for other gadgets like different levels of land degradation (Jayasuriya, 2003). However, lack of a well-functioning land market in developing countries makes it more difficult to estimate the cost in these countries (King and Sinden, 1988). As market prices implicitly reflect the buyers' knowledge of costs and benefits related to the land's productive capacity, this method appears to underestimate the costs of degradation, especially in case of off-site costs (Bishop, 1995).

3.2.2 Contingent Valuation Method

It is a nonmarket-valuation method in determining monetary value of non-marketed produce, i.e. widely used in cost–benefit analysis and environmental impact assessment (Venkatchalam, 2004). In this method, individual's willingness to pay (accept) is measured in a hypothetical market scenario as a stated amount of money (price, entrance fees, taxes, meals etc.) that a person would be willing to pay (accept) for an increase (decrease) in the provision of the goods and services (Freeman, 2003; Bhogale, 2011). In India, the contingent valuation method (CVM) does not always provide a correct value of recreational use benefits of an environmental resource because of large size of the parallel economy involving different categories of income group families having capacity to move as tourists (Chaudhary and Tewari, 2006). In general, 'participant observation method' and 'unstructured interview schedule' are necessary tools used in such cases. In addition, a 'structured interview schedule' is also used for primary data collection particularly in the travel cost method (TCM) and in the CVM under normal circumstances. Tilahun et al. (2011) applied a discrete choice contingent valuation to assess the factors influencing rural households' willingness to pay (WTP) and willingness to contribute labour (WTCL) for *Boswellia papyrifera* forest conservation in Ethiopia and observed household income as the most important factor affecting WTP, whereas number of household labour is the most important factor affecting WTCL. Mean lower bound annual WTP of US$ 4.68 and WTCL of 7.03 days per household have been estimated, where people desire to contribute for conservation of the resource. Though monetary values obtained are contingent on the hypothetical market scenario and the described resource, this method however, involves severe criticism, which revolves mainly around the validity and the reliability of the results, and associated with a number of possible biases, which lead to either under- or overestimation of willingness to pay (Venkatchalam, 2004). Contingent valuation, as well as choice experiments, is a suitable method to value off-site effects related to land degradation.

3.2.3 Choice Experiments

Choice experiments are also a survey-based method, in which individuals are asked to choose the most preferred option or alternative from a set of proposed options (Burgess et al., 2012). These options differ in their characteristics or attributes depending upon the environmental conditions and livelihood alternatives. Different attributes are selected in a way that they meaningfully describe differences between various options in order to explain the preferences. Each attribute consists of a set of levels to represent variations in the respective attribute among the options. Attributes and levels are combined into options according to statistical design principles described by Louviere et al. (2000). Choice experiments can detect the relative importance of the different attributes and can identify willingness to pay for single attribute changes as well as for aggregate benefits of different policy scenarios. For example Goibov et al. (2012) estimated the non-market values of agri-environmental attributes and their changes in the Konibodom region of Tajikistan using a detailed household level survey of 117 representative farmers. Focus group discussions and a combination of personal interview and ‘pick and drop’ approaches were selected and Conditional Logit and Random Parameter Logit (RPL) Models applied, where significant improvements were achieved through the inclusion of interaction terms into the RPL model. The results of both the RPL models reveal that preference heterogeneity exists amongst farmers, indicating that a decision for land allocation under different crops is jointly associated with other socio-economic and environmental factors, influencing one another (Goibov et al., 2012).

3.3 Productivity change approach

This is the most commonly used method in evaluating land degradation. This method is based on the idea that a value can be earmarked on the services the land provides, which is in the form of agricultural output or biomass produce from the land (CBD, 2013; Zhou et al., 2013). The assumption is that all impacts of land degradation are clearly evident through a loss in productivity. Thus land is valued in terms of lost production and in general called as ‘*Production equivalent of degradation*’. This measures the physical effects of soil erosion, salinity and soil compaction on crop yields and biomass production (Telles et al., 2013). Productivity depends not only on land quality but also on a variety of factors, like management practices, choice of crops/species, climatic factors and pest and diseases infestation. Therefore, productivity is the result of the dynamic interaction of numerous factors, and thus it is very difficult to separate the effect on yield related to land degradation only (Lal, 1987). It is important to select an appropriate benchmark against which the changes are compared. The impacts of soil erosion on productivity are estimated econometrically or through biophysical models that simulate the interaction between biophysical factors on productivity. Some of the models are 'The Erosion Productivity Impact Calculator (EPIC) that generates erosion rates and the resulting loss of crop yields, at a given farm management practices (Williams et al., 1983) and the 'Tropical Soil Productivity Calculator' for special conditions in the tropics (Aune and Lal, 1995). Despite of relatively straightforwardness in the implementation the productivity change approach is also has some shortcomings. For example, crop prices may be poor indicators of value when markets are poorly developed or distorted by the political system (Crosson, 1998). It is also difficult to account for farmers' land to degrading soil characteristics as farmers are likely to adopt a mix of inputs to offset damages caused by erosion.

4. ECONOMICS OF LAND DEGRADATION

Land degradations are influenced by the diversity, distribution and specific vulnerability of soils however; they also depend on geology, relief and climate. The different ways to categorize impacts include the on-site and off-site impacts, cost of suffered damage and damage avoidance cost, direct and indirect use values and the non-use values. The major cost categories are: on-site costs, off-site costs and non-use costs. Assessment of economic impacts of soil degradation have revealed that off-site costs exceed on-site costs by 12:1, whereas the cost of suffered damage observed higher than damage avoidance cost (Gupta, 2013). Decrease in land productivity as a result of desertification is the direct economic costs reducing the income of the land users. These 'onsite' costs are experienced either by the land user who degrades the land, or by another user who uses this land subsequently. Just after the UN Plan of Action to Combat Desertification agreed at the UN Conference on Desertification (UNCOD) in 1977, United Nations Environmental Programme (UNEP) estimated global direct cost of desertification at $26 billion per annum in 1980. Direct costs estimate of land degradation in India as a proportion of national income indicate 2% of Gross Domestic Product (GDP) of the country (Reddy, 2003) and 0.4% of the GDP in the USA (Pimentel et al., 1995). Direct costs of desertification of agriculture land in China in 1999 estimated at RMB 40 billion (Liu, 2006), which was only 2.7% of AGDP, but more than twice the estimate of Zhang et al. (1996) at RMB 17 billion for 1995 (i.e., 1.4% of agriculture GDP in that year). In 14 Latin American countries namely Argentina, Belize, Bolivia, Chile, Colombia, Costa Rica, Ecuador, El Salvador, Guatemala, Honduras, Nicaragua, Panama, Paraguay and Peru also, the direct costs of land degradation ranged between 8% and 14% of agriculture GDP, where it varied markedly between the countries (Morales et al., 2011). According to IFPRI (2000) there are about 40-75% reduction in the world's agricultural land's productivity due to land degradation. In drylands of the developing countries the costs of land degradation estimated at 4-8% of their national gross domestic product (GDP) each year.

According to Food and Agriculture Organization of United Nations (FAO, 2011), out of 24 ecosystem services studied in dry areas, fifteen are showing a declining trend. It was observed that some 50% of the highlands of Ethiopia has already been eroded causing an annual loss of land productivity by 2.2% (Tamene et al., 2006). Natural regeneration of vegetation cover and soils in arid areas takes 5-10 times longer than in favourable areas with greater and more regular rainfall. Between 1983 and 2003, approximately 24% global lands have been degraded, but it was highest in forests and least in croplands. However, a global average of 16% land has been improved, which ranged between 20% cropland and 43% rangeland. The application of sustainable land management (SLM) has shown to increase yield by 30-170%, but the land lost annually due to degradation could produce 20 million tons of grain. Thus desertification and degradation represents an income loss of US$42 billion per year globally (Table 4.5). The effects of erosion on soil properties can be examined from the perspective of certain indicators of soil characteristics such as soil nutrient content, soil moisture capacity, soil organic matter etc. The effects of erosion on production can be valued in terms of the reductions in crop/biomass yields, which can be directly captured through the loss in market value. The most common approach for valuing land degradation in terms of the loss of soil and soil nutrients is the replacement cost method. This is based on the cost of replacing soil nutrients with artificial fertilizers or the cost of physically returning eroded sediment to the land (i.e., labour costs or the cost of buying fertilizers). Because crop yields are not dependent on soil productivity only but are also determined by a number of factors like rainfall, fertilizer application rates, climate, pests, and irrigation practices, the replacement cost approach is most preferred one.

Table 4.5 Extent of degrading and improving lands globally under different land use type and corresponding economic loss.

Land use type	Degrading land	Recovering land	Loss per year
Rainfed	-	-	US$ 8.2 billion
Cropland	20%	18%	US$ 10.8 billon
Rangeland	20-25%	43%	US$ 23.3 billion
Forests	42%	23%	
Global	24%	16%	US$42.3 billion

On-site cost of soil erosion are estimated by analyzing soil nutrient expressed per ton of soil basis focusing mainly on macro-nutrients like on nitrogen (N), phosphorus (P) and potassium (K) in terms of the equivalent levels of urea (46 0 0), single superphosphate (P_2O_5, 0 16 0) and murate of potash (K_2O, 0 0 60). The nutrients lost are multiplied with the price of fertilizer per kilogram of the nutrient to get the replacement costs. For estimating the monetary cost of sedimentation, one use the maintenance cost approach. There are mainly three methods, i.e. sediment sluicing, flushing and dredging to reduce the amount of sediments flowing into the reservoir, thereby prolonging the life of the reservoir. The off-site costs are related to the effects of land degradation/desertification on the surrounding environment, particularly the downstream impacts of sedimentation and related link with change in irrigation, hydropower generation and carbon benefits and thus the global effects on land services. However, a strict categorization of sedimentation as a cost factor may not be adequate, because sedimentation may be beneficial to downstream users by providing farmers with fertile, nutrient-rich soil (Clark, 1996) or by serving as construction input (Enters, 1998). Some of the studies related to valuation of soil and forest degradation are summarized in Box 4.1.

Loss of at least US$10 billion annually because of land degradation in South Asian countries like India, Pakistan, Bangladesh, Iran, Afghanistan, Nepal, Sri Lanka and Bhutan is a shocking conclusion of the study sponsored by FAO, UNDP and UNEP (Nkonya et al., 2011). This is equivalent to 2% of the region's GDP, or 7% of the value of its agricultural yield (Kar, 2012). In this soil erosion caused by water is the most widespread affecting 83 million ha land, i.e. (25% of all agricultural land in the region). It is severe in many areas of the sloping land causing permanent loss of the productive capacity of the lands. Soil loss due to wind erosion affects 59 million ha agricultural land in the dry areas. While the decline in soil fertility due to lowering of soil organic matter and loss of soil nutrients was primarily because of increased and incorrect use of fertilizers, the lowering in land productivity through the rise in groundwater close to or above the soil surface (i.e., water logging) is caused by incorrect irrigation management. Soil degradation caused by increase of salt in the soil (i.e., salinisation) is due to incorrect irrigation management or intrusion of sea water into coastal soils arising from over-abstraction of groundwater. Both of these reduce crop yield and in some cases result in complete abandonment of agriculture land.

Lowering of the groundwater table caused by over-extraction of groundwater further reduce crop production. Altogether 140 million ha of total agricultural land has been suffered from one form of degradation or more in the region. Of this, 31 million ha is strongly and 63 million ha is moderately degraded. The worst affected country is Iran (94% of agricultural land degraded), followed by Bangladesh (75%), Pakistan (61%), Sri Lanka (44%), Afghanistan (33%), Nepal (26%), India (25%) and Bhutan (10%). Estimated economic loss calculated based on the loss of agricultural productivity or output; the cost of replacing soil nutrients (through additional fertilizer); or the costs of land reclamation and restoration showed total on-site annual losses of US$ 9.8 to 11 billion annually. In this contribution of water erosion is US$ 5.4 billion, wind erosion US$1.8 billion, fertility decline US$ 0.6-1.2 billion, water logging US$ 0.5 billion and salinisation US$ 1.5 billion. The off-site costs (such as losses caused by river silting, floods, landslides and so on) have not been counted (Nkonya et al., 2011).

Box 4.1. Examples of economic valuation techniques applied to soil and forest degradations

- Anderson (1987) applied productivity approach in evaluating the effects of shelterbelts on crop protection and farm forestry and observed an increase in rate of return from 5% (wood benefits only) to 13-17%, and from 7% to 14-22%, respectively in northern Nigeria.
- Brandon and Hommann (1996) valuated the cost of inaction: valuing the economy wide costs of environmental degradation in India using replacement cost and market value approaches, where cost of deforestation during 1981-1990 was US$ 183.1 million and US$ 244.3 million annually, respectively.
- Bann (1998) valuated the economic values of forest watershed protection/water supply functions by replacement cost of nutrients and flood damage at $46 per ha.

- Chichilnisky and Heal (1998) used the provision cost approach to measure the value of clean drinking water provided by the Catskill watershed in New York City by estimating the cost to construct and maintain a water filtration plant.
- Scrimgeour and Shepherd (1998) used contingent valuation survey of the wider community and of farmers to estimate both use and non-use values associated with loss of soil structure (compaction) in the Manawatu region of New Zealand.
- Feather et al. (1999) used the travel cost method to value the water-based recreational benefit of soil conservation programmes in the United States that were aimed to reduce soil erosion and improve water quality.
- Hansen et al. (2002) used the defensive expenditures method to estimate the cost of soil erosion in a watershed in the United States by estimating dredging costs.
- Drechsel et al. (2004) used the replacement cost approach to value soil fertility by looking at the cost of fertilizers needed to replace the soil nutrients to maintain a certain level of productivity.
- Colombo et al. (2005) used choice modeling to identify preferences for reducing the off farm effects of soil erosion in the Alto Genil watershed in Southern Spain.
- Sarraf et al. (2005) assessed the annual cost of environmental degradation in Iran at US$ 10000 million using productivity change and willingness to pay methods, where land and forests accounted for at US$ 2840 million annually.
- Sparling et al. (2006) used the productivity change approach to value the food provisioning and regulating services generated through soil organic matter recovery in three contrasting New Zealand soil orders.
- Verma et al. (2006) evaluated land degradation using replacement cost approach where the average value of degradation was estimated to be Rs.3607.7 per hectare for the year 1999-00 and Rs.3612.8 per hectare for the year 2000-01 from the area devoted to agriculture in Himachal Pradesh, whereas it was Rs. 1502 per hectare to Rs.1557 per hectare during 1997-98 and 2001-02, respectively in Madhya Pradesh.
- Anon. (2008) used both replacement cost approach and productivity change approach in valuing the economic impacts of topsoil removal by replacing the nutrients, leveling the land and application of tank silt, which was Rs. 2,475 per acre, whereas the total income loss due to yield reduction was Rs. 3,250 per acre per annum with a difference of about Rs. 780 between these two approaches.
- Damnyag (2012) valuated the cost of deforestation employing opportunity and replacement cost techniques, where US$ 133,650,000 of gross revenue from the four ecosystems' services is lost annually due to deforestation.
- Samarasinghe and Greenhalgh (2013) used hedonic pricing and examined the relationship between soil characteristics and rural farmland values in the Manawatu catchment of New Zealand.
- Qadir et al. (2014) undertaken comparative evaluation of the economics of 'no action' and 'action' with regard to salt-affected lands and estimated that global annual cost of salt-induced land degradation in irrigated areas as US$ 27.3 billion under the lost crop production.

Estimates of the indirect costs of land degradation are less common than those of direct costs. Major constraints in estimating the indirect costs of land degradation are (i) lack of reliable biophysical information on land degradation and its many impacts; (ii) variations in offsite cost estimation like a small number of impacts, e.g. airline delay (Liu, 2006) or human health (Cheng et al., 2012), inappropriate cost estimates for the same area, (iii) many of the costs do not have market prices etc. Estimation of the impact of soil erosion on the siltation of hydroelectric reservoirs by avoiding the cost of dredging the reservoirs is one way, while cost of replacing hydro-electricity by electricity generated from fossil fuels or other sources is another way (Clark, 1996; Hansen and Hellerstrein, 2007). During wind erosion soil particles are propelled by strong winds and are abrasive and the air pollutants cause health problems (Montanarella, 2007). Further, increased oxidation of biomass carbon due to soil erosion, loss of biodiversity and biological activity, carbon dioxide is released into the atmosphere, and is contributing to global warming. This action can also be seen as a feedback mechanism because global warming intensifies rainfall, which in turn increases erosion further (Pimental, 2006). Increased land degradation also increases the demands of natural resources like lime for neutralizing acidity or water for flushing irrigation salinity in order to repair the degrading lands that leads to off-site pollution and further losses of productivity and amenity values of the areas (Gretton and Salma, 1997). Some studies indicate deposition of about 40 million tons of nitrogen and 10 million tons of phosphorus into the water bodies annually leading to high water pollution causing eutrophication in lakes, reservoirs and water bodies leading to severe impacts on fish and human populations (Corcoran et al., 2010; Rockström et al., 2009).

4.1 Economics of land degradation in India

The World Bank has observed that India, which enjoys higher economic growth as compared to many countries, loses at least Rs. 3.75 lakh crore each year due to environmental degradation and pollution (The Hindu, 2013). Loss of farm produce due to land degradation, productive lives cut short because of bad water supply, poor sanitation and hygiene, and pollution are the some of the reasons for the economic loss, which estimated at 5.7 per cent of the India's GDP (in 2009-10). The first economic estimate of land degradation was based on individual estimates for 442 districts covering 14 regions of the country in 1988-89 (NRSA, 1995). However, Reddy (2003) compared this estimate with estimates of the Agro-Climatic Regional Planning Unit (ARPU, 1989) for 241 districts in eight agro-climatic zones in 1990 as well as the estimate of Sehgal and Abrol (1994), who applied the Global Assessment of Soil Degradation (GLASOD) approach of the UNEP (Table 4.6). However, there is significant variation in estimated costs based on these approaches and was because of differences in the degraded area estimated by different sources. While the NRSA and ARPU estimates of the total area affected by soil erosion, i.e. 32 and 58 million ha respectively are comparable, the 166 million ha estimate of Sehgal and Abrol (1994) represents half the entire area of India. Further, both NRSA (1995) and Sehgal and Abrol (1994) estimate included the areas affected by soil erosion, salinization and alkalinization, and waterlogging, but the ARPU (1989) estimate was restricted to soil erosion only (Table 4.6). According to the Tata Energy Research Institute (TERI), New Delhi, the economic losses caused by lowering crop yields, and reduction of reservoir capacity has been estimated in the range of 89-232 billion rupees, which results in a loss of 11-26% of agricultural output. Total annual costs of land degradation because of land use and land cover change in 2009 as compared to 2001 in India have been estimated at 5.35 billion US$, where share of Rajasthan is 7.6% (Mythili and Goedecka, 2016).

Table 4.6 Soil degradation statistics (area in million ha) and annual direct cost (Rs in billion) of land degradation in India.

Variables	MoA		NRSA	ARPU	Sehgal and Abrol	TERI
	1980	1985	1988-89	1990	1994	1997
Soil erosion (water & wind)	150.0	141.2	31.5	58.0	162.4	167.0
Salinization, alkalinization	8.0	9.4	3.2	-	10.1	11.0
Waterlogging	6.0	8.5			11.6	13.0
Shifting cultivation	4.4	4.9			-	9.0
Decline in soil fertility	-	-	-	-	3.7	
Total	168.4	175.1	34.7	58.0	187.8	187.8
Cost of soil erosion due to lost nutrients			18.0	33.3	98.3	
Cost of soil erosion due to loss of production			67.6	124.0	361.0	
Cost of salinization, alkalinization and waterlogging in loss of production			7.6	-	87.6	
Total direct cost			75.2	157.3	448.6	

Source: Reddy (2003); (NRSA and APRU); Sehgal and Abrol (1994).

4.1.1 Nutrient Removal and Loss

Loss of soil nutrients from the soils depends upon soil types, vegetation cover/crop types and the related climatic and environmental factors. Losses of nitrogen, phosphorus and potassium estimated at 10 kg/ha (kilogram per hectare), 3 kg/ha, and 0.06 kg/ha, respectively from a medium black soils under cultivated fallow through 3.4 tons of soil loss per hectare (Verma et al., 1983). In another study the loss of nitrogen, phosphorus and potassium through 1 ton/ha loss of soil, was 6 kg/ha, 1.31 kg/ha, and 0.54 kg/ha, respectively depending on crop species and management practice. Intensive farming has led to decline in soil organic content from 0.5% in 1960 to 0.2% in 1990. Loss in soil organic carbon means wasteful application of fertilizers, loss in soil biological activity, and poor moisture retention. The soil yield loss function can be derived from empirical studies relating the productivity level of soils for a given land use/crop to the varying rates of erosion (Sparovek and Schnug, 2001). Removal of major nutrients like nitrogen, phosphorus and potassium by the growing crops in India is about 20.2 million tons, but the corresponding addition through chemical fertilizers and organic manures is nearly 5.66 million tons (Tandon, 1992). While considering the nutrients losses due to soil erosion, the loss of nutrients from the top soil comes to about 43 million tons, which is about 0.24% of the nutrient reserves of the soils. In another study, Brandon et al. (1995) has estimated annual loss in production of 11 major crops in India due to depletion of nutrient because of unsuitable agricultural practices at 0.5 to 1.3 million tons. Vashishth et al. (2003) has translated land degradation in terms of economic losses according to which the country looses Rs. 285.51 billion annually at current prices and Rs.89.38 billion at 1979-82 prices. This is worked out to around 12% of the total value of agricultural output in the country. The economic losses vary between 10 to 27% of the value of agricultural output due to nature and severity of degradation of land and the cropping pattern across the states. The magnitudes of economic losses are quite severe in the States of Andhra Pradesh, Gujarat, Karnataka, Maharashtra, Madhya Pradesh, Rajasthan, Tamil Nadu and West Bengal. These states together account for nearly 73% of the total losses in the country due to land degradation. However, decreased production due to land degradation is generally masked by increased use of fertilizer. For example, fertilizer consumption in India has increased from 16.19 million tons in 1997-98 to 27.74 million tons in 2011-12 indicating 1.72-fold increase in these 15 years. During 1997-98 to 2012-13, the increase in total food grain production was from 192.26 million tons to 250.14 million tons showing 1.31-fold increase. Negative nutrient balances developed for the Indian soils represent severe on-going depletion in nutrient capital, degradation of the environment, and vulnerability of the crop production system in terms of its ability to sustain high yields (Tandon, 2007). Data presented in Table 4.7 indicates a net negative NPK balance with annual depletion of 9.7 million tons of nutrients, i.e. 19% N, 12% P, and 69% K.

Table 4.7 Net balance and gross balance of soil nutrient ($x10^3$ tons) in India and Rajasthan. (Source: Tandon, 2007).

Nutrient	Net balance sheet			Gross balance in India			Gross balance in Rajasthan		
	Addition	Removal	Balance	Addition	Removal	Balance	Addition	Removal	Balance
N	5,461	7,690	-2,229	10,923	9,613	1,310	547	835	-288
P_2O_5	1,466	2,961	-1,496	4,188	3,702	486	137	235	-88
K_2O	1,018	6,994	-5,976	1,454	11,657	-10,202	7	1,068	-1,061
Total	7,945	17,645	-9,701	16,565	24,971	-8,406	1375	1631	-256

In a recent efforts made to estimate the loss of available nutrients in the topsoil of each of the 24 soil types in India, the land area under each type, and the annual erosion rate in these soils (Sharda et al., 2013) indicates that India has lost nearly 74 million tons of major nutrients annually due to erosion. However, 61% of the soil is moved and the effective loss is 39%. Of the remaining, the country loses 0.8 million tons of nitrogen, 1.8 million tons of phosphorus, and 26.3 million tons of potassium every year. The data available with status of Indian agriculture (SIA, 2012-13) indicates increase in total fertilizer use in India by 6.7% and in Rajasthan by 43.9% during 2009-10 to 2011-12 (Table 4.8) and is indicative of increased production cost.

Table 4.8 Fertilizer use (kg/ha) in Rajasthan and India during 2009-10 to 2011-12.

	India				Rajasthan			
Nutrient	2009-10	2010-2011	2011-12	% increase	2009-10	2010-2011	2011-12	% increase
N	79.57	46.15	90.01	13.1	32.51	40.03	42.01	29.2
P	37.15	41.88	41.18	10.9	14.25	19.01	19.14	34.3
K	18.55	18.28	13.14	-29.2	1.56	1.61	1.20	-25.5
Total	135.27	146.32	144.33	6.7	43.33	60.64	62.35	43.9

4.1.2 Sedimentation and Sand Deposits

Most applied approach in assessing the cost of sedimentation is replacing a service by the least costly alternative (Adhikari and Nadella, 2011; Nkonya et al., 2011). Reservoirs are linked to a number of environmental services, including the generation of energy through reservoir hydropower production, irrigation of crops and recreational activities. Erosion and sedimentation of watersheds can lead to decreased hydropower output, structural damage to reservoirs and other water infrastructure, and flooding. Under assessment costs of sediment sluicing, sediment flushing and dredging are applied. Sediment sluicing is the name given to a type of reservoir operation that pulls down the sediment level at the start of the flood season and then allows as much sediment-heavy floodwater as possible to pass through the dam before it has a chance to settle. This method can drastically slow down the rate of reservoir sedimentation but has been used successfully only in a few projects (Jauhari, 1999). Sediment flushing is a method of washing out the accumulated deposits from a reservoir. Flushing out a long reservoir requires several months and in general has little impact on a reservoir high silt load. An obvious way of restoring reservoir capacity is dredging where removal of sediment accumulated over time are taken back to the bottom to its natural condition- restoration and reclamation process. However, the last one is extremely expensive and is normally viable only for small, urban water supply reservoirs where water consumers can afford the cost, and landfill sites are available to take the dredged sediment. The study (Mahmood, 1987) cited in Bruijzneel and Bremmer (1989) reported the cost of dredging at 2–3 dollars per cubic meter in 1987; around 20 times more than the cost of providing additional storage in a new dam. Restoring the original capacity of a major reservoir would require the removal (and transport and dumping) of billions of cubic meters of sediment.

Estimations of the costs due to the sedimentation of reservoirs conducted in the Philippines (Cruz et al., 1988) and in Java, Indonesia (Magrath and Arens, 1989) show loss in hydropower generation capacity (Clark, 1994). Analysis of Abelson (1979) also highlights the impacts of sedimentation on irrigation water by estimating the decline in the output of dairy farms that used water for irrigation and the value of water lost due to lower storage capacity calculated from the social value of milk production based on world market prices. Vieth et al. (2001) estimated the off-site costs of soil erosion in the Upper Mahaweli watershed in Sri Lanka in the form of reduction in irrigated area, hydropower production and the increased water purification costs due to reduced capacity of the reservoir to store water for irrigation. Hansen and Hellerstein (2007) valued the impacts of soil conservation on reservoir services in terms of reduced dredging costs for a one-ton reduction in erosion across the 2,111 U.S. watersheds. Siltation or sedimentation in a reservoir is a very serious problem that reduces its storage capacity and life. The life of a reservoir depends on the rate of silt inflow and its dead storage capacity. Globally the cost of the siltation of water reservoirs is about $18.5 billion (Basson, 2010).

Many of the reservoirs in India are losing capacity at a rate of 1% – 2% every year (SOER, 2001). In order to estimate the cost of sedimentation, two approaches are in use. The first approach is to estimate the value of lost storage capacity of the reservoir and the second one is to use the maintenance cost method, i.e. how much it cost to remove sediment from reservoir or the waterways. The cost of removing sediments from the reservoirs is an indicative value of the costs imposed by off-site effects of erosion. Because of different hydrology, the cost of treating sediments varies considerably between reservoirs and rivers. This results in variation in estimated cost. Estimation of White et al. (2010) indicates a loss of about 0.5 percent of annual water storage due to sedimentation from the soil erosion. In arid zone of north western India, high sediment yields are generated due to erratic and torrential rainfall, sandy and eroded rocky drainage basins, and biotic activity. Sediment yield increases with increasing rainfall and drainage basin slope and its magnitude depends upon the nature of surface material. However, sediment yield can be reduced by 65-94% by promoting vegetation and construction of check dams in the drainage basin (Sharma, 1996).

Table 4.9 Sediment yield (m^3 ha^{-1} $year^{-1}$) in arid zone of India and the influences of vegetation and rainwater harvesting devices on sediment yield. (Source: Sharma, 1996).

Physiographic region	Average sediment yield	Effect of vegetation on sediment yield			Effect of water harvesting on sediment yield	
		Vegetation cover (%)	Without vegetation	With vegetation	No check dams	Check dams
Sandy plain	3.4	4	3.6	0.6	-	-
Dune complex	4.8	3	2.3	0.8	-	-
Younger alluvial plain	2.7	6	8.9	0.5	-	-
Older alluvial plain	18.4	3	5.2	1.2	16.6	4.8
Rocky/gravelly piedmont	14.3				4.2	1.2

Effect of sand deposits even in humid region of Assam significantly affects crop yields, like productivity losses in paddy ranges between 92 and 246 kg of paddy per hectare with an average presence of 54% sand in the soil (Das, 2012). Considering that one kg of paddy costs Rs 7.5 and approx. 11,331 hectares of land in the district Dhemaji have been affected by sand, the total annual loss lies between US$ 150 - 400,000 in the district. The annual damage costs from sand deposition in the study area has been worked out to US$ 13 to 35 per hectare (Das, 2012). At current price India is losing Rs 2,850 billion because of land degradation that comes to about 12% loss as per the total value of the productivity of these lands (Rai, 2010). Predicted annual loss is Rs 1105–1137 million by accounting for loss in power generation and reduction in irrigated area alone in the command area under avoiding proper soil and water conservation measures, including forest plantation in the catchment area of the Sardar Sarovar reservoir (Pande et al., 2014). Estimated total annual sediment load is 4.69×10^{-3} million ha meter in the reservoir at a sediment loss of 5.34 ha-m/km^2/year, which results in total annual storage loss as 0.49%. Similarly, the annual dead storage loss works out as 0.13%. At a fixed tariff of Rs 4.18/unit, the estimated annual hydropower losses due to siltation work is Rs 17.7 million and Rs 45.4

million in a deficit monsoon and Rs 20.8 million and Rs 53.4 million in a surplus monsoon considering loss in total storage and dead storage, respectively (Pande et al., 2014). Likewise the loss of irrigation potential varies between 44,608 and 46,070 ha. The estimate of Rs 407–434 million is based on loss of total storage and Rs 1045–1114 million is based on loss of dead storage. The off-site effects of aeolia activities in western Rajasthan also leads to siltation affecting IGNP canal, water bodies and other infrastructures enhancing costs of their maintenance. Study has also been carried out on the desiltation of Nadi (small pond) where desilting material was used in strengthening the bank of Nadi and includes the improvement of nadi catchment/ channel affected by sedimentation under water and wind erosion (Table 4.10). This indicates a huge investment in desiltation work to maintain these traditional infrastructures in the rural area of Rajasthan. Some power companies operating a hydropower reservoir elect to conserve upstream forests that maintain a sediment retention service if the cost of conserving the forests is less than the costs of reduced hydropower potential, sediment removal, and dam replacement (NCP, 2011).

Table 4.10 Cost estimates under desiltation for revival of traditional water harvesting structures (TWHS) in Nagana and Godavas villages in Barmer district of Rajasthan.

Activity	Nagana		Godavas	
	Amount	Cost (Rs)	Amount	Cost (Rs)
Cost of desilting Nadi	10,00,000 cubic feet	5,66,000	25,00,000 cubic feet (i.e., 70750 m^3)	12,50,000
Making approaches and livestock drinking stands		34,000		10,00,000
Total		6,00,000		22,50,000

Source: Das and Sharma (2003). Rates of desiltation was Rs 17.67/ cum.

Economic valuation of forests in Halol Range, Panchmahal District, Gujarat based on change in soil fertility using the replacement cost technique has also been done (Kiran and Kaur, 2011). Here the economic value was assessed on the basis of the amount required for replacing nutrients which are deficient in the soil or the amount that is saved where nutrients are retained in the soil. Thus the amount of N, P and K, lost from the soil or retained in the soil was estimated, and then subjected to economic valuation based on the market cost of the equivalent fertilizers during the respective years. Though the 1997 analysis showed overall economic loss, but the restoration activities had not only overcome this loss, but brought in economic benefits of about Rs 388.13/ha in 2009.

4.1.3 Silt Load and Water Quality

Sedimentation causes a higher level of turbidity (Vieth et al., 2001), which increases the cost of water purification. The cost of extra chemicals that are needed to coagulate the particles in the water is the cost of this off-site impact (Moore and McCarl, 1987; Nkonya et al., 2008). Dearmont et al. (1998) calculated the chemical costs of municipal water treatment expressed as a function of raw surface water quality and observed an increase in water treatment cost of $ 95 per million gallon (per 3785 m^3) from a base value of $75 when regional raw water contamination is present. Further, there is increase in chemical costs by 0.25% with 1% increase in turbidity.

4.1.4 Siltation, Flooding and Aquifer Recharge

Soil and water conservation measures increase infiltration of water in the soil because of reduced runoff and thus higher water availability in the aquifer (Singh, 2011). Off-site damage is also related to conservation practices (Richards, 1997). Koteen et al. (2002) have examined six water quality parameters and their influence on water uses. The water quality parameters are turbidity, quantity, salinity, total suspended solids, temperature, and dissolved oxygen. Changes in these parameters have been evaluated to determine values for municipal, agricultural, recreational, industrial, hydropower, and nonmarket uses of water. Various techniques such as the travel cost method, the contingent valuation method, and the hedonic method have been used and data collected on changes in water quantity per acre-foot and its effect on recreationists' benefits. Results indicate that valuing water for a particular use can help in planning and decision making in restoring forests and degraded lands as well.

4.1.5 Soil Erosion and Recreational Damage

Soil erosion also has recreational impacts, as particles and pollutants reduce both the air and water quality (Munthali et al., 2011). In addition, siltation and weed growth interfere with boating and swimming activities, thus decreasing the site‘s recreational value. Clark (1985) has recorded recreational damages on freshwater fishing, marine fishing, boating, swimming, waterfowl hunting, and accidents. Using travel cost models, Feather et al. (1999) have also estimated the benefits of freshwater-based recreation, wildlife viewing, and hunting of the Conservation Reserve Program in the United States. Bejranonda et al. (1999) have examined property values at Ohio state park lakes to analyze the effect of sedimentation and found higher property values on lakes with less sedimentation.

However, nonmarket valuation approaches like contingent valuation method and choice experiments are also under use to value several off-site effects. For example Colombo et al. (2003) have used contingent valuation method and observed that a majority of the catchment‘s population is willing to pay to reduce off-site damages. Choice experiment has also been conducted (Colombo et al., 2005) in watersheds in southern Spain, where respondents are found to care about the negative effects of soil erosion on surface and groundwater quality, landscape desertification, and flora and fauna.

5. ECONOMICS OF DROUGHTS

Rainfed lands have little resilience and are worse affected by drought (Conway, 2008). Climate driven droughts have direct impacts on agricultural production, though such shocks also have many indirect effects, when transferred through space and time to society as a whole. Economic costs of natural hazards including drought depend on the severity of the hazard, the vulnerability of the people affected by it, and their exposure to it. It includes the losses in crop and livestock productivity, decreased tourism and decline in other ecosystem services provided by the prevailing environment. Deaths and long-term losses of livelihoods are also included in computing the economic losses from drought. The economic cost of drought is also determined by the onset, duration, location, and severity of the drought (Below et al., 2007). Average annual economic cost of meteorological disasters—including drought, extreme temperatures, and wildfires during 2000 to 2008 has been estimated at $9.39 billion globally. In United States the annual cost of drought is about $6–8 billion (Wilhite and Buchanan-Smith, 2005). Through a global assessment of 104-year period from 1900 to 2004, Below et al. (2007) has recorded a total of 392 drought events (four droughts per year) resulting in global total economic loss of about $79 billion. In this, Africa contributed about 36 percent of the total number of drought events. About 12 million died as a result of droughts during the period. However, the number of deaths from drought and other natural hazards has been declining due to adaptation. Global study by Vos et al. (2010) also indicates an average annual economic cost of meteorological disasters including drought, extreme temperatures, and wildfires between 2000 and 2008 as $9.39 billion. Report of Khera (2004) indicates a small decline in area sown accompanied by a large fall in total output of Bajra- the sturdiest cereals in terms of tolerating high level of moisture stress. For example a fall of just 4 % area under cultivation of Bajra result in a fall to the tune of 70%. Maize is the only crop that manage to survive in spite of a large decline (nearly 60 per cent) in the area. Investment on relief operations also accounts handsome money as the expenditure of State government of Rajasthan, India was Rs. 151.5 billion during 1981-82 to 1989-90, and Rs. 105.7 billion during 1991-92 to 1999-2000.

However quantification of the productivity losses, as well as off-site effects are challenging and requires over time, taking into account dynamics, aggregation over time, and nonlinearities in various factors. Further, many of the key processes are difficult to measure in terms of individual components and interactions between them over time and across space (Berry et al., 2003). A comprehensive framework for an assessment that would include consideration of environmental, social, institutional, and economic factors needs define (Requier-Desjardins et al., 2011). Such a framework would require a common definition of all relevant costs and would need to cover the total economic value of land resources in order to accommodate the full range of impacts of DLDD on terrestrial ecosystem services on and off site.

6. CONCLUSION AND FUTURE PERSEPECTIVES

Severe pressure from both human activities and climatic conditions is resulting in land degradation, which ultimately brings differences in ecosystem and increases the vulnerability of particularly marginal lands. A negative relationship between land degradation and production is also linked with income and costs. The factors aggravating land degradation further, may be temporary, includes drought, climate variability, soil erosion, salinity, water logging, population pressure, human activities and resources exploitation. On-site and off-site impacts, suffered damage and damage avoidance cost, direct and indirect use values and the non-use values etc., are the different ways to categorize the impacts of desertification or land degradation. The on-site impacts reduces soil organic carbon and nutrients, and land productivity and increases the production costs due to increasingly more inputs to address the negative physical impacts of land degradation. The off-site impacts of land degradation are deposition of eroded soil in water bodies, reservoirs, water channels that decreases in air and water quality and reduces water storage capacity of the reservoirs and ultimately decreases in power generation and irrigation capacities.

Though all ecological functions are related closely to the economic functions, many important ecosystem functions have no markets, hence no apparent economic value. In such a circumstance, the decreasing contribution of forest/ other ecosystem in the total economy of a country is major cause of neglect, which ultimately results in making use of forest land for other land uses. Indeed off-site costs of degradation are many folds higher as compared to the on-site costs. Further, the cost of suffered damage is higher than the damage avoidance cost.

Various direct and indirect methods are used to evaluate the economic and social costs of land degradation including forests for its utilization in developing cost-effective policies and strategies for addressing Desertification, land degradation and drought (DLDD). The direct economic costs are incurred through reductions in income obtained by land users because of reduced productivity. However, lack of reliable biophysical measurements of the extent and rate of change of desertification; use of different economic estimation methods; embryonic nature of the economic research in this direction; and most importantly the isolation from estimates of the benefits of actions that cause degradation are central to decision-making and its appraisal lead to variation in estimation even within a region or country. Additional complications are the market prices, which are not available for many of the impacts, and vary among the regions as well as country.

In general, different types of economic values associated with the range of ecosystem services affected by DLDD such as direct use (timber, fuel wood, fodder etc) or indirect use (soil carbon, nutrients etc.) option values are based on maintaining these resources for future use or existing values depending upon the utility value derive from knowledge about species, habitats, landscapes etc.

Among the factors responsible for land degradation, soil erosion is the dominant one with both onsite and off-site effects that increases the cost of production and maintenance of infrastructure facilities. This is ultimately related to socio-ecology of the region. Thus tackling desertification or land degradation is not just about adopting physical remedies, as social remedies are equally important. This means that economic impacts and social impacts need to be tackled in an integrated manner, rather than in isolation. Unfortunately the cultural and socio-religious way of conservation of natural resources are dwindling at faster rate under materialistic approach, industrialization and development (Gaur and Gaur, 2004).

Rate of desertification or land degradation can be reduced if the policies are evaluated before application to check for unintended consequences; societal institutions are audited to check for constraints that lead to poor people degrading land instead of managing it sustainably; and an integrated approach to be taken to national land-use planning and government policies.

Operative policies and strategies need to be developed for land, forest, water and other natural resources management in improving forest/land management and promote sustainable development of the region. These policies should be based on the best available knowledge and science most pertinent to the local, national and regional conditions and the circumstances. It means there is greater investment in scientific research on DLDD in order to better develop and formulate effectual policies.

Soil and water conservation practices are worth implementing not only in farmers' land but also in forestlands. This not only prevents nutrient loss and retains soil moisture but also enhance forest diversity and provide additional income by increasing farm yield (Mishra and Rai, 2014). Interventions adopting watershed approach generate employment, reduce people migration, improve the environmental quality, increase vegetation cover, reduce runoff, soil loss and land degradation and provide resilience towards climatic abrasions by ensuring regular and sustained multiple outputs (Pathak et al., 2013).

For this effective interactions and promoting synergies are essential at regional, national and local levels with effective sharing of financial resources in a more efficient and balanced way.

5

RESTORATION STRATEGIES IN DRY AREAS

Desertification and land degradation have serious global implications for biodiversity, eco-safety, poverty eradication, socio-economic stability and sustainable development. While land degradation is resulting in a loss of billions of dollar annually, the forest degradation is hampering the basic human right to life and livelihood of the local communities, whose life is closely linked with the resources and immediate environment. Prevention, protection and restoration or a combination of these are applied to develop and manage the degraded lands. Restoring degraded areas has tremendous economic benefits by producing wood and non wood products, protecting and maintaining water resources and soils, sequestering atmospheric carbon, increasing biological productivity and climate resilience etc. Restoration of degraded lands is very much essential for increasing crop yields, regulating greenhouse gas fluxes, conservation of biodiversity, and improving economic development and social stability. This chapter deals with different methods and approaches including historical approaches from community level to landscape level for restoring degraded dry areas. This also describes the strategies like rehabilitation, reconstructions, reclamation and replacement. Besides, it includes the economics of degraded land restoration, required policy interventions and participatory planning and management for enhanced values of restoration measures in benefits of regional people.

1. INTRODUCTION

By supporting over 2 billion people globally drylands are major providers of critical ecosystem goods and services. Out of this about 90% population live in developing countries. Drylands, however, are one of the most susceptible biomes to degradation of varying degrees. Land degradation in dry lands (i.e., desertification) is a global issue, with serious implications worldwide for biodiversity, eco-safety, poverty eradication, socio-economic stability and sustainable development (Baeza et al., 2011). In many underdeveloped countries overpopulation causes pressure to exploit drylands for farming and exploitation of other natural resources (Neely et al., 2009). The marginally productive regions are overgrazed, the land is exhausted and groundwater is over extracted. Because of fragility of the drylands, the impact on people, livestock and environment may be damaging leading to displacement of some 50 million people in the next decade as a result of desertification. Though desertification played a significant role in human history, contributing to the collapse of several large empires and the displacement of local populations, but the present pace of land degradation is estimated at 30 to 35 times the historical rate. The increased frequency and severity of droughts under projected climate change, is likely to further exacerbate desertification and poverty (Gladman and Muchapondwa, 2014).

Daily (1995) estimated that vegetated terrestrial areas of the Earth had lost about 10% of their potential to provide benefits to agriculture and forestry. At the same time the recovery is around 5% over 25 years period. In a recent assessment, about 24% of the global land has been degraded during 1983 and 2003, whereas about 16% of the land has been recovered, of which 20% is cropland and 43% is rangeland. Such degradation is resulting in a net loss of about 42.3 billion dollar annually (Brauch and Spring, 2009). Increasing forests degradation is hampering the basic human right to life and livelihood of the local communities, especially the indigenous community whose life is closely linked with the resources and environment also (Banerjee and Chowdhury, 2013). Restoration have tremendous economic benefits in terms of production of wood and non wood forest products, restoration of water resources, soil protection, etc in addition to the regeneration of the vegetation cover (Babulo et al., 2006). In a study, Leu and Mussery (2014) observed that rehabilitation of drylands alone has a carbon sequestration potential of 15-20% of current anthropogenic CO_2 emissions in addition to the several fold increase in biological productivity and resilience. In an agro-ecosystem too, the restoration activities increase overall biodiversity of all organisms by an average of 68%. Besides, an increased supply of supporting ecosystem services by 42% and regulating ecosystem services by 120% have also been recorded relative to the levels in the pre-restoration phase (Barral et al., 2015).

While the need to restore drylands is widely recognized and large amounts of resources are allocated to these activities, rates of restoration success remain insignificant (Bernhardt et al. 2005; James et al., 2013). However, the informations related to failed experiments on restorations are relatively less as the failed outcomes are rarely published (Zedler, 2007). There is need to accelerate progress in dryland restoration and put forward the field of restoration ecology beyond the conceptual frameworks of quantitative and predictive systems that could capture the probabilistic nature of ecosystem response to management (Restrepo et al., 2013). Restoration of degraded lands are very much essential for (i) increasing crop yields, which is crucial to meet the increasing demands for food, feed, biomass energy, fiber, and timber etc for the growing population (Daily and Ehrlich, 1992; ICRAF, 2011); (ii) mitigate human induced changes in land productivity, which have deleterious impacts on major biogeochemical cycles regulating greenhouse gas fluxes and determine global energy balance (Houghton et al., 1990); (iii) conservation of biodiversity, which depends to some extent on increasing yields on human-dominated areas to alleviate pressure of remaining natural habitats (Barbier et al., 1994); and (iv) land is often a limiting factor of economic output, and its degradation threatens to undermine economic development of under developed countries and social stability at the global level (Khosoo, 1992; Homer-Dixon et al., 1993).

It is satisfying however, that interest in the ecological restoration of forests is growing at present. This is reflected by the development of international policy targets such as those of the Convention on Biological Diversity (CBD) and Reducing Emissions from Deforestation and Forest Degradation (REDD+), in which latter includes, among its aims, the enhancement of forest carbon stocks through ecological restoration (UNEP, 2011). Substantial funding has already been provided to support REDD+ implementation, yet it has attracted criticism for its focus on the single ecosystem service of carbon storage with possibility that other ecosystem services, biodiversity, and social issues could be adversely affected by this initiative (Stickler et al., 2009; Bullock et al., 2011).

2. MESURES TO COMBAT DESERTIFICATION

Because of substantial variation in situation and degree of gravity of degradation in different regions, special care and priority are required to the areas, where the majority of people are affected by desertification. Field researches show that degraded dry lands ecosystems can self-recover after ceasing human activity for 7-8 years in certain regions with annual precipitation of about 400 mm (Zhao et al., 2004). In fact self recovery of highly degraded lands mainly depends on how much of the natural environment remains intact around the degraded area. Low to medium degraded land undergoes self-recovery more easily than severely degraded land, given the same precipitation, while very severely degraded land that includes active sand dunes, saline/waterlogged areas etc., cannot self-recover unless some artificial measures are taken to support it. Natural regeneration in arid areas takes 5-10 times longer than in the favourable areas with greater and more regular rainfall. However, the land in the seriously degraded category is increasing hence these severely degraded lands should not be neglected. Depending upon the extent of severity and the ecological services requires from these degraded lands development of the dry area confront with three most important dealings. Preventive measures to combat desertification are generally adopted on the land slightly or not degraded, whereas for moderately degraded land corrective measures are applied to regenerate the productivity. For seriously degraded land rehabilitation and repair measures are generally applicable to restore the productivity. Thus prevention, protection and restoration or a combination of these are generally applied to develop and manage the degraded areas.

2.1 Prevention

Measures that protect soils from erosion, salinization, and other forms of soil degradation effectively prevent desertification. Sustainable land use can address human activities such as overgrazing, overexploitation of vegetation and trampling of soils ((Liu, 1982). Measures to spread the pressures of human activities, such as transhumance (rotational use) of pasturelands and well sites, promoting tree on farmlands, stocking rates matched to the carrying capacity of ecosystems, and diverse species composition and forest thinning to protect it from future fires are the management strategies in preventing land/forest degradation (Pandey, 1991; Santos, 2015). Improved water management practices like revival and use of traditional water-harvesting techniques, water storage, and diverse soil and water conservation measures, and maintaining management practices for water capture during intensive rainfall period also helps prevent surface runoff and soil loss (Singh and Singh, 2016). Improving groundwater recharge through soil-water conservation, upstream revegetation, and floodwater spreading and controlled water withdrawal from stream and ground water can provide reserves of water for use during drought periods. Maintaining and protecting vegetative cover to protect soil from wind and water erosion is a key preventive measure against desertification. The preventive measures in forest managements include: prevention from fire, insect or pathogen attack, excess withdrawal of water or forest produces and most importantly prevention from invasive species (Love and Babu, 2009; Obiri, 2011; Sankaran, 2007) like lantana *(Lantana cámara)*, bittervine (*Mikania micrantha*), thoroughwort (*Chromolaena* spp.), tropical whiteweed (*Ageratnm conyzoides*), Santa Mariafeverfew (*Parthenium hysterophorus*), and pignut (*Hyptis suaveolense*).

2.2 Protection

Protecting an area from human and livestock interferences in the form of harvesting and cutting of trees and removal of woody material or plantation damage/grazing allow maintenance and where necessary restoration of natural vegetation regimes. This reduces erosion, revives aquifers and maintains sustainable livelihoods for local communities. Protected areas in drylands embrace a full range of management approaches, ranging from strict protection to protected landscapes where conservation is integrated with traditional lifestyles. It varies from national parks to ancient examples of community conserved areas like sacred groves or pasturelands (Bhagwat et al., 2005; Dudley et al., 2014). Evidences from a growing body of case studies demonstrate that protected degraded forest is able to recover in a relatively short time and help recover and regenerate many species, i.e. *O. europaea* (Aynekulu et al., 2009; Yayneshet, 2011). Judicious use of all the resources, i.e. land, water, vegetation in an area for providing an answer to alleviate drought, moderate floods, prevent soil erosion, improve water availability and increase food, fodder, fuel and fiber on sustained basis help protect our drylands. For example protection has increased biomass by more than 2-fold and species richness by more than 3-fold in Udaipur region of Rajasthan, India. By capitalizing on improved organization of labour, more extensive soil and water conservation, increased use of mineral fertilizer and manure, and access to new market opportunities leads many land users, who have achieved higher productivity in areas of the Africa and Asia.

2.3 Restoration

Establishing short-rotation single- or multiple-species plantations on degraded soils/ wastelands, restoration plantings in secondary forests or assisted regeneration in degraded forest are few examples of the wide spectrum of forest restoration approaches (Lamb, 2010; Pandey and Prakash, 2014; Sayer et al., 2004). The commonality in all is that they consist of management interventions, which aim at recovering ecosystems that have been degraded, damaged or destroyed by human activities (Birch et al., 2010; Rey-Benayas et al., 2009; Singh et al., 2013a). Ecological restoration is therefore an important practice that may increase the levels of biodiversity and assists in the recovery of resilience and adaptive capacity of ecosystems that have been already degraded (Brudvig, 2011; Lamb and Gilmour, 2003; Nagendra, 2010; Rodrigues et al., 2007) and mitigates the impact of climate change (Aronson and Alexander, 2013; Harris, 2009). This incrementally returns the ecosystem to a state that is within a historical range of variability of conditions influenced by anthropogenic activities and potential climate change impacts (Budiharta et al., 2014; Millar and Woolfenden, 1999). Some degraded lands have the potential to be used for crops cultivation that can help in securing access to raw materials while reducing the need to convert more natural ecosystems for agriculture. Degraded lands can also be restored to a natural state, i.e. reintroducing and enhancing local ecosystem services and biodiversity (Fleishman et al., 2003; Zhao et al., 2007). Restorations of degraded areas are of particular importance due to the heavy impact humans have had in these areas. It is a broad scientific framework that includes ecological approaches like structural and compositional replication, functional success, and durability as well as mutually beneficial for human and land interactions (Nagendra and Gokhale, 2008). Restoration techniques include activities such as: (i) reforestation and tree regeneration; (ii) effective water management-saving, reuse of treated water, rainwater harvesting, desalination, or direct use of seawater for salt-loving plants; (iii) fixing the soil by use of cover crops, micro wind-breaks, shelter belts and woodlots; (iv) enrichment and fertilization of soil through planting; and (v) promoting natural regeneration and their proper management including silvipastoral systems, farmlands or farmer managed natural regeneration through selective pruning and thinning of trees and shrubs (Araujo et al., 2014). Prescribed tree cutting and fire, decommissioning of roads, stabilization of slopes and removal of invasive species are other restoration methods.

3. HISTORICAL APPROACHES

The traditional view in ecology dominated until the 1990's. Since then the idea that species distribution pattern is the result of the abiotic and biotic interactions determining the environment is developed. In the early 1990's, it was realized that species diversity also affects the abiotic environment, and even the functioning of ecosystems (Schulze and Mooney, 1993).

3.1 The community approach

Interventions usually designed to accelerate natural succession or bypass some intermediate successional phases focusing particularly on restoring forest biodiversity fall under this approach. Many studies that apply facilitation as a restoration tool of woody communities are typical examples of the community approach to forest restoration (Gómez-Aparicio, 2009). Further, planting late-succession tree species under early-succession nurse species has been found an effective mean of restoring forests under high abiotic stress and is typical example of the community approach to forest restoration (Gómez-Aparicio et al., 2004; Aerts et al., 2007).

3.2 The ecosystem approach

Ecosystem approach acknowledges human participation and interests; but put emphasis on maintaining the interactions within and functioning of natural systems; and its applicability over a wider range of scales (Maltby, 2000). In fact ecosystem approach is a strategy for the integrated management of land, water and living resources that promotes conservation and sustainable use. Under restoration, it includes species richness and community structure over time that implies increasing ecosystem complexity and functionality (Palmer et al., 1997). Primary production, energy flows and nutrient cycles are the guiding principles on which restoration efforts are based and aim at restoring suitable abiotic conditions that allow recolonization of species (Naeem, 2006). The ecosystem perspective typically starts from a landscape point of view, building on spatial heterogeneity and at broad spatial scales (Bell et al., 1997). The connections or barriers between neighbouring ecosystems have an effect on the resource balances and set limits on the communities that can be restored (Ehrenfeld and Toth, 1997). Reforestation of degraded sites with trees that alter the physical and chemical characteristics of the soil and that affect the biochemical cycles through litter fall or root activity presents a typical example of the ecosystem approach to forest restoration (Russel et al., 2004). However, Waylen et al. (2014) suggested more effort and attention in implementing this approach particularly in context of CBD.

3.3 Biodiversity-Ecosystem Function (BEF) Approach

The functioning of an ecosystem incorporates processes such as decomposition of organic matter, fixation of carbon, nutrient and water cycling and degradation of toxic compounds. These ecosystem functions on an average increase with increasing number of species (Cardinale et al., 2007). The success of the idea that biodiversity affects ecosystem properties and functions was because of offering a comprehensive framework to evaluate the consequences of biodiversity loss caused by human activities, and at the same time provides a powerful incentive for biodiversity conservation and ecological restoration (DeClerk et al., 2010; Naeem, 2002; Ruiz-Jaen and Potvin, 2011). Naeem (2002) was in view that restoration ecology is beneficial by enhanced biodiversity and the related ecological function, and this idea was further elaborated by Wright et al. (2009). This idea strongly focuses on restoring the relationship between biodiversity and ecosystem functioning (Naeem, 2002). There are many experiments that have adopted the BEF framework where the effects of tree species richness on ecosystem functions have been evaluated (Maestiro et al., 2013; Garnie et al., 2016).

3.4 Landscape approach

Forest Landscape Restoration (FLR) approach is applied to regain ecological integrity and enhance human well-being in deforested or damaged landscapes (Newton et al., 2012). Combining existing principles and techniques of development, conservation, and natural resource management, this approach integrates site-specific forest (land) restoration activities with desired landscape-level objectives (Mansourian et al., 2005). It provides tools and concepts for allocating and managing land to achieve social, economic, and environmental objectives in areas where agriculture, mining, and other productive land uses compete with environmental and biodiversity goals. It is based on the key principles of landscape ecology incorporating the interactions between the temporal and spatial aspects of a landscape and its flora, fauna and cultural components (Dover and Bunce, 1998). The basic principles of landscape ecology are: (i) development and dynamics of spatial heterogeneity; (ii) promotion of interactions and exchange across heterogeneous landscapes; (iii) studying the influences of spatial heterogeneity on biotic and abiotic processes; and (iv) management of spatial and temporal heterogeneity of the landscape (Smith and Tripathi, 2011). However, a number of challenges to Forest Landscape Restoration implementation have also been encountered that include the difficulty of achieving strong engagement in FLR activities among local stakeholders, lack of capacity for community-led initiatives, and the lack of an appropriate institutional and regulatory environment to support such restoration activities (Newton et al., 2012). These authors stressed upon new collaborative alliances among stakeholders, empowerment and capacity building of local communities to enable them to fully engage with restoration activities, and an enabling public policy context to enable local people to be active participants in the decision making process. Sayer et al. (2013) synthesized the current consensus on landscape approaches and provided 10 summary principles to support implementation of a landscape approach. These principles are: continual learning and adaptive management; common concern entry point; multiple scales; multi-functionality; multiple stakeholders; negotiated and transparent change logic; clarification of rights and responsibilities; participatory and user-friendly monitoring; resilience and strengthened stakeholder capacity; emphasizing adaptive management; stakeholder involvement; and multiple objectives.

4. RESTORATION STRATEGIES

Control of woody growth, development of degrading resources, revegetation by planting seedlings or grasses and a good management approach are most commonly applied actions to mitigate desertification. The complex environmental issues involving social, economic and political driver of land degradation cannot be addressed without adopting an integrated approach (Ostrom, 2007). Cutting across food security, poverty, climate change and human rights, addressing land degradation and biodiversity loss requires a multidisciplinary approach and multi-stakeholder integration. At the same time where lives of millions of starving people are at stakes and the long term survival is crucial, there is need of courage to stand against the fixed minded people. Further, there is need for investing in “social transition”, in order to ensure that the degradation process does not reappear once the rehabilitation measures in the field have been completed and the forests are maintained in a healthy state in the long-term (Kleine et al., 2009). Most of the programs described under forest rehabilitation activities are mainly addressing issues of access rights to resources, community organization, self-governance, and benefit sharing between the local communities and the forest department/government. These social changes are considered indispensable for long-term successful forest rehabilitation (Pagdee et al., 2006). To allow these changes to happen, significant investments in terms of financial resources, advisory services and assistance to local communities are required and should be considered as an integral component of any rehabilitation programme.

Two most important strategies adopted in general to aid the recovery of large areas of deforested and degraded lands are active and passive restorations strategies. Vegetation measures like amount of understory cover and species richness particularly trees and density differ between the two restoration strategies (Morrison and Lindell, 2010). Active restoration is where management techniques such as planting seeds or seedlings at high density are implemented and managed involving a more active role of the restorer (Reay and Norton, 1999). Passive restoration imply minimal human intervention and is based on natural succession process, and in this way the restorer has a passive role regarding the process, however action like ceasing the environmental stressors like agriculture or grazing are implemented (DellaSala et al., 2003; Rey Benayas et al., 2008**)**. Passive restoration strategies are simple, inexpensive, and based on natural regeneration processes, but there is strong evidence that to effectively conserve biodiversity and ecosystem services, passive conservation and protecting remnant ecosystems is no longer adequate (Dobson et al., 1997). There is a need for active restoration of degraded ecosystems that accelerate the restoration of ecosystem functioning through the activation of soil biogeochemical cycling of nutrients and carbon sequestration (Celentano et al., 2011; Suding et al., 2004), particularly in dry areas, whereas natural succession is either very slow or does not exist (Abella, 2010). Sometimes both passive and active restoration strategies are adopted in maintaining functions of ecological processes though superiority of these strategies depends upon the types of process and the related products, i.e. soil organic carbon and cation exchange capacity under former strategy (Budiharta et al., 2014; Restrepo et al., 2013). The restoration includes rehabilitation, reconstruction, reclamation, and replacement (Stanturf et al., 2014).

4.1 Rehabilitation

Rehabilitation seeks to repair damaged or blocked parts or sectors of ecosystem functions, with the primary goal of regaining ecosystem productivity. This alters the degraded ecosystem and the resulting natural processes lead to the desired function like a climax seral state though other seral states may be desired in functional restoration, particularly to support threatened or endangered species (Stanturf et al., 2014). Two approaches to rehabilitation are conversion and transformation, where former apply to complete removal of an existing vegetation and replacement with other species (Zerbe, 2002; Spiecker et al., 2004; Hansen and Spiecker, 2005). Windstorms, hurricanes, and other intense disturbances provide opportunities for conversions. Transformation applies to a more extended process of partial removals and species replacement (Pommerening, 2006). Altering structure by thinning, planting desired species to restore composition, and seeding native species to enhance biodiversity as well as to serve as fine fuel to carry prescribed fires are some examples of rehabilitation (Walker and Silletti, 2006). Some activities include establishment of seed banks, restocking of organic matter in soil and organisms that promote soil nutrients and plant establishment and growth, and reintroduction of selected species. Other rehabilitation practices include investing in land through practices such as terracing and other counter-erosion measures, control of invasive species, chemical and organic nutrient replenishment, and reforestation.

4.2 Reconstruction

Reconstruction restores native plant communities on land recently in other resource uses, i.e. agriculture, pasture etc. In this amelioration of the soil to increase organic matter, decrease soil bulk density and reduction of soil seedbank of weeds, and planting of seedlings or direct seeding are active approaches, whereas promoting recolonization of open areas is a passive approach. However, later one is limited by natural dispersal because of proximity to appropriate source plants and composition of initial seral species (Benjamin et al., 2005). A combination of approaches may be more useful as direct seeding/planting of keystone species at wide spacing and subsequently relying on passive dispersal to fill remaining niches with other desired species (Scowcroft and Yeh, 2013). In fact reconstruction affords the opportunity to restore ecosystems that have simple or complex structures, comprised of an overstory with one or many species and an understory that develops from recolonization or planting and seeding (Lamb, 2011). Decisions on which methods to use will be framed by overall objectives, initial site conditions, and landscape context.

4.3. Reclamation

Reclamation is restoring a severely degraded land generally devoid of vegetation, often the result of resource extraction like bare sand dunes, mining areas, oil and gas drilling pads/sites etc. Waterlogged and saline soils, deterioration of soil as well as environmental quality due to dumping of mine wastes or disposal of wastewater requires special attention, where more intensive management techniques are usually necessary to revegetate such sites (Abrol and Gupta, 1990; Arya and Lohara., 2006; Gill et al., 1990; Jain, 1984; Shankarnarayan and Kolarkar, 1988; Singh et al., 2014a). However, natural recolonization on such lands including sand dunes may also be effective (Singh et al., 2003b; Prach and Hobbs, 2008). The methods may include amelioration to improve soil physical, chemical, and biological status; seeding or planting of seedlings; and providing regular irrigation and weed control to ensure early survival and growth (Singh and Rathod, 2002; Evans et al., 2013; Zipper et al., 2013). Sometimes exotics are used as nurse plants to encourage the ultimate occurrence and proliferation of native vegetation (Lamb et al., 2005; Parrotta, 1992; Parrotta et al., 1997; Rathore et al., 2015). Reclamation may require multiple interventions to achieve subordinate objectives, with the ultimate desired function not achieved for decades.

4.4. Replacement

Replacement of species with new species (or new genotypes) in response to climatic variation or change in physical conditions falls under this category that has been historically absent from the site (Williams and Dumroese, 2013). Climate change also affects species composition and structure, hydrologic cycles, genetic complexity, nutrient cycling regimes, mycorrhizal relationships, a host of food webs, and biodiversity (Lensing and Wise, 2006; Kulakowski and Veblen, 2006; Lenoir et al., 2008). The number of plant species used in such type of restoration/reforestation is increasing rapidly ranging from a reduced set of well-known, easy to propagate and grow and widely used species to a large variety of promising native species (Vallejo et al., 2012).

5. ECONOMICS OF RESTORATION

Economics plays a central role in restoration ecology and economic analysis is central in determining where scarce land management resources should be directed across the landscape to maximize expected economic benefit from restoration given relevant biophysical and financial constraints (Newburn et al., 2005; Naidoo et al., 2006). Though a huge literature exists outlining linkages between restoration and economics, but mostly focuses on methods of quantifying the costs and benefits of restoration and strategies on funding (Holl and Howarth 2000; Aronson et al., 2010). The missing part is development of our ability to accurately analyze cost and benefit, which entirely depend on prediction to restoration outcomes. Historically, economic analyses of ecological restoration in dryland systems have used a number of ad hoc approaches (expert opinion, consensus papers, etc.) to parameterize conceptual ecological models to compare how ecosystems would change with and without restoration treatments (e.g. Epanchin-Niell et al., 2009; Taylor et al., 2011). Quantitative ecological models, allow for more realistic predictions of ecological routes of treatment sites under alternative restoration strategies that include the alternative of not pursuing any restoration activity. The economic benefits of restoration are measured as the difference in the flows of monetized ecosystem goods and services. Such models allow us to identify how variation or manipulations of certain processes or environmental conditions influence the likelihood of a successful restoration outcome (McBride et al., 2010). This also allows in conducting sensitivity analysis to determine which portion of the system can be manipulated to yield the maximum increase in the probability of a successful outcome and thus benefits from restoration.

The restoration cost depends upon the site conditions (barren or woody growth, types of interferences, rainfall etc.), types of soils, number of seedlings planted per unit area and species to be planted (Fig 5.1). Evidences suggest that ecological restoration is generally effective in increasing the provision of ecosystem services (Rey Benayas et al., 2009), however very little information is available regarding whether such restoration is cost-effective (TEEB, 2009). TEEB (2009) evaluated the cost-effectiveness of restoration projects on the basis of a “benefits transfer” approach, reflecting the lack of studies providing estimates of both costs and benefits. Results of the TEEB review indicates an average benefit : cost ratio (BCR) of 28.4 for woodlands and shrublands, against annual cost of forest loss at between $2 trillion and $5 trillion (TEEB, 2009).

Active restoration is a costly affair in any of the areas. Cost of restoration by planting tree seedlings in arid and semi-arid areas of Rajasthan varies from 200 to 450 mandays equivalent per hectare (Siyag, 2014). Protecting the area appears to be most costly affair because of high population of both human and livestock. The required manpower in fencing cost of a linear plantation along roads or in shelterbelts increases to 900 mandays equivalent (Siyag, 2014). Facilitating ecosystem restoration by encouraging natural regeneration has considerable potential and is cost-effective in landscape-scale restoration (Butler, 2009). Taylor et al. (2011) calculated typical dryland forest restoration treatment costs at US $408 hectare^{-1}, which was based on the cost involved in a combination of prescribed fire, herbicide application and seeding treatments (http://www.ut.nrcs.usda.gov/technical/ technology/ economics/2011_cost_data_practices.html).

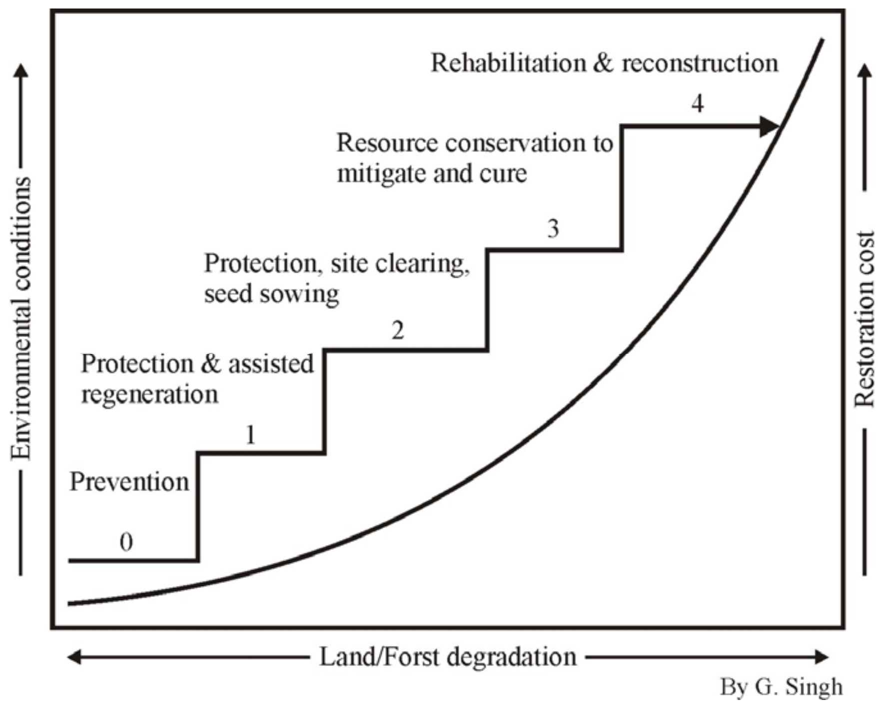


Figure 5.1 A thematic relationship between environmental conditions, land degradation and cost of restoration.

However, variations in restoration cost from $3577 hectare^{-1} to $985 hectare^{-1} depended upon the site conditions like edaphic factors, woody growth, invasive species, firewood load as well as climatic factors. Budiharta et al. (2014) estimated restoring cost of 6.1 million ha degraded tropical forests of Kalimantan, Indonesia at approximately US$8.37 billion considering both the implementation and opportunity costs, and US$3.24 billion in the case of accounting for the implementation cost only. This is equivalent to $1372.1 hectare^{-1} and $531.2 hectare^{-1}, under respective category. Though old the estimated cost of treatment to combat desertification in India ranged from Rs 11000 hectare^{-1} in arid region to 12000 hectare^{-1} in dry subhumid region of Indian drylands (Chouhan, 2005). This includes awareness generation, conservation measures, production and developing alternative livelihoods (Table 5.1). Thus increasing environmental harshness, which affects productivity and facilitate land degradation, increases the cost of restoration.

Table 5.1 Cost estimates for treatment of desertification in different bio-climatic region (Cost in Rs. per hectare). Source: Chouhan (2005).

SNo.	Cost Component	Bio-climatic Region		
		Arid	Semiarid	Subhumid
1	Creation of awareness and capacity building of PRIs including entry point activities	1000	1000	2000*
2	Conservation measures – 70% for water resource development and 30% for soil conservation	5000	5000	5000
3	Production system	3000	3000	4000*
4	Alternative livelihood systems	2000	2000	1000*
Total cost per hectare		11000	11000	12000*

PRIs; panchayat raj institutions; *Includes cultivation of medicinal plants and processing and marketing of minor forest produces.

From field experimentation it becomes clear that seedling planting can be a means to quickly develop productive vegetation even on highly degraded areas. However, depending on the soil conditions and climatic, biotic and abiotic risks, this is an expensive activity. Further, areas with the adverse climatic and anthropogenic factors decrease growth potential of forests or tree plantations, thereby increasing production costs, are also areas where spontaneous regeneration, suffering from these same factors, is extremely difficult. In such a case cost-effective approach could be combined with strategies of assisted natural regeneration and plantation development, especially in areas where mosaics of different degradation states and other land uses are available (FORM, 2013).

6. FUNCTIONAL APPROACH

Restoration consists not only of restoring ecosystems, but also of developing human uses of these lands that are in harmony with the disturbance regime of the ecosystems (Sinclair et al., 2009). It could not account timber management; fuels reduction, habitat improvement, and other single resource management activities rather support human well beings in a holistic approach incorporating agriculture, livestock, pastures, forests, land settlement and energy policies (Barral et al., 2015). Thus it accounts the rehabilitation of the entire affected area, where integration of soil, water, pastures, forests and wildlife has to be considered giving priority to socio-economic and cultural aspects of the inhabitants of the region. The potential negative social impacts of restoration include loss of livelihoods or access to lands undergoing restoration, a risk that is particularly high in areas where land tenure is insecure.

In forest restoration approaches including *functional diversity* of tree or shrub species assemblages will enhance biodiversity and provision of multiple ecosystem services, while also improving human well-being (Aerts and Honnaay, 2011). In this empowering inhabitants and ensuring their well-being by diversification of income opportunities can increase the resilience of communities and help in the sustainable use of natural resources of the drylands. Favorable policies, financial assistance and ground tested technologies help the local people combat desertification in better ways (Adeel et al., 2006). Such interventions are required to be implemented at local to global scales, with the active engagement of multiple stakeholders and local communities. Unfortunately some restoration projects involve local people by employing them as labour only to avoid perverse of social impacts (Birdlife International, 2014); for creating incentive systems to ensure that the restored forests are protected and maintained (Limin et al., 2008), and provide alternative livelihoods through better management of non-timber forest products generated by the restored forests (Rahmawati, 2013, Birdlife International, 2014).

In its 'Two policy failures' UNEP (UNCCD, 2011) highlighted the importance of dry zone forests. The failure was largely due to underestimation of the value of dry zone forests (invisible to policy-makers) and the policy approaches focusing on forest, land and water resources independently, rather than considering them as a trilogy being naturally interdependent and function together. Thus any restoration programme must be conducive in terms of policy interventions, participatory planning and management and site level decisions with major emphasis on human well being.

6.1 Policy interventions

The recent developments in preventing and reversing desertification have been derived more from integrative and systematic theoretical approaches and multi-causal factoral analysis (Geist and Lambin, 2004). This helps navigate the inherent complexity of desertification and dryland development and in identifying and synthesizing the factors important to the research, management and policies. Ecological restoration is making a positive contribution to sustainable development by strengthening the provision of natural resources on which human livelihoods depends (Nellemann and Corcoran, 2010). During last three decades several efforts have been made in combating desertification worldwide. For example, the United Nations has periodically focused on desertification and drylands, notably adopting the Convention to Combat Desertification (CCD) in 1992 (UNCCD, 1994). Indeed, any national and international project that assesses land degradation and restoration actions help land users to improve land management decision making comply to the National Action Programs (NAPs) of the three International Conventions (i.e. UNCCD, CBD and UNFCCC). The NAP emphasizes people participation and the creation of an enabling environment designed to enable local people to reverse land degradation. Besides, NAP acknowledges the medium-term strategic framework of government, which is an outcome based approach. These are also illustrated by the incorporation of ecological restoration among the objectives of global environmental policy; Strategic Plan for Biodiversity 2011-2020, with its Aichi Targets aiming for reduction in rate of loss of all natural habitats including forests to at least halved and where feasible brought close to zero, and degradation and fragmentation to a significant level (CBD, 2010); a target of restoring biodiversity and ecosystem services by the European Union (Jørgensen, 2015) and many national policies (MoEF, 2010); and “Hyderabad Roadmap” in achieving the 20 Aichi Biodiversity Targets agreed to in Nagoya, Japan in Indian context (GoI, 2011b).

Despite these forests of dry zone or dryalnds as such are the result of neglect viewing invisible benefits from them (Box below). In most of the cases the policies, whether implemented at the national or international level do not take full account of the challenges faced by communities living in extreme dry areas. Some forces of globalization, while striving to reduce economic inequality and eliminate poverty, are also contributing to exacerbating desertification. Though promoted in the interest of national farmers, the perverse agricultural subsidies are such examples. The incentives is being provided currently by the government, in terms of feed-in tariff, capital subsidies, tax holidays etc. have been proven to work, but the execution of these policies and incentives need strengthening. For example, government announcement of feed-in-tariffs are much higher than what a solar power producer normally gets; and national Bio Fuel Policy (GoI, 2009), the targets of which have not been met. Insufficient resources at the disposal of state and local institutions to develop coherent, cohesive and integrated policy approaches complicated by the socio-economic profile of the region also lead to failure. National governments typically do not have sufficient resources to address the management issues, leading to ineffective policy integration. This is often further exacerbated by poor implementation at the local level due to lack of capacity and societal motivation (Sarkar, 2009). These and other relevant factors need to be coinciding in fund distribution. To counter these effects, one is with immense human resource, technological, institutional and even financial resources, but lack in coordination and approaches (Alam, 2014). There needs to allot these resources in building capacities to monitor, analyze and solve the local problems. Global efforts for data gathering and synthesis must also be reinforced, so that policy arguments at the local, national and regional levels could be connected at the international arena.

> "There is a mistaken view that because these are dry areas, they are destined to provide little in the way of food and are simply destined to endure frequent famines,"
>
> "But drylands can and do support significant crop and livestock production. In fact, the famine we are seeing today is mainly a product of neglect, not nature."
>
> Dennis Garrity, Director General, The World Agroforestry Centre (ICRAF)

6.2 Participatory planning and management

Active involvement of local stakeholders in planning and management decisions is considered to be an essential component of forest restoration, with an assurance that local needs are adequately addressed, and that the distribution of benefits is equitable (Milne et al., 2006, Nagendra, 2007; Tole, 2010). Understanding the context of stakeholder processes to achieve stakeholder involvement, identification of key stakeholders, understanding stakeholder interests and interactions, and managing multi-stakeholder processes are the basic steps to involve stakeholders actively (Kusumanto, 2007). As ecological, economic, social, spiritual, ethical, and aesthetic perspectives all have a role to play in bringing conservation science into the hearts and minds of people, a careful use of cultural resources like local knowledge and environmental ethics provides further options to design innovative policies and programmes for forest (land) restoration (Pandey, 2003). While most of the people are not aware about the importance of native plant species of dryland forests which varies among regions, and even among different communities residing in the areas (del Castillo et al., 2011), activities under restoration of forest area compete with animal husbandry and agricultural cropping and could become one of the important constraints in active participation. As most forests are typically limited to low-quality sites such as steep sites or areas with very poor soils the contribution of forest resources found little to community aspirations, though fuel wood and fodder are collected from the forests to meet local needs. In such a scenario active participation is often difficult to realize in practice (Reed, 2008). Kobayashi et al. (2014) observed that ranchers operating on healthy rangeland have sufficient private incentive to maintain rangeland health, while ranchers operating on degraded rangeland will pursue rehabilitation only if treatment success rates are improved or treatment costs reduced relative to current levels. Further failing to understand the relationships among grazing pressure, vegetation treatments, and rangeland ecological dynamics, their management results in higher short-run profits, but lower long-run profits, and greater ecological degradation (Kobayashi et al., 2014).

Emphasizing on empowerment, equity, trust and learning could be ideal philosophy in developing relationships between the communities and forest managers or community mobilizer. More emphasis should be given in case of lacked strength in the capacity of the communities to undertake social and economic development activities (Reed, 2008; Chazdon et al., 2009). Further, based on incremental, experiential learning and decision making there should be adjustment in management actions in managing complex ecosystems.

6.3 Site-level decisions

Site prioritization is an issue that has been little researched, but contributes significantly to improving a restoration programme (Maginnis and Jackson, 2007). Efforts have been made in identification of criteria and indicators for prioritizing restoration efforts applying Delphi survey method, use of 'PRACTICE' approach and frequent interactions and workshops (Dreber et al., 2014; Orsi et al., 2010; Prasad and Kotwal, 2001), but the numbers of relevant variables are generally too large from which development of a generally applicable set of criteria and indicators is difficult to select. For example, by conducting a series of workshops and interactive meeting for developing relevant and applicable set of criterion and indicators for sustainable forest management in the forest management unit (FMU) level a set of 8 criteria and 55 indicators were obtained (Prasad and Kotwal, 2001). Further, 'PRACTICE' approach appeared a better evaluation tool for management and/or restoration actions and can be better applicable as monitoring tool, i.e. degradation assessment (Reed, 2008). Orsi and Geneletti (2010) examined the practical implementation of landscape approach by applying selected criteria to generate suitable maps for forest restoration. In this maps are created for each criterion, then these maps are combined using spatial multicriteria evaluation (MCE) techniques to generate a series of restoration options. The performance of each reforestation option is evaluated with respect to both improving the ecological functioning of the landscape and the provision of ecosystem services to the people. This enables ranking of different restoration options, and helps identify preferred options (Orsi and Geneletti, 2010). The spatial MCE approaches enable the implications of different values (or weights) held by different stakeholders to explore through the use of mapping tools, linked with GIS.

6.4 Maintaining biodiversity and ecosystem functions

Both passive and active approaches of natural regeneration and artificial establishment of native trees/shrub species are used to restore dry forest landscapes. However, restoration of landscape heterogeneity and stand structural complexity is of particular importance in the restoration of dry forests. Principles for biodiversity conservation developed by Lindenmayer et al. (2010) are broadly applicable to any forested area. This includes maintenance of forest connectivity, landscape heterogeneity, and structural complexity. Forest connectivity influences key processes influencing biodiversity, including population persistence and recovery after disturbance, the movement of individuals and genes in a population, and the colonization of different locations within the landscape. Likewise diversity, size, and spatial arrangement of habitat patches are important determinants of habitat suitability for many taxa, and are influenced by the extent of landscape heterogeneity (Lindenmayer et al., 2010). Though restoration process involving rainwater harvesting enhances floral diversity (Singh et al., 2010a; 2011), but quantification of such ecological restoration indicates increasement in provision of biodiversity and ecosystem services by 44% and 25% respectively (Rey Benayas et al., 2009). However, such benefits are observed only in the moist forests in other studies (Echeverría et al., 2007; Newton et al., 2009; 2012). Most forests of dry areas are progressively fragmented and degraded because of human disturbances, which reduces species richness (Rocha-Loredo et al., 2010) and requires active restoration efforts (Souto et al., 2011). However, a simulation study of dry forest indicates resilience to different anthropogenic disturbances like small, infrequent fires and large, frequent fires, where grazing and fire were found to act synergistically (Cantarello et al., 2011; Newton et al., 2012). Problems of woody growth or invasive species are also critical to diversity in dry forests, where the spread of the invasive exotic species (like *Acacia dealbata, Prosospis juliflora*) occur only in the presence of fire when combined with browsing and/or cutting of the native vegetation (Newton et al., 2011; Singh et al., 2014b) and could be controlled effectively (Babu et al., 2009, Provencher and Thompson, 2014).

6.5 Enhanced human well-being

Under the wake of the Millennium Ecosystem Assessment (MEA, 2005) (ECOSYSTEMS AND HUMAN WELL-BEING) the interest in the concept of ecosystem services and the benefits provided by the system to the people has grown up rapidly. Human well-being in relation to health, food security, nutrition and security is at risk from dryland degradation which costs developing countries an estimated 4-8% of their gross domestic product each year (UNEP, 2011). This is also illustrated by the conceptual framework (Fig 5.2) of Intergovernmental Platform on Biodiversity and Ecosystem Services (IPBES) focusing on co-construction of integrative knowledge shared by an increasing number of initiatives worldwide (Díaz et al., 2015) and increased investment in drylands to strengthen links between science and policy, and diversified livelihoods for communities to relieve pressure on other natural resources (UNEP, 2011).

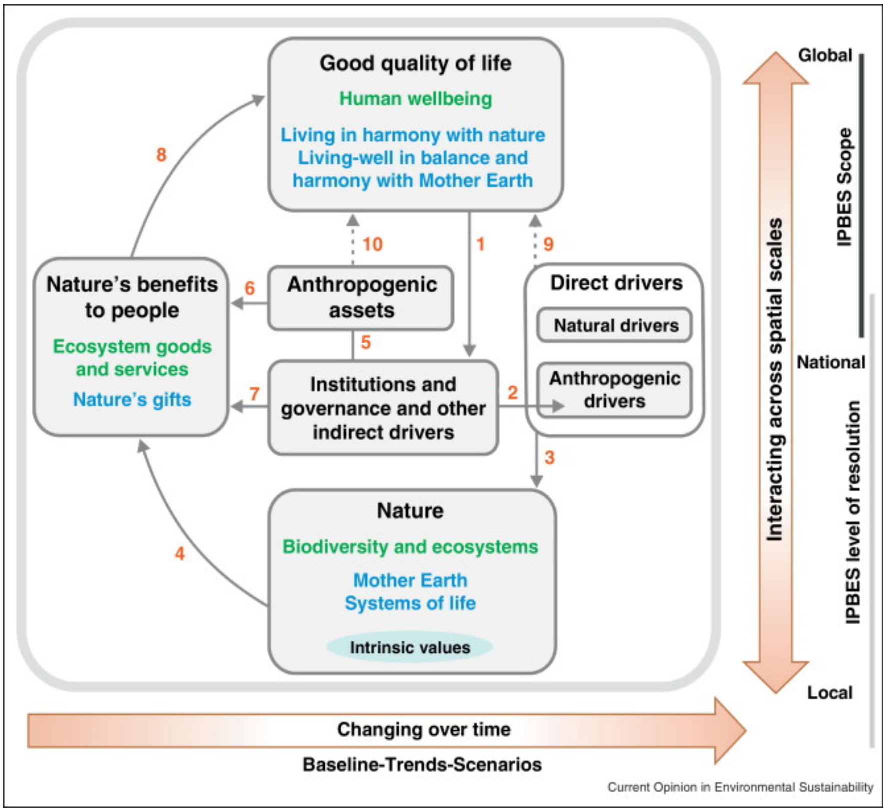


Figure 5.2 Conceptual framework of relating human well being and dryland degradation. Here 1 is natural world with an emphasis on the diversity of living organisms and their interactions; 2 is built infrastructure, health facilities, knowledge including ITK and technical or scientific knowledge, as well as formal and nonformal education; 3 is *Nature's benefits to people*' that include all the benefits to humanity — individuals, communities, societies, nations or humanity as a whole — in rural and urban settings — obtains from nature, ecosystem goods and services — including provisioning, regulating and cultural services; 4 is '*Institutions and governance systems and other indirect drivers*' the ways in which people and societies organize themselves and their interactions with nature at different scales; 5 is '*Direct drivers*', both natural and anthropogenic, affect nature directly; and 6 is *Good quality of life*' the achievement of a fulfilled human life (Diaz et al., 2015).

In general meeting the needs of local people has major implication for the practices of ecological restoration (Bullock et al., 2011) therefore it should always be a central objective of any restoration programme (Maginnis and Jackson, 2007). Though ecological restoration increases provision of biodiversity and ecosystem services (Newton et al., 2012), their values in a landscape are strongly context specific (Birch et al., 2010). Therefore, the importance of property rights and local institutions in shaping the distribution of restoration costs and benefits is going to play an important role in this direction. Tagging of these restoration works with Clean Development mechanism or REDD+ may be more beneficial in human well being as highlighted by Corbera et al. (2007), where a project had provided payments for carbon sequestration by afforestation activities in Chiapas, Mexico, in which the poorest farmers, women, and the landless were sometimes excluded from project activities.

7. GUIDING PRINCIPLES FOR RESTORATION

FAO (2013) developed guidelines for restoration of degraded forests focusing to four major strategic components and putting in place an enabling environment to address the underlying causes of forest degradation and desertification in drylands. These include: (i) Policy implications; (ii) planning; (iii) filed implementation; and (iv) monitoring and evaluation.

7.1 Policy implications

Policies that create incentives for rehabilitation and restoration of drylands include capacity building, capital investment, and supportive institutions. The success of restoration and rehabilitation activities depends on the availability of human resources, sufficient funds and infrastructures, as well as on the degree of dependence on external technologies and cultural perceptions. Benefits of increased education, improved governance, enhancement of ecosystem services and adequate access to these resources can lead to successful rehabilitation and also help in reducing poverty in the region. However, in a situation of not meeting these conditions restoring degraded dryland services may thus be difficult even with major policy and technology interventions. For a successful restoration or rehabilitation programme following policy interventions need (FAO, 2014) to be taken care of:

- Establishment of supportive governance mechanisms and improving national policies and legal frameworks.
- Strengthening inter-sectoral cooperation and partnerships including long-term capacity development.
- Supporting the institutional development of grassroot organizations through capacity development and education.
- Awareness generation about the approaches to landscape restoration.
- Multidisciplinary and applied research in direction of dryland restoration/rehabilitation.
- Supporting the development of training modules on forest landscape restoration based on up-to-date research findings and including them in the curricula of training institutions.
- Support to the development and sustainable functioning of tree seed centres and nurseries including seed certification.
- Strengthening extension services and promoting farmer-to-farmer extension approaches.

- Establishment of networks and forums for sharing knowledge and skills on sustainable financing.
- Promoting long-term cost-sharing strategies to fund restoration programmes, including public and private sources and contributions from the local people.
- Development of innovative funding mechanisms like payments for ecosystem services (e.g. watershed services, biodiversity conservation and carbon sequestration).
- Incorporating restoration costs in development initiatives and conservation efforts.
- Creating community-based enterprises addressing the entire value chain (from seed to end-product).
- Promoting alternative cost-effective technologies in restoration/ rehabilitation programmes.

7.2 Planning

Given the attachment to the land by the small farmers and landowners residing in the region as well as the need for collaboration and for a broad-based action plan, a participatory planning process should be attempted. All restoration or reforestation programs should be prepared in advance, based on average conditions (e.g., institutions plan to rehabilitate or restore a certain number of patches per year) and understanding of ecology, i.e. relationship between soil, plants, hydrology, climate and land management options (Castaritini et al., 2016). All stakeholders including governmental organizations, private partners, farmers and natural resource industries (i.e., mining) would eventually have to be convinced to work with forest managers and scientists in setting up restoration programmes. At one level, successful restoration would require the collaboration of a variety of government departments, whereas at another level, it would require the collaboration of the remaining stakeholders for effective long-term collaboration (Kashwan, 2006). It should include soundness of the experiment as well as social marketing. Further, considering the climate change projections of an increase of drought and more severe fire regime in dry areas, the main target of plantation technology development in context of drylands rehabilitation is to overcome transplant shock and likely adverse periods the plant is going to face. These are mostly related to water limitations and the other related problems. For this plant species selection, improved nursery techniques, and improved planting techniques are some of them to mention. The number of plant species used in reforestation is relatively high particularly in Indian conditions and is increasing rapidly, moving from a reduced set of well-known, easy-to-grow, widely used species, to a large variety of promising native species. Available technologies allow reintroducing native plants and recovering critical ecosystem functions of the degraded drylands. However, climate change projections introduce large uncertainties about the sustainability of current restoration programmes. To cope with these uncertainties, adaptive restoration approaches seems more appropriate on the basis of improved plant quality, improved techniques for optimizing rain use efficiency in plantations, and exploring native plant species, including provenances and genotypes, for their resilience to fire and water use efficiency at the local levels. For this following steps may be followed at the planning levels:

- Devising restoration or rehabilitation priorities and goals.
- Planning at the landscape level and selecting priority sites and types of interventions.
- Conducting biophysical and socio-economic baseline studies, which include in-depth multistakeholder analyses and studies on land and forest tenure.
- Undertaking GIS analysis and mapping to assess restoration needs, plan restoration actions and monitor their impacts.
- Defining and balancing ecological, economic, social and cultural objectives of the programme.
- Defining cost-effective restoration options and technical operations like assisted natural regeneration, farmer-managed natural regeneration, enrichment planting and direct seed sowing.
- Defining effective tradeoffs between socio-economic interests and sustainable land use practices.
- Improving ecosystem services across the full range of land uses.
- Supporting the active participation of relevant stakeholders together with people involvement as a central elements of the rehabilitation plan.
- Collaborative planning and action involving multi-stakeholder and multisectoral mechanisms.
- Defining clear roles and responsibilities of each stakeholder in planning and implementation together with costs and socio-economic benefits for each stakeholder.
- Developing strategic cooperation among private-sector investors, land managers, the public sector and civil-society actors.
- Selection of suitable species and related genetic material for the site and ensuring high-quality reproduction material.
- Selecting species following participatory approaches involving local communities and relevant stakeholders.
- Selecting high-value species (i.e., trees, shrubs and herbaceous species) based on a combination of socio-economic and environmental criteria and benefits that can serve multiple purposes both for local community and the environment with preference to native and adaptive species.
- Careful consideration in the use of exotic species to ensure minimal negative effects on the local ecosystems.
- Establishing seed banks of trees or shrubs or other species of interest.
- Evaluating the genetic material of targeted sites (e.g. adaptation to drought and soil type, resistance to disease and fire, and the variability of the genetic pool), where possible making use of existing studies to avoid the duplication of the efforts.

- Supporting the production and use of high-quality reproduction material having high genetic diversity.

7.3. Implementation at the field level

Rehabilitation or restoration seeks to repair damaged or blocked parts or sectors of ecosystem functions, with the primary goal of regaining ecosystem productivity. Restoration ecology has advanced both as a scientific discipline and as a practical approach to environmental management (Young et al., 2005; Brudvig, 2011). Applying sustainable forest management practices helps to combat desertification and to recover and rehabilitate land, soil, water and vegetation. Field level experiments demonstrate that seedling establishment is generally undermined by herbivoures and that protection; particularly against livestock as well as wildlife is essential for successful rehabilitation (Holmgren et al., 2006; Gutierrez et al., 2007; Squeo et al., 2007). These activities include establishment of seed banks, restocking of organic matter in soil and organisms that promote soil nutrients and plant establishment and growth, and reintroduction of selected species. Other rehabilitation practices include investing in land through practices such as terracing and other counter-erosion measures, control of invasive species, chemical and organic nutrient replenishment, and reforestation. At field level following activities can be taken care into a successful restoration or rehabilitation programme policy:

- Promoting assisted/farmer-managed natural regeneration in the relatively less degraded areas.
- Combining assisted natural regeneration with direct seed sowing or planting.
- Using agroforestry and conservation agriculture technologies.
- Using innovative technologies for improving plant production in nurseries and onsite planting and field operations, that includes:
    - planting operations and technologies to improve site conditions,
    - planting density/proper spacing,
    - sowing seeds,
    - planting period,
    - soil preparation for seedlings plantation,
    - watering during planting and maintenance operations, and
    - planting techniques that mimic ecological interactions.
- Implementing measures for:
    - soil and water conservation,
    - countering wind and water erosion through terracing and rainwater harvesting,
    - enriching the soils with nutrients,
    - forest protection and rotational grazing including pasturelands, and
    - forest management.
- Managing fire.
- Developing and implementing management plans for restored areas.

7.4 Effective monitoring and evaluation

Assessing sustainability of a rehabilitation proagrmme combining environmental, social, and economic conditions appears beneficial in success of the programme (Ghate and Nagendra, 2005). This further includes coordinated research to better address the dryland requirements. Sharing of experiences on dryland management across the regions or nations and pooling of resources from different sectors is the key to success (Janssen et al., 2010). Integration of biophysical and socioeconomic indicators and the collaboration between researchers, managers, and decision makers make the approach effective and sustainable. However, the full impact of new management approaches can often be measured through long-term monitoring. For example results from long-term studies on the regeneration of grasslands at Hunshandake Sandland, China, demonstrated the previously under-recognized potential of the elm (*Ulmus pumila*) sparse forest grassland ecosystem to regenerate itself. Case studies from South Africa have also illustrated the potential of exotics, especially eucalypts, in providing much needed timber besides protecting the natural forest (Van Wyk et al., 2006). After genetic improvement the yield reached to more than 20 m^3 ha^{-1} $year^{-1}$, even under relatively dry conditions. But the risk of using exotics eucalypts and Australian Acacias in terms of water use, uncontrolled spread and destruction of local biodiversity was generally undermined. Thus adapting to environmental change and combating land degradation require understanding the tradeoffs in ecosystem services and adjusting restoration decisions in response to monitoring and evaluating both biophysical and socioeconomic metrics (Bautista et al., 2010) in following ways:

- Incorporating objectives, performance standards and protocols for monitoring in restoration plans.
- Monitoring forest landscape restoration programmes over long periods to detect major environmental and socio-economic processes and dynamics.
- Monitoring, backed by the compilation of lessons learned, to inform adaptive management and the sharing of know-how for further replication to other similar areas.

8. CONCLUSIONS AND RECOMENDATIONS

The rates of land degradation are very high as compared to recovery resulting in a net loss of over $42 billion annually and hampering the basic human right to life and livelihood. Extent of vulnerability of land towards desertification depends on the interactions of natural and human-derived factors. Likewise developmental measures (like preventive, protective and restorative of these lands) also depend on the severity of degradation. Restoration have tremendous economic, social and environmental benefits in terms of crop yields, forest produce, restoration of water resources, soil protection, regeneration of vegetation cover and social stability in the region. Various approaches are adopted ranging from community level to landscape level that promotes a single plant species in an ecosystem to as much as covering societal and economic benefits along with enhancing biodiversity.

Rehabilitation, reconstruction, reclamation and replacement are the ways, which involve passive and active restoration strategies or a combination of these both. In this, collective decision and planning, defining cost-effective restoration options and technical operations, selection of suitable species for restoration, effectual field level application, appropriate resource conservation measures and monitoring and evaluation for adaptive management are the different steps under effective restoration. The strategies for restoration of degraded forest lands using natural regeneration without human assistance is observed cheap but appears extremely slow. On the other hand, intensive plantation management is very quick, but also cost -intensive. In such a circumstance a mix of transplanting and managed natural regeneration would be more cost efficient.

Involvement and cooperation of local stakeholders and the community would prove to be more effective in restoration of degraded ecosystems. In addition to the planning processes, the involvement of local community in both collecting and interpreting scientific data would build social capital by linking local people together and help stimulate an approach broad enough to allow for multiple interests beyond the restoration efforts. This is making the science transparent to local groups and building bridges among landowners, farmers, mine owners, cooperatives, managers and corporate actors. It means recognizing the motivations and interests of the stakeholders, where cost and benefits must be equally shared.

To avoid local and regional conflicts in the decision making processes this should be participatory and democratic. In absence of this the conservation and restoration initiatives are going to be badly affected (Lele et al., 2010). Though nation level legal frameworks are available that aims to ensure sustainable use of natural resources, however the problems are associated underlying philosophies and effective implementation at the state and local level.

Most notable limitation is the top-down application of public policies that do not take into consideration local and long-term needs, capacities, and aspirations of the local communities' thereby often resulting in many programmes to failure. Another common feature of the political context relates to the overlap of power of governmental agencies, often causing contradictory or competing actions. Public policies on restoration of degraded lands including forestlands should consider all stakeholders and local groups and enable them to participate actively in the decision making process.

Besides it could happen when sufficient awareness among the stackholders is generated and capacity is developed to conceive and implement the restoration programmes and reduce the negative impacts of desertification, land degradation and drought.

Monitoring and evaluating the costs and benefits associated with restoration works is essential to develop cost-effective policies and strategies for addressing land degradation. Tackling desertification is not just about adopting physical remedies, as social remedies are equally important. This means that economic and social impacts need to be tackled in an integrated manner.

6

WIND EROSION AND SAND DRIFT: CONTROL MEASURES AND SUSTAINABLE MANAGEMENT

Wind erosion is a serious land degradation problem wide spread in dry lands. The extent of land degradation due to wind erosion in India is about 4.1% and is most prevalent in northwestern India. Wind causes erosion and deposition in environments where sediments have been recently deposited or disturbed. Though barren dunes are generally mobile, but the sand dunes loosened due to biotic inferences are more prone to wind erosion and as the result loose sand is blown to nearby area under strong wind action. Sand drift and dune forms are also influenced by topography, surface roughness, soil types, lack of vegetation and low soil moisture content. Sandy plains and various forms of sand dunes are created as the result of wind action. Enhanced sand transport, reduced supply of sand upwind and deflection of moving sand to other sides are the approaches to tackle the problem of wind erosion, whereas (i) transposing, (ii) planting, (iii) paving, (iv) paneling, (v) fencing, and (vi) use of oil, are the methods of sand drift control. These are either employed singly or in combinations. Temporary measures include shielding the ground with stable material and erection of fences or micro-windbreaks. Sand shielding includes stone mulch, chemical stabilization, biological crusting and use of geotextiles. The fences for sand drift control are vertical barriers that disrupt wind flow across a surface. Though geotextiles supported by seed sowing could be effective, but the effective method of sand dune stabilization and sand drift control is biological method, which is more effective and long lasting. This chapter describes different methods of sand drift and wind erosion control, suitable vegetation species for sand dunes, interdunes and sandy plains, plantation and post planting care and making the sand dune stabilization more remunerative and beneficial in terms of people livelihood and environmental ameliorations.

1. INTRODUCTION

About 15 per cent of the Earth's ice-free land surface is affected by different forms of land degradation (GLASOD, 2005). In this accelerated soil erosion by water is responsible for about 1093.7 million ha (55.6%), wind erosion is about 548.3 million ha (28%), salinization is about 76.3 million ha and waterlogging is about 10.5 million ha (Oldemann et al., 1991). Besides, barren rock out crops and ravines are other degraded land forms. In a recent review the estimated global total degraded area is ranging from less than 1 billion ha to over 6 billion ha, with equally wide disagreement in their spatial distribution (Gibbs and Salmon, 2015). Drifting sands, increasing salt concentrations and problem of water logging are some of the important types of stresses affecting biomass production and people livelihood in dry areas (Jouanjean et al., 2014). In India extent of land degradation due to wind erosion, chemical deterioration and water logging is 4.1%, 4.2% and 3.5%, respectively (Majhi et al., 2010). A rapid rise in water table because of intensive irrigation as well as seepage of water by canal system is further augmenting the proportion of salt affected area. Wind erosion which includes loss of top soils, terrain deformation and overblowing is a major threat in the dry areas of many of the world's regions including the grasslands, where moving sand dunes ruin the fertile lands (Mesbahzadeh and Ahmadi, 2012). Soils from the degraded lands enter into suspension and become part of the atmospheric dust load. Dust obscures visibility and pollutes the air and water, causes automobile accidents, fouls machinery, and imperils animal and human health. In most of the cases, reduction of clay content, water holding capacity, field capacity, organic carbon, available phosphorus, total nitrogen, exchangeable Mn and Fe coupled with reduction of number of perennial plant species and their density, and increase in exchangeable Ca, Mg, Na, electrical conductivity, pH and exchangeable K and Zn are indicators of deterioration of ecosystem (Panchal and Pandey, 2002). Rehabilitation is the restoration, repair or stabilisation of a degraded system to as natural a state as possible. Stabilization is ensuring that sediment contained in a system is maintained and that loss caused by human activity is minimized.

2. WIND ACTION

Eolian landforms are common in many regions of the earth where erosion and deposition by wind are the dominant geomorphic forces shaping the face of the landscape. Dry regions of the earth are influenced by wind that include arid deserts (**BW**) and semiarid steppe (**BS**) according to the ***Köppen Climate Classification Systems*** **(**Kőppen, 1936). Wind causes erosion and deposition in environments where sediments have been recently deposited or disturbed. These environments include lake and ocean coastline beaches, alluvial fans, and agricultural fields where topsoil has been disturbed by cultivation. Wind and water erosion are the widest spread problems of environmental degradation since the second half of the nineteenth century, specifically in the areas with contrasting seasonal climate and increased human activities (Bakker et al., 2007; McTainsh et al., 2011). Wind erosion is the phenomenon of transportation of worn-out soils and their accumulation in any other place by the action of wind (Acar and Dursun, 2010). He et al. (2011) observed highest climate factor index of annual wind erosion in summer and lowest in winter, where climate factor index has a very good exponential relationship with the wind speed.

The aeolian process is divided into three stages like erosion, transportation and deposition, starting when the wind moves a particle from rest and carries it for some distance. Further, sand grains move in three different modes based on their grain sizes (Table 6.1). For example coarse grains move slowly down-wind by creeping while the fine grains move in suspension where sand particles remain for long distances suspended in the air. The third and most important mode of movement is the saltation where sand grains are unable to remain in suspension and fall on the ground. In their fall they bombard other particles to move in definite trajectories to hit other grains to move. Sand grains may escape the dune bodies and move between dunes as drifting sand. The speed of the drifting sand depends on several factors including the textural sand characteristics, grain size and shape, wind characteristics, and topography. Wind speed, direction, cohesionless soils, large exposed area and lack of soil protection lead to wind erosion (Chepil and Woodruff, 1963). Thus sand drift and dune forms are influenced by topography, roughness, soil types, soil particle size, lacking of vegetation and low soil moisture content.

Table 6.1 Susceptibility of soil particle sizes to wind erosion.

Particle diameter (mm)	Wind Susceptibility
0.42	Highly erodible
0.42 to 0.84	Difficultly erodible
0.84 to 6.40	Usually non-erodible
> 6.40	Non-erodible

2.1 Process of sand dune formation

The origin of sand dunes is very complex, but three essential prerequisites are: i) an abundant supply of loose sand in a region generally devoid of vegetation, i.e. ancient lake bed or river delta; ii) a wind energy source sufficient to move the sand grains; and iii) a topography whereby the sand particles lose their momentum and settle out (Goudie, 2008). Sand is transported by three different mechanisms. Suspension accounts for 5% of the transport and involves very small particle sizes (100 µm). Almost 75% of the sand travels by saltation, a trajectory movement for medium sized particles, whereas large particles move by surface creep and represent 20% of the transported sands (Bagnold, 1971). Dunes first begin their life as a stationary mound of sand that forms behind some vertical obstacle. When they reach a certain size threshold they continue growth with active surface migration. In a migrating dune, grains of sand are transported by wind from the windward to the leeward side and begin accumulating just over the crest. In this process, the dune migrates over the ground because sand is eroded from one side and deposited on the other side leading to cause the appearance of the dune to take on a wave shape. Active movement of sand particles across the dune causes windward slope to become shallow, while the leeward slope maintains a steep slope known as slip-face. Sand movement is highly affected by geomorphology, vegetation, shapes and height of terrains, and the grain sizes of the sand and wind energy. The most important factors that affect sand movement are:

- Wind speed of a minimum of > 4 km/hr is needed for sand transport.
- Sand particle size, as heavy particles creep on the soil surface, while fine and very fine sand (0.25 to 0.05 mm) fly in suspension.
- Terrain type is important factor as sand transport is rare on a sand sheet with near-surface seawater because of wet surface.
- Vegetation cover increases surface roughness, thus decreasing surface wind speed.

- Groundwater at shallow depth resists sand dune advancement.
- Precipitation directly affects surface hardness and vegetation growth.
- High temperature, dry sands and high wind speed have important bearing on sand drift as high temperatures increase the mobility of sand particles.

Landscapes created from wind erosion consist of loose sand and various forms of sand dunes (Yaping, 2008). This process occurs throughout the world, even in the wet and humid areas and creates serious impacts (Alghamdi and Al-Kahtani, 2005). The risk of wind erosion is lower than water erosion but greatness and aspects of wind erosion is higher than water erosion globally (Refahi, 2009). Loss of soils and nutrients increases with increase in wind velocity (Santra et al., 2013). For every 1000 kg soil eroded by wind, there is loss of 15 kg organic matter, 227g available nitrogen, 262 g available phosphorus and 120 g available potassium (Gao et al., 2014). Important characteristics of dune sands are extremely low natural moisture content ranging between 0 and 3–4%, because of the infrequent rainfall, deep water table and high capacity of evaporation in the region. The coefficient of permeability is in the range of 3.4×10^{-4} to 1×10^{-2} cm/s (Al-Sanad et al., 1993; Yuan et al., 2008; Al-Taie et al., 2013), indicating a predominant free draining soil, i.e., water can permeate down directly into the sand bed because of low moisture holding capacity of these sands. The maximum water absorption value of these soils does not reach more than 1% (Yuan et al., 2008; Al-Ansary et al., 2012). The particle size for aeolian sands has been found in the range 0.08–0.80 mm or even between 0.08 and 0.40 mm. Likewise specific gravity of aeolian sands range from 2.44 to 2.87 and increased specific gravity making the sand an excellent fill material (Elipe and López-Querol, 2014).

2.2 Types of dunes

Sand dune type deserts and sand cover only about 20 percent of World's deserts. Inventory of deserts define five types of dunes: crescentic, linear, star, dome and parabolic, but there are some sub-types of these major types (Pidwirny, 2006). Sand dunes form however, related to availability of sand sediment and vegetation status, evaporation and precipitation in an area and the intensity and variety of available wind (Lancaster, 1995; Fig 6.1).

Sand burial rate generally vary widely like 3-10 m per annum in Taklimakan Desert, and depends on the landform types, dune position, wind speed and dune density (Han et al., 1993; Wang et al., 1999). Though wind speed of 2-4 m/s and 4-6 m/s also leads sand drift in some of the region, where later one is most degenerative wind (Rahdari et al., 2014), but a wind speed of a minimum of 6–8 m/s is needed for sand transport in most of the region. Crescentic is the most active dune and the crescent is generally wide than long and is also known as barchans or transverse dune (Table 6.2). Straight or slightly sinuous sand ridges, which are much longer than wide are called linear dunes. Star dunes are radially symmetrical and pyramidal sand mound with slipfaces on three or more arms that radiate from the high center of the mound. Dome dunes are rare but are oval or circular mounds that generally lack a slipface and occur at the far wind margins of sand seas. Parabolic dunes are U-shaped mound of sand with convex noses trailed by elongated arms. The average rate of dune movement ranges from 5 to 15 m depending on the dune height (Philip et al., 1992), the smaller the dunes faster the movement. Linear and crescentic dunes are the main dune types in the Sahara, which form sand seas. Star dunes occupy smaller areas within the sand seas especially in Algeria and Libya (Breed et al., 1979).

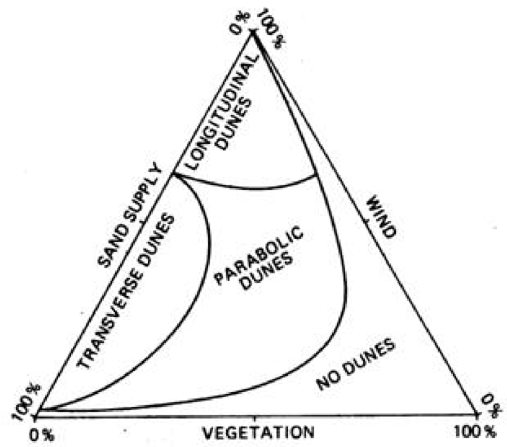


Figure 6.1 Effect of sand supply, vegetation and wind speed on types of dune formation (Source: Hack, 1941).

Table 6.2 Major types of sand dunes throughout the world.

Dune type	Description
Barchans dune	These are crescent-shaped dune whose long axis is transverse to the dominant wind direction. The wings of the Barchan dunes are curved downwind and enclosing the slip-face partially. These are formed where there is a limited supply of sand, generally on flat ground, and a fairly even flow of wind from one direction. It has single slipface.
Transverse dune	These dunes are long asymmetrical that form at right angles to the wind direction. These are formed when there is an abundant supply of sand under low wind velocity. These dunes have generally a single long slipface.
Parabolic dune	Crescent-shaped dune whose long axis is transverse to the dominant wind direction, but the points of this dune curve upwind. It has multiple slip-faces. In general, these dunes are formed when scattered vegetation stabilizes sediments and a U-shaped blowout forms between clumps of the plants or vegetation.
Barchanoid Ridge	It is a long, asymmetrical dune that runs at right angles to the prevailing wind direction. A barchanoid ridge consists of several joined barchan dunes and looks like a row of connected crescents. Each of the barchan dunes produces a wave in the barchanoid ridge. It occurs when sand supply is greater than in the conditions that create a barchan dune.
Longitudinal	These are sinuous dunes and are more than 100 kilometers long and 100 meters high. These are created when strong winds from at least two directions occur. The dune ridge is symmetrical, aligned parallel to the direction of prevailing wind, and has slipfaces on either side.

Dune type	Description
Seif	A sub-type of longitudinal dune that is relatively shorter and has a more sinuous ridge.
Star Dune	These are large pyramidal or star-shaped dunes with three or more sinuous radiating ridges from a central peak of sand. This dune has 3 or more slipfaces because of variable wind directions. In general this dune does not migrate along the ground, but does grow vertically.
Dome	These are mound of sand that are circular or elliptical in shape and have no slip-faces. This may be formed by the modification of stationary barchans and deposition of sand at the same place.
Reversing	These dunes are intermediate between a star and transverse dune. Ridge is asymmetrical and has two slip-faces in general.

2.3 Wind Erosion in western India

About 75% area of western arid Rajasthan is affected by wind erosion of different intensity, 13% area by water erosion and another 4% is affected by salinity and water logging. Soils of arid region are low in organic matter and have low levels of fertility (Ram and Sen, 1992; Singh et al., 2007). The soil is sandy and high wind velocity occasionally lead to dust storms (Narain et al., 2000). Wind erosion results in sand drifting and dune formation because of sparse natural vegetation cover and dominantly sandy terrain (Singhvi and Kar, 2004). Decreasing rainfall and soil moisture gradient from east to west and increasing wind strength in the same direction, along with the high erodibility of aeolian sediments determine the spatial pattern of wind erosion and deposition of sands in the nearby water bodies (Kar, 1993; NIH, 1997). Parts of Jaisalmer, Barmer and Jodhpur have very high erosion potential that results in dune formations of varying shape and size (Plate 6.1). The area between Barmer and Nagaur/Bikaner has moderate to high erosivity, whereas the rest of the area in the east and north, including Jalore, Pali, Sikar, Churu, Suratgarh and Ganganagar shows low to very low erosion potentials (Figure 6.2).

The minimum daily wind speed that initiates sand movement is 4 km h^{-1} and sand movement increases rapidly beyond 9 km h^{-1} wind speed, and become very high over 14 km h^{-1}, whereas sand grains up to 0.2 mm size are eroded at the wind speed of 46 kg m^{-2} h^{-1} (Ramakrishna et al., 1990). The minimum threshold velocity is 5 km h^{-1} at Bikaner and 10 km h^{-1} at Jaisalmer (Gupta et al., 1981). The rate of movement of an isolated barchans dune of 2.25 m height has been reported to be 1.70 m in 3 days of sandstorm with an average wind speed of 29 km h^{-1}, i.e. 0.57 m per day (Kar, 1994). In Pakistan border area of Bikaner, the mean dune shift during 2010 and 2011 was estimated to 1.25 m (Sam et al., 2015). A maximum sand transport rate of 530 kg m^{-2} day^{-1} was recorded from the crest of the dune during a windy (wind speed of 6.9 m s^{-1}) day in April 1989 (Ramakrishna et al., 1994). The soil loss however, vary with wind speed and vegetation status as during the high wind regime of summer 1990, Gupta (1993) recorded a soil loss of 1449 tons ha^{-1} from bare sandy plain compared to 22 tons ha^{-1} from a crop field with a cover of 45 cm tall pearl millet stubble at Bikaner. Sand storm with a mean wind speed of 20 km h^{-1} eroded 273.7 kg soil ha^{-1} day^{-1} from a bare sandy soil at Bikaner, 15.6 kg soil $ha^{-1}day^{-1}$ from a loamy sand soil with clod formation characteristic at Jodhpur and 76.7 kg soil ha^{-1} day^{-1} from a sandy soil with grass cover at Chandan near Jaisalmer (Gupta, 1993). Increase in vegetation cover from 4.3 to 17 % decreased the average rate of advancement of dunes from 3.4 m $annum^{-1}$ to 1.9 m $annum^{-1}$ (Tsoar et al., 2002). In contrary, deep ploughing of fields using tractors facilitates soil loss heavily, while the soils under 8-12% cover of natural vegetation are protected (Dhir et al., 1992).

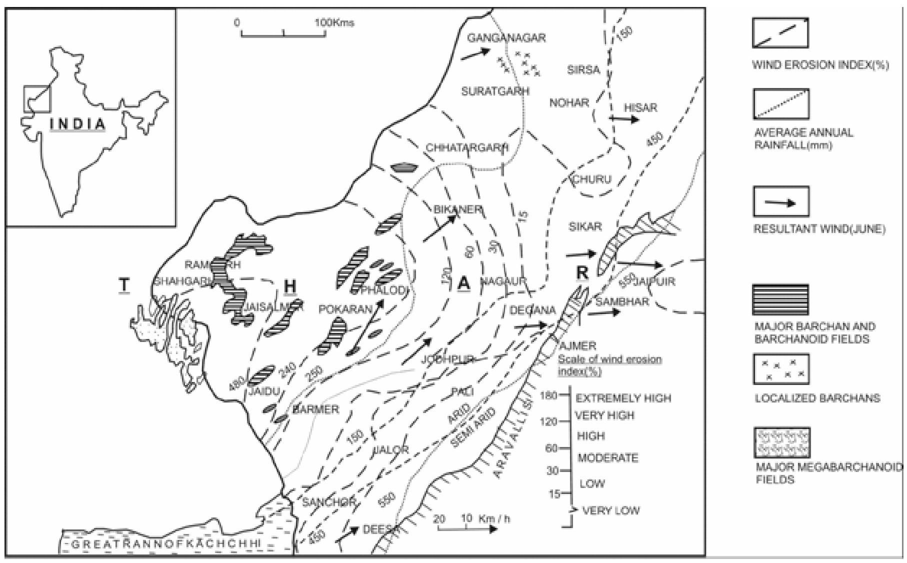


Figure 6.2 Spatial pattern of wind erosion index in the Thar Desert indicating wind erosion index, annual rainfall and mobile crescent dunes (Source: Sighvi and Kar, 2004).

The sand sheet or the sandy plain is developed over a large tract and is gently featureless, undulating with tabular deposit of sand ranging from a few cm to several meters in thickness (Grover, 2012). Strong summer monsoon wind results in various types of dunes depending upon age and structure of the dune. The earlier study defined only four types of old dune in Indian desert, e.g. parabolic, linear or longitudinal, transverse and major obstacle dunes (Singh, 1982). The recent studies however, describes compound parabolic in Shergarh area, linear or longitudinal in Drishadavati in the north east Thar, transverse along Indo-Pak border, star like dunes in Mohangarh and Suratgarh areas, barchans or megabarchanoids and network dunes with height ranging from about 2 m to 50 m or more in different locations (Wadhawan and Sural, 1992; Kar, 1993). The longitudinal dunes run in NNE-SSW direction, i.e. parallel to the prevailing winds and occur in the form of parallel to sub-parallel sand ridges (Kumar et al., 1993). Sometimes these dunes merge to form Y-shape coalesced longitudinal dunes. The transverse dunes align across or perpendicular to the prevailing wind direction and occur over large areas in the eastern and southern parts of the Thar Desert (Kar et al., 1998). The parabolic dunes are 'U' to 'V'-shaped sand ridges with elongated arms and convex crest against wind direction. These dunes are developing in sand sheet areas having some moisture and vegetation. However, establishment of vegetation on the crest changes the dynamics of transverse and barchans dunes. Trapping of sand by plants results in a change in the shape of the windward slope from convex to concave (the dune gradually becomes parabolic). The compound parabolic dunes get elongated and finally change to linear dunes (Grover, 2012). Barchans dunes show concave sides facing the wind and are predominant in the central part of 'Thar Desert' (Fig 6.3).

Figure 6.3 Barchans dues are fastest moving dunes affecting most of the area.

Obstacle dunes are developed at many places where the wind velocity decreases and the sand carried by wind gets deposited due to obstruction, particularly hills, buildings and bushes. These are present on either side of the hill. These are generated by low sand deposition by winds. The best sand streak zones are seen in north and northeast of Sambhar Lake. However, about 48% of the total area of western Rajasthan is covered by sand dunes as compared to 52% and 58% reported earlier. Such decrease in sand dune area appeared to be due to leveling of dunes for cultivation in Ganganagar, Hanumangarh and other irrigated areas, transport of sands as building and fillings materials etc.

3. CONTROL MEASURES

Frequent strong winds and low P: PE ratios allow destabilization of soil, particularly through human disturbance. Tillage activity is much erosion prone leading to soil loss up to 2837 tons ha^{-1} from ploughed area as compared to only 207 tons ha^{-1} from the long fallow (Kar et al., 2009). Reduction in tilling seems to be beneficial in controlling soil loss and land degradation. Remote sensing data covering various dune regions of the world however, indicates no major changes in desert dune orientations since last three decades (Varma et al., 2014). The problems of wind-blown sand can be dealt by four different ways like:

(i) Enhancing sand deposition by use of ditches, fences or tree belts;

(ii) Enhancing sand transport, using streamlining techniques like creation of smooth texture over the land surface, or by erecting panels to deflect the air flow;

(iii) Reducing the supply of sand upwind using surface stabilizing techniques like fences or vegetation; and

(iv) Deflecting the moving sand to other side using fences or tree belts.

The movements of dunes can be tackled through three approaches: (i) by removing them mechanically, which is relatively difficult; (ii) by dissipating them using reshaping, trenching or surface stabilization techniques; and (iii) by immobilizing them through altering their aerodynamic form by surface stabilization or by using fences. Various methods and materials used in wind erosion and sand drift controls are summarized, which vary in cost also (Table 6.3).

Table 6.3 Sand drift control methods in the different countries in the world.

Country	Location	Method	Material/species used
India	Thar desert	Chemical stabilization	Polymer concret compsits, bentonite and lime
	Barmer	Afforestation and aerial seeding	Acacia, Calligonum, Prosopis, *Colophospermum mopane*, Ziziphus, Cassia, Cenchrus, Lasiurus, Citrullus etc
	Thar Desert	Biological stabilization	Acacia, Calligonum, Prosopis, Ziziphus, Cassia
China	Gansu Provence	Sand shielding	Chemical mulching, use of water
		Afforestation and aerial seeding	Pinus, Salix, Populus, Calligonum, Amorpha
	Cele County	Biological stabilization	Shrubs
		Vegetation	Tamarix, Populous, Albania
Pakistan	Mastung Valley	Chemical stabilization	Clay, mud, petroleum products
		Afforestation	Tamarix, Calligonum, Comosum.
Iran	Khuzistan and Khorasan	Physico-chemical	Petroleum mulch, wind breaks, checkerboards, etc
		Biological	Haloxilon, Atriplex, Calligonum, Artemizia, Tamarix
UAE	Al Khatim and Bida Zayed area	Sand shielding	Leveling, crude oil, wood fibers, sandstill
		Vegetation	Haloxylon, Tamarix, Zizyphus, Acacia, Calligonum
Kenya		Vegetation	Acacia-Indigofera
Libya	Tripolitania	Vegetation	Acacia, Tamarix, Castor, Robinia, Eucalyptus, Pinus
Occupied Palestine	Negev desert	Sand shielding	Biological crusting
USA	Michigan	Vegetation	Grass, shrubs, trees
	Federal Highways	Shielding	Stone mulch
	North Carolina	Vegetation	Bare-root seedling and grass

In China, the areas of sand dune activity have decreased during the second half of the 20th century due to a slight increase in precipitation during the early spring season making the water available for grasses and other annual herbs, when the strongest wind occur (Cordova et al., 2005). The minimal increases in moisture led to the reduction of most active dune as they stabilized with grasses, sage, and shrubs. In little Sahara State Park also, there is relatively rapid stabilization, where fully active sand dunes in 1937 had now been stabilized and vegetated by sages, tall and short grasses, yuccas, and sand plum shrubs. Although sand dune stabilization has increased in recent decades, the question of the fate of the dunes in a major drought still lingers (Cardova et al., 2005). There is significant decrease in the wind velocity, sand drift potential and sand transportation rate with increasing vegetation coverage (Mao et al., 2014). Wind erosion volume per unit area and vegetation coverage follow an exponential function relationship in natural conditions, while wind deposition volume per unit area does not conform to any functions, which has close relationship with topography and arrangement patterns of vegetation besides vegetation coverage (Mao et al., 2014). Vegetation is observed as the decisive factor for controlling wind erosion; but the inhibiting effect of vegetation height on wind erosion is greater than that of the vegetation coverage (Gao et al., 2014). Protection of vegetation cover and restoration of degraded land are two fundamental approaches to control wind erosion and sand drift in the region. Stabilizing a dune to control the sand drift and its movement could be achieved chemically, mechanically or biologically. Kerr and Nigra (1952) presented six different methods of sand drift control that are employed singly or in combination to control aeolian sand. These are (i) transposing, (ii) planting, (iii) paving, (iv) paneling, (v) fencing, and (vi) oiling. Sand drift control and stabilization could be temporary or permanent. Accordingly, different methods have their own advantages and disadvantages.

3.1 Temporary measures of sand drifts control

Temporary sand drift control measure is used at an initial stage during the application of a permanent control method in general. The main function of it is to control the moving dunes or sand drifting during the installation of a permanent system. This may include shielding the ground with fixing material (Abdel-Salam, 1984), erection of fences (Willets and Phillips, 1978; Phillips and Willets, 1979; Alhajraf, 2002) or windbreak. The material used in this system should be cheap and locally available vegetation like *Crotalaria burhia* and *Leptadenia pyrotechnica* etc.

3.1.1 Shielding of the sand

Sand shielding is done by different means and includes stone mulching, water/brines or wastewater wetting, chemical stabilizing or biological crusting. Sand shielding methods also involve covering of the ground by plastic sheeting, nets, geotextiles, cloth, etc.

3.1.1.1 Stone Mulch: Stone mulching often used in deserts. Fixation of the surface of active sand dunes are being done by using stones on the sand dune surface, or constructing trenches on the canal banks to protect from the dangerous mobile blown sands (Abdelmoaty et al., 2011). A 25 mm thick layer formed of gravel smaller than 13 mm can resist wind velocities up to 137 km per hr. In this gravel, stone or crushed rock blankets are used as the mulches. The Egyptian Desert Institute (1983) has recommended the use of gravel with diameter greater than 2 mm like fine gravel of about 20 tons per acre, medium gravel of 50 tons per acre and crushed rock or clay of about 100 tons per acre. In case where establishment of vegetation is almost impossible the uses of stone mulch as permanent sand control measure is generally recommended. To make it more effective the required particle size distribution are:

- Gravel smaller than 4 cm 100%
- Gravel smaller than 2.5 cm 60-90%
- Gravel smaller than 0.6 cm 0-20%

Permanent erosion resistant ground cover of large loose, angular stone with fabric or granular underlining to protect soil from erosion losses called 'rip rap' is also used at places. In this pebbles, macadam, and other materials cover the surface to a thickness of upto 2-3 cm in a checkerboard-style pattern in lengths of 1m × 1 m or as appropriate. Here the leeward side of the embankment covered to a width of 10 m with sufficient length and at a distance of about 200 m from the railway line/roads observed to be rugged, durable, and able to resist wind and heat, and retain water (Chen, 2004). Alternatively, a semi-concealed sand barrier with a grid-like surface is filled with rubble on the leeward side of the embankment, with a width of 10 m with sufficient length and 150 m from the line. It has been observed effectively reducing the surface wind speed in different directions, fix the *in situ* sand surface, and also prevent sand from other places depositing around the barrier (Yang et al., 2012). Boulder Net installed on the slope also helps prevent boulders from falling into railway track or roads. In order to create a dense barrier using stone, the scientists of Mangolia estimated the average sand flux amount and the physical process of the wind that was considered to be the main factor in sand movement. For this reason, the dense barriers were placed on a slope inclined at less than 10°. It had been found that all types of barrier are effective to some degree in fixing sand. The efficiency of the stone barrier is more dependent on the position of sand dune and less influenced by the height, which in some cases showed negative influence by increasing the blow out rate.

Gabion mattresses are used to stabilize costal dunes from erosion, and made from polypropylene rope basket of 1m × 2m × 0.5m or 1m × 1m × 0.5m interconnected to form monolithic structures. Different types of gabion structures for beach erosion control are Gabion mattress, Gabion Groynes and Vegetated Gabions. Because of flexibility, Gabion mattress has the ability to endure excessive deformation without failure in case of excessive subsidence, scouring or dynamic loading. Since the gabion walls are permeable (30-40% voids) in nature, it prevents the hydrostatic forces from developing and helps in dissipating the wave energy instantly (Dias et al., 2011). In addition they have a positive impact on the environment and are harmless to microorganisms and biological communities in proximity. Structures built using flexible systems can sustain settlement and deformation very effectively with lighter design section, without requiring elaborate foundation treatment.

3.1.1.2 Chemical Stabilizers: The chemical industries produce a variety of chemicals that can be used as stabilizers to control erosion until a permanent control system is applied. Vinyl, asphalt, rubber, red-mud or clay liner, ceramic tile waste, mixture of bentonite and lime anionic and nonionic polyacrylamide (PAM), and biopolymers are examples of chemical stabilizers that are sprayed onto an exposed soil surface to hold the soil in place and minimize erosion losses (Kalkan, 2006; Fabre et al., 2010). In the last few years, considerable research has been conducted to examine different types of chemical additives and their potential as sand stabilizing agents. Different methods of stabilization have been reported in the literature including the use of cement (Aiban, 1994; Al-Aghbari and Dutta, 2005; Moosavi and Kalantari, 2011; AlKarni and, ElKholy, 2012; Ghrieb et al., 2013), cement kiln dust (Baghdadi and Rahman, 1990; Al-Refeai and Al-Karni, 1999; Freer-Hewish et al., 1999; Albusoda and Salem, 2012), bentonite and lime (Wayal et al., 2012; Panwar and Ametha, 2013), bitumen emulsions (Al-Abdul Wahhab and Asi, 1997; Asi et al., 2002), polymer emulsions (Lahalih and Ahmed, 1998; Al-Khanbashi and Abdalla, 2006; Zandieh and Yasrobi, 2010; Homauoni and Yasrobi, 2011), polypropylene fibers (Santoni and Webster, 2001; Parto and Kalantari, 2011) and even, waste (Mohamedzein et al., 2006; Mohamedzein and Al-Aghbari, 2012; Ametha et al., 2013). Chemical soil stabilizers can be used in areas where vegetation cannot be established, or on rough grading, cut and fill areas, temporary stockpiles, temporary or permanent seeding, or for site winterization, dormant seeding in the fall, staging areas, or other disturbed soils. Saudi Aramco used about 300,000 bbl/year of heavy crude oil tar-oil for general purposes including sand control and berm stabilization, where oil stabilization was observed to be most effective in large areas (Asi et al., 2002; Alghamdi and Al-Kahtani, 2005). Use of emulsified asphalt in stabilization of sandy clay loam soil reduces the erosion rate by 61.58%, 72.42%, and 86.14%, respectively at the asphalt use of 60 cm^3 per sq m, 80 cm^3 per sq m, and 100 cm^3 per sq m (Bunga, 2012). Application of PAM creates an electrochemical reaction that draws fine particles close together, forming larger particles which are more resistant to erosion and large enough to settle from suspension (Cohn, 2001). Use of biopolymer mixtures like Xanthan gum produced by *Xanthomonas campestris* (Sutherland, 1994; Ay-Eldeen et al., 2015), and polymers concrete composites (Gopal, 2006) are viable soil improvement measure for short-term wind erosion control and it can be effective as sand dunes stabilizer, specially to protect the irrigation channels/canals. Vehicle mounted and air-borne mechanical spraying systems and grouting techniques for polymer concrete composites are used for construction of chemically stabilized temporary (50 m × 30 m) and semi-permanent helipads (50m×50m), experimental road (50m×4m) and other civil structures in Indian Desert (Gopal, 2006).

The process consists of applying portland cement and sand mixed together and blown onto the sand surface known as 'guniting' is also helpful in sand drift control. The equipment consists of mixers for blending cement and sand with or without the addition of a small quantity of water. At the nozzle or the exit port for the mixture, water is introduced to make a slump mortar for effective surface binding. Though this is expensive, but the use of clay is effective in sand drift control, where blankets of clay 10 to 15 cm thick are spread over the unstable dune sand, after which permanent seeding (seed sowing) or plantings can be made. Sand dunes with slopes flatter than 1 to 3 are stabilized with relatively small amounts of gravel or crusher waste. The important thing is to make complete coverage with materials not subject to movement by the wind. While a 5 cm cover is used on 1:3 slopes, a 10 cm cover is used on steeper slopes (Stoesz and Brown, 2012). For right ingredient and treatments, clay samples are mixed with sand and different amount of water, and sprayed on sand dune bed. For example, the mulch treatments like (1): 250 g dune sand + 250 g clay + 25 g straw; (2) 250 g clay + 25 g straw; (3) 250 g sand + 250g clay; (4) 250 g clay; (5) 125 g sand + 125 g clay and (6) 125 g clay mixed with 500 ml water. Addition of wheat straw adds resistance to erosion (Majdi et al., 2006). The added stability of mulch is due to the increase in mulch thickness and also due to increase in clay and silt content. The mulch with two layers and higher mixture of clay and sands has been found the best for the stabilization of sand dunes. Use of cement kiln dust (CKD) in sand dune stabilization has also been tested (Albusoda and Salem, 2012). Stabilization of collapsible soils with CKD provides tremendous economical advantages too (Aiban, 1994).

3.1.1.3 Biological Crusting: Availability of water in arid ecosystem governs the survival and survival strategies of plants and animals (Dadheech et al., 2012). Dewfall is a process whereby moisture from the atmosphere condenses on the earth's surface. The frequent occurrence of dew can serve as an important source of moisture for biological crusts, which can contribute to the stabilization of sand dunes (Danin et al., 1989). The crust so formed by biological activity of blue-green algae promotes the stability of the sand dunes. However, Kidron et al. (2003) studied micro-biotic crust control of runoff generation on sand dunes, where concentrations of chlorophyll *a* and carbohydrates of the cyanobacterial crusts showed positive linear relationships with runoff coefficients, but a significant reduction in runoff yield was obtained once the moss-dominated crust inhabited the wettest habitat within the dune field. However, there is large seasonal variation in developing biogenic crust covers that are not necessarily related to the growth of new crust but rather to the exposure of old crust buried under the deposited soil layer (Amir et al., 2014).

3.1.1.4 Use of geotextile covering: A geotextile is defined as any *permeable* textile material that is used with foundation, soil, rock, earth, etc to increase stability and decrease wind and water erosion. A geotextile may be made of synthetic or natural fibers. Geotextile-related materials such as fabrics formed into mats, webs, nets, grids, or formed plastic sheets are not the same as the geotextiles. Geotextiles have historically been made of natural plants; modern geotextiles however, are usually made from a synthetic polymer (such as polypropylene, polyester, polyethylenes and polyamides) or a composite of natural and synthetic material. Plant fibre-based erosion control geotextiles like jute, wood fiber, paper or cotton are subject to decomposition and have a limited shelf life and on-site use of these blankets degrade in a way that can produce an ineffectual installation. On the other side, the synthetic polymers have the advantage of not decaying under biological and chemical processes, but being a petrochemical-based product they use non renewable resources in their construction, and cause environmental pollution in their manufacture and use, and have associated health risks. When spread on the sand surface, it protects the surface from raindrop impact, wind and stormwater erosion and allows vegetation to grow (EPA, 2008). Geotextiles are also used to stabilize the flow of water in channels or swales, to protect seedlings or vegetation, to protect exposed soil, or to separate soil from other slope stabilization treatments (EPA, 2008). The other erosion-control netting options are use of biogeotextiles mates of leaves of different species including leaves of Borassus spp. (Jankauskas et al., 2012). Use of vinyl and iron nets for establishing a low-density barrier is also effective. Geotextiles are also superior to hydroseeding in conditions:

- When the growing season is short and plants cannot stabilize the slope quickly.
- At high altitudes with less access.
- Where major storms are a frequent occurrence.

Synthetic geotextiles are used in situations where hydroseeding would be a far more appropriate choice. Because of the ease of use and low maintenance the use of geotextiles is now common (Gratzfeld, 2003). Natural fibre geotextiles degrade to form organic mulch and help in quick establishment of vegetation. Different fibres will degrade at different rates, i.e. coir geotextiles degrade in 2-3 years while jute degrades in 1-2 years. Coir is therefore useful in situations where vegetation will take longer to establish, and jute is useful in low rainfall areas because it absorbs more moisture. In arid and semi-arid areas the action of the wind causes considerable erosion. Thus geotextiles made from natural fibre such as coir, or jute can be used for wind erosion control, dust control, sand dune formation and stabilization. Jute is particularly useful for dust control because of the hairiness of the fibres. More important is spreading of geotextiles that should be carried out in such a way that it has continuous contact with the soil surface, or where erosion can occur. Geotextiles can also be pinned in place with stakes made up of wood, metal, corn plastics, or live cuttings. Biodegradable fiber materials should be preferred to minimize any potential disturbance to wildlife.

3.1.2. Fences or windbreaks

Sand fences or windbreaks are vertical barriers that disrupt wind flow across a surface, causing wind-borne sand to deposit just downwind of the windbreak and are mechanical measures used in sand dune stabilization and appear cost effective (Nordstrom et al., 2000). These are commonly composed of vertical wood slats, plastic netting, or biodegradable fabric. Many studies have shown that windbreaks help in the restoration of degraded sea beach landscapes (Mendelssohn et al., 1991; Miller et al., 2001; López and Marcomini, 2006) and other geomorphic features, namely steep dune blowouts (Bleeker et al., 2013). Corrugated metal plates of 1.5 m and 2 m high, constructed soil ridges (i.e., dykes), brushwood and synthetic materials vary in cost like low-cost strawberry netting to expensive polypropylene, nylon, or composite wire/synthetic webs. Chestnut paling fence is commonly used for dune management in England as it is widely available and shows good life expectancy of 2-5 years (Scottish Natural Heritage, 2000). Fence characteristics, as well as windbreak placement, play a critical role in determining the subsequent morphology of sand deposits and the vegetative communities that survive on them (Grafals-Soto, 2012). Many researchers prefer to use mechanical barriers for fugitive dune fixation. Three different types of mechanical barriers are generally tried, which are based on the use of clay, net-materials and stone barriers. Use of clay barrier is developed by Chinese scientists and was tried in an area of transverse sand dunes in the Tenggeri desert in the 1990's. In this, the scientists created triangle walls, approximately 30-40 cm in height, among the sand ripples. This parallel barrier system prevents sand flux along the general wind direction, thus stabilizing sand dunes. Though the fences appear to be effective at reducing aeolian sand movement, but show a limited effect on reducing the overall movement of sand on the active blowout face. Thus to stabilize steep slopes of the dunes, the managers can consider using the fences in conjunction with another technique that reduces the down slope mass movements of the sands. These fences are of several types like (i) Vertical slat windbreak, (ii) Horizontal slat windbreak (sometimes also called a snow fence), (iii) Palm-leaf windbreak also called as a brush or Arabian fence and is similar to the two preceding fences except that palm leaves are used instead of slats; and (iv) Jet windbreak or European fence, which is a vertical-slat windbreak but with tapered slats.

Picket windbreaks are located approximately at right angles to the prevailing winds and cause temporary deposits of sand, but when located at a tangent to the prevailing winds, they direct the sand-laden wind and may cause sand scouring. Two parallel lines of windbreak 30 feet apart are needed to get proper and stable shape in the dune. The pickets are 4 feet long and made from 2.5 to 10 cm lumber. The openings between pickets are equal to the width of the picket. A smaller space caused scour along the windbreak. A greater space allowed the wind to move sand through the fence unstilled. The top of the picket fence is even, because unevenness at the top causes the dune to be uneven. Following are general design criteria for the windbreaks or fences (Alghamdi and Al-Kahtani, 2005).

- The windbreaks should be perpendicular to the prevailing wind direction.
- Because of their brittle behaviour in sun exposure, use of plastic slats can be avoided.
- A vertical slat windbreak has better aerodynamic stability than to a horizontal one.
- Windbreak heights should range between 0.5 m to 2.0 m and without leaning.
- Erection of an extended windbreak is better than adding a new parallel windbreak.
- Location of the windbreaks should be in areas where the creation of a large artificial dune could not pose any problems.
- The optimum porosity should be 40–60% (porosity ratio is the ratio of the space between slates to the slat area) because increases in the porosity to a maximum value, frontal accumulation decreases and backward accumulation increases. Solid windbreak should be avoided.
- Efficiency increases with the decrease in slat width.
- A windbreak can accumulate sand of $10H^2$ m^3 per meter length.
- The recommended aspect ratio length/height should be 40.
- Allow for 10H as a boundary condition end effect. For example, for a facility of 50H width, a fence with 70H width is required.
- Distance to the facility should be at least 100H.
- In case of required gap between two parallel windbreaks, the overlap length must be at least 10H. Here, the suggested bottom gap is 10% of the height, to avoid direct drift accumulation.

- Parallel windbreak may be used for a high rate of drift, where spacing between parallel fences should be 40H. Multiple rows of windbreaks can trap more than 80% of wind-borne sand.
- Windbreaks require regular maintenance and renewal to avoid deterioration.
- Posts should be made of carbon steel pipes, 50 mm in diameter, 3 m long, 3 m apart, and 4 mm in thickness, painted with primary and protective coating. Galvanized or coated wires should be used with gauge 10 or higher.

3.1.2.1 Checkerboard windbreak: The checkerboard windbreaks are constructed of plant remains (straw) or plastic nets in a rectangular pattern similar to the checkerboard (Lihui et al., 2015). A typical checkerboard system is 50-70 cm high forming 3m × 3 m rectangles. This system can withstand weather conditions for few years, and is long enough to implement the permanent solution of sand drift control. For example semi-buried straw checkerboard barriers and porous upright fences show better sand drift control effects (Han et al., 2003). The plastic checkerboard sand barrier, also known as plastic nets, plastic checkerboard-shaped sand barrier or plastic checkerboard sand-barrier net, is one of the new type of sand-fixing materials made up of high-density polyethylene material (HDPE) mostly mingled with anti-aging agents, HALS—3 of stable agents also belongs to the mechanical measure for desert control (Liu and Sunato, 2014). After considering erosion (deposition), sand protection benefits and costs of different sizes of straw fences (1 m × 1 m, 1.5 m × 1.5 m and 2 m × 2 m) and slope positions (toe, middle and top of the windward areas), large size at the toe and medium size at the middle of windward slope are the most practical combinations, while small size is suitable to play an emergency treatment role in some extremely serious hazard areas (Lihui et al., 2015). However, fence deployment that prioritizes the creation of topographically diverse dunes within a restricted space may increase the diversity and density of the vegetation, and the resilience and value of developed dunes (Grafals-soto, 2012).

Use of mechanical measures like straw barriers and gravel layer covers could promote vegetation establishment on the mobile sand dune by sowing and planting introduced species (Zhimin and Wenzhi, 2001). Li et al. (2006a) evaluated the role of wheat straw established in checkerboard in the process of ecological restoration and its environmental effects. The results indicate that the straw checkerboard enhanced the capacity of dune systems to entrap dust deposition, leading to the accumulation of soil organic matter and nutrients and to the development of soil formation on the dune surface. The straw checkerboard increased the silt and clay content, thereby changing coarse soil texture to fine texture. A significant difference in plant species richness, herbaceous cover, dust deposition, and soil physicochemical properties observed when a straw checkerboard is used to stabilize the dunes before establishing sand-binding vegetation. This suggests the use of the straw checkerboard as key technique for restoring desert ecosystems and could be an important component of efforts to further extend ecological engineering projects in arid desert regions. Using the measured wind data, a monthly average sand transport rate can be calculated and used to determine an effective life span of a 3 m high windbreak. Micro-windbreaks in conjunction with straw checkerboard are recommended to control sand drifts into the Minqin Oasis (Krishnappan and Burrell, 2012). Bamboo fences have been observed the most efficient setup to nourish sand dunes. The newly nourished dunes are then covered with dried giant *Miscanthus* (*Miscanthus floridulus*) which serves as mulches, with Littoral Spinegrass (*Spinifex littoreus*) planted atop for further stabilization and appeared valuable aids for the restoration of barrier beaches in Taiwan (Huang and Yim, 2014).

3.1.2.2 Fore dune windbreak: The fore dune fences or wind break are similar to the vegetation belts except that they are made of palm leaves, wood, fiber glass, concrete, etc. The life of the fence will depend on its material, its porosity, and its surface condition and on the wind energy (Khalil, 2008). The volume of foredunes tends to increase more on wider beaches (Keijsers et al., 2014). The main purposes of such windbreaks are either to reduce the wind velocity or to divert wind direction from the area that needs to be protected. These are categorized into impounding and diversion fences. The impounding fences are made of palm leaves, wood or fiber glass and are usually constructed normal to the wind direction. Multiple rows of fences are relatively more effective as compared to single row particularly at high wind speeds. Porous fences are as efficient as the solid ones as they are more economical, can withstand strong wind and are relatively fast to establish. The porosity of the fence and the arrangement of the spaces affect the percentage of the trapped sand. The individual fence designs have different sand trapping abilities at different wind velocities. Effective control can be achieved either by dispersal of the accumulated sand by the use of the turbulent bar located at the top of the dunes, of by fencing e.g., impounding and diversion sand fences have effective roles in the control of sand movement (Philip et al., 2004).

3.1.2.3 Diversion windbreaks: The diversion windbreaks not only trap the sand but also deflect it away from the area that needs to be protected (Watson, 1985; Abdulmalik and Al-Kahtani, 2005). They are erected either as single windbreak slanted at about 45^o from the wind direction or in the form of a V-shaped windbreaks pointing up-wind. Multiple rows of windbreaks are more effective than single rows. The effectiveness and life span of the diversion windbreaks depends on the material of construction, height and porosity.

3.2 Permanent sand drifts control

The precautionary measures to reduce wind erosion under sand drift control are: (i) maintaining a vegetative cover, either growing plants or crop residues, (ii) reducing cultivated fallow, (iii) reducing or eliminating tillage or selecting a tillage implement that buries less residue, (iv) planting and maintaining field shelterbelts, and (v) avoiding overgrazing. Vegetation development either through seeding or afforestation is considered the only effective and permanent sand dune stabilization with long-term stability option (Jensen, 1985; Pandey and Rokad, 1992). In fact every dune site has its own history and management policy (Provoost et al., 2011). Biological method of sand dune stabilization involves careful plantation of trees, shrubs and grasses and observed more effective as compared to physical and chemical methods (Bofah and Owusu, 1986; Shankarnarayan et al., 1987). The importance of surface growing vegetation are such that as little as 4% vegetation cover could reduce soil loss by 15% compared to bare ground in an area with 356-

915 mm mean rainfall (Fryrear, 1995). However, success of biological sand dune fixation largely depends upon the delicate balance between the availability of soil nutrients/ moisture and their use for biomass production. The problems are scarcity of water, inadequate soil, high temperature and thus high loss of soil water through evaporation. Though most of the sites have enough soil seed bank that re-establish vegetation naturally if the causes of degradation are being managed, but other site may require introduced planting to either accelerate or complement natural growth (Misak and Draz, 1997). For this, there is need to maintain optimum field conditions for wind erosion in a manner and scale that allow it to act as a landscape differentiating process. The process management strategies consist of: (1) an overall management plan for a period of 10-15 years; and (2) a short-term (1-3 years) maintenance plan to keep the erosion potential in the selected deflation zones sufficiently high (Riksen et al., 2008). Process management with scheduled maintenance will result in a more stable drifted-sand habitat in which the typical drift-sand vegetation and fauna species are better able to survive. Revegetation efforts on the sand dunes may have a low survival rate, so planting or seeding may be required in subsequent years too, or after some vegetation has established to provide protection for emerging plants. The success of vegetation control systems will lead to the following results:

- Decrease in the wind speed.
- Protection of the ground from scouring.
- Change in the microclimate in the area.
- Enhanced soil condition for further plant growth.
- Creation of recreational areas.

Different methods are used on the basis of land use and the best plant species, suitable for harsh desertic conditions. Land uses suffering most from desertification are agricultural areas, highways, railways, roads, cities, industrial places and mining areas. Some plant species used for combating desertification in China are *Hedysarum laeve*, *H. scoparium*, *Amorpha fruticosa*, *Lespedeza bicolor*, *Caragara microphylla*, *C. korshinskii*, *Artemisia halodendron*, *A. sphaerocephala*, *Astragalus adsurgens*, *Ulmus pumila*, *Hippophae rhamnoides*, *Haloxylon ammodendron*, *Calligonum mongolicum* etc. where transplanting seedlings, direct seed sowing, use of cutting and air seeding techniques are generally used for greening such areas (Heshmati, 2011). Introduction of undershrubs and grasses along with tree species provides beneficial effects in controlling sand reactivation and drift, particularly, at the time when planted seedlings attain the size of a tree resulting in free air movement under the canopy and reactivation of sand drift. The increased plant height, number of branches, crown cover and crown volume reduces sand drifting by 47.2 to 96.7%. Planting of natural wind breaks/shelter belts, stabilization of sand dunes, minimum tillage, and conservation of rainwater are some of the measures found effective in checking wind erosion. The practices of sand dune stabilization (Muthana, 1982; Harsh and Tewari, 1993; Singh and Rathod, 2002) (Plate 6.2) involve:

(i) Protection of the area under intervention, through windbreaks that keep away livestock and human interferences.

(ii) Creation of micro-wind breaks on the dune slopes, using locally available vegetation like *Aerva pseudotomentosa*, *Crotalaria burhia*, *Leptadenia pyrotechnica* etc or development of live wind break of *Cassia angustifolia* (Plate 6.2) either in a checker board pattern or in parallel strips to counteract sand drift.

(iii) Direct seeding or transplantation of indigenous and exotic species in the centre of the squares.

(iv) Plantation of grass slips or direct sowing of grass seeds on leeward side of the micro-wind breaks.

(v) Management of revegetated sites by effective caring.

Important factors needed to successfully implement afforestation control system are therefore plant species, water availability and site maintenance.

3.2.1 Plant species

The success of plant growth depends on the selection of the species that can survive under the prevailing environmental conditions, water quality and soil condition. Among the species occurring naturally or introduced in arid region of Rajasthan, some of them shows extensive root system to extract water from deep soil profile and redistributes water (Annexure I). For example, a wind exposed root of *Aerva pseudotomentosa* was extended up to 43 feet horizontally demonstrating its capability in resource mobilization for its survival in the region (personal observation). Likewise roots of other species viz., *Calligonum polygonoides*, *Leptadenia pyrotechnica*, *Acacia jacquemontii*, *Prosopis cineraria* etc mines the area many more times than their canopy and deeper soil layers as well. During excavation of a *Prosopis cineraria* tree of diameter at breast height 65 cm, the vertical tap root had penetrated $CaCO_3$ layer (available at 80 cm soil depth) up to 17 feet under sharp tapering, whereas feeder roots showed radial (horizontally in top 30 cm) extension up to 62 feet (Singh, 2014b). This indicates that maintaining rhizome connections in many species of dry regions helps plants to tolerate erosion in drylands and hence selected accordingly. Most plants death is associated with root exposure and sand loss around transplants or burying of the plants with wind deposited sands and appears a regular phenomenon (Petru and Menges, 2004; Liu et al., 2013; Stoffel et al., 2013). The exposed roots or rhizomes may be partly or entirely re-buried (Liu et al., 2006; Ma and Liu, 2008), and exposed again by erosion during the next wind event (Petru and Menges 2004). In such a conditions, species with connected rhizome alleviates the negative effects of erosion (*Psammochloa villosa* and probably other species like *Aerva pseudotomentosa*) very likely because the erosion-stressed ramets received water and/or photosynthates translocated from those connected ramets that were not subject to erosion (Yu et al., 2008). Tolerances to various degrees of sand burial or wind erosion among the plant seedling vary widely among the species (Zhang and Maun, 1990; Danin, 1997; Gilbert and Ripley, 2008; Burylo et al., 2011). Some dunes are created under constant wind direction (Ardon et al., 2009), but wind direction in many other regions is not constant and often varies by seasons resulting in change in position and directions of the dunes. Closer spacing appeared to slow sand loss and plant death for November plantings. Thus selection of the plant type should depend on:

- Quantity and quality of the available water.
- Soil moisture content.
- Salts concentrations in the soil.
- Speed and direction of wind.
- Rate of sand movement.
- Rate of plant growth.
- Capability of the plant to multiply.
- Capability of the plant to enhance the soil condition.
- The root system of the plant.

Use of trees (*P. silvestris* var. *mongolica*) and shrubs (*A. halodendron*, *S. gordejevii* and *C. microphylla*) on cultivated grasslands and enclosed natural vegetation prevent development of shifting sands and ensure transport together with increased vegetation cover from <10% before treatment to 30% to 50%, organic matter content by 6 to 8 times, fine particle content of less than 0.01 mm by 2 to 4 times; and decreased velocity of sand flow by 60% to 70% (Wang and Xue, 2010). A phytosociololgical data on the vegetation of obstacle dunes and sandy plains of area near Ajmer indicated availability of *Acacia senegal, Acacia tortilis* and *Eucalyptus camaldulensis, Acacia leucophloea* and *Maytenus emarginata* (Sharma and Sharma, 2011). Among the cultivated plant species like *Acacia saligna, Prosopis jullflora* and *Morus alba* in sand deposited areas in North Sinai, *Acacia* plants were observed superiors in minimizing of sand encroachment than *Prosopis jullflora* and *Morus alba*. The growth behaviour of *Acacia saligna* and *Prosopis jullflora* were superior to *Morus* species (Gad and Abd-El Hamid, 2011). Several plant species including the genus Tamarix, Prosopis, Acacia, Atriplex, Casuarina, and Calligonum have successfully been used to stabilize dunes in arid areas across the world (Draz et al., 1992; Ndiaya et al., 1993; Draz and El-Maghraby, 1997; Gad, 1999; Singh, 2004a). Prior to vegetation a temporary stabilization using ground shielding is also necessary.

Planting tree only does not serve the purpose of effective sand drift control. Sand dune fixation models have also been designed to prevent the movement of sand long enough to enable either natural or planted vegetation to become established in arid region of western Rajasthan (Kaul, 1985; Singh and Rathod, 2002). Singh and Rathod (2002) planted seedlings of *Acacia tortilis*, *Prosopis juliflora* and *Calligonum polygonoides* species and *Cassia angustifolia* and *Cenchrus ciliaris* were sown to develop undercanopy vegetation. Growth of species differed significantly and *P. juliflora* was the best performer to cover soil in a best way. *C. polygonoides* produced the highest biomass in the form of fuel wood utilizing minimum amount of soil water. *C. polygonoides* with *C. ciliaris* was the best combination for fuel and fodder production, whereas combination of *C. polygonoides* and *C. angustifolia* was best to increase production with additional benefits of sand drift control. Production of *C. angustifolia* was higher with *C. polygonoides* as compared to *P. juliflora* and *A. tortilis* (Singh et al., 2003a). *C. polygonoides* has also been observed as the best neighbour and a suitable planting partner for *C. angustifolia* in promoting the effective stabilization of dunes (Plate 6.3).

A combination of tree, shrubs or grass in sand dune stabilization provides multiple benefits including fodder, fuel wood etc to the villagers. Artificially created corridors of faster wind flow through the belts of planted trees help control the dunes from forward movement (Kar, 1996). Based on natural occurrence and existing literatures, various species of trees, shrubs and grasses have been tested and used for dune fixation (Table 6.4). Among these, shrub species *Leptadenia pyrotechnica* and *Calligonum polygonoides* provide good protection and establishes well with medium irrigation and when protected from sand blasting at early establishment. *Lasiurus sindicus* and *Panicum turgidum* grasses are difficult to establish, but are extremely efficient in settling drifting sand when found in a cluster. *Prosopis juliflora* has reasonable establishment potential and good sand settling properties making it a good choice, whereas *Acacia tortilis* tolerates well hard conditions and is aerodynamically very successful on large scale. Besides, *Prosopis cineraria*, *Tecomella undulata*, *Ziziphus mauritiana*, *Z. nummularia*, *Acacia jacquemontii*, *Calotropis procera*, *Clerodendrum phlomidis*, *Lycium barbarum, Aerva pseudotomentosa*, *Cenchrus ciliaris*, *Dactyloctenium sindicum*, *Ochthochloa compressa* etc. are other important species for sand dune stabilizations.

Rooting pattern of a species also makes the species suitable under stress conditions. Root of *C. angustifolia* penetrates >30 cm within two days and > 1 m in dune sand within a year providing its better chances of survival and sand drift control. The other property of this species is its phenology as it remains green during summer months, when maximum sand drift takes place (Singh et al., 2003a). Likewise, *Hardwickia binata* and *Colophospermum mopane* show deeper roots penetrating even through the hard layer of $CaCO_3$ (Singh and Singh, 2015). This type of rooting is more pronounced in seed sown 9 months old plants of 18 cm height and extended its root to 121 cm penetrating the hard layer of calcium carbonate available at 70 cm soil depth (Singh and Rathod, 2006a). The extent and intensity of available surface vegetation also influence the root growth pattern of the planted seedlings for the best fit survival. Availability of tap root as well as surface spreading roots (>crown spread) in *Acacia tortilis* depended on the existing natural conditions, i.e. only surface spreading roots were observed when grown in a bare dune to exploit surface available moisture. In semi-stabilized dunes, where availability of natural vegetations are relatively less, both tap root and surface spreading roots were observed because of lesser amount of competition imposed by the sparse vegetation. In flatland where competitive effect from surface vegetation, i.e. *Dactyloctenium sindicum,* was high the planted *A. tortilis* showed deep penetrating roots for better access to the deep available soil resources (Fig 6.4).

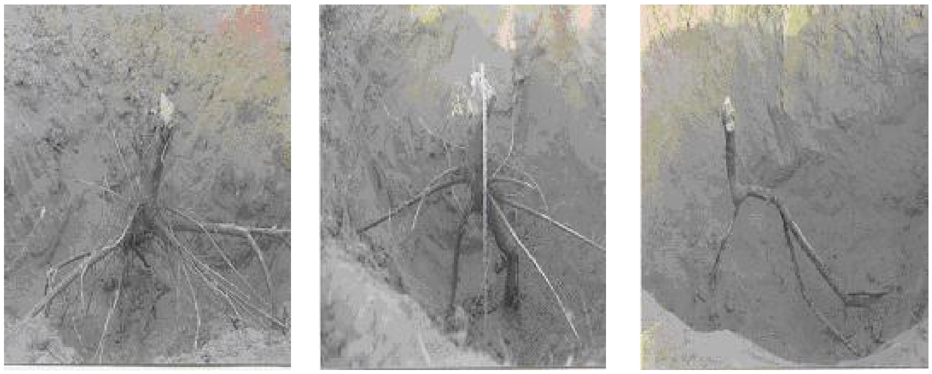


Figure 6.4 Rooting pattern of *Acacia tortilis* planted in bare dune (left), semi-stabilised dune (middle) and flatland (right).

Table 6.4 Plant species suitable for sand drift control in Thar Desert.

Rainfall zone (mm)	Trees	Shrubs/creepers	Creepers/Grasses
150-300	*Prosopis juliflora, P. cineraria, Acacia tortilis, A. senegal, Moringa concanensis*	*Calligonum polyg-onoides, Haloxylan salicornicum, Leptadenia pyrotec-hnica, Aerva persica, A. pseudotomentosa, Zizyphus nummularia*	*Citrullus colosynthis, Cymbopogon jwarncussa, Lasiurus sindicus, Panicum turgidum*
300-400	*A. tortilis, A. senegal, A. nubica, A. planifrons, P. juliflora, P. cineraria, Tecomella undulata, Parkinsonia aculeata, Colophospermum mopane, Cordia rothii, Zizyphus mauritiana*	*Acacia jacquemontii, Z. nummularia, C. polygonoides, H. salicornicum, L. pyrotechnica, A. persica, A. pseudotomentosa Dichrostachys glomerata*	*C. colosynthis C. jwarncussa, Cenchrus ciliaris, C. setigerus, L. sindicus, Desmostachya bipinnata, Saccharum munja*
400-550	*A. tortilis, P. cineraria, P. juliflora, A.senegal, Dalbargia sissoo, Ailanthus excelsa, Albizia lebbek, P. aculeata, T. undulata, C. mopane, Z. mauritiana*	*A. jacquemontii, Cassia auriculata, D. glomerata*	*C. ciliaris, C. setigerus, S. munja, D. bipinnata, P. antidotale*

The deflated interdunes between linear dunes protection measures like compaction of the back-filled material in the trench, first with a mat of *Panicum turgidum* grass and then with a layer of *kankar* provide greater resistance to the high wind in the narrow interdune corridors and along the flanks of the dunes (Kar et al., 2004). Few trees like *A. nilotica, A. indica, H. intigrifolia, S. oleoides, T. aphylla* and *Z. mauritiana* are also growing in this habitat accompanied with *A. jacquemontii, C. procera, C. decidua, C. auriculata, C. phlomidis* and *M. emarginata* shrubs. Other species are *Aerva persica, A. pseudotomentosa, Crotolaria burhia, Tephrocea* *purpurea*, *Lasiurus sindicus*, *Panicum turgidum* and *C. colocynthis.* The species planted in this landform must have good drought tolerance ability, especially during the first two to three years of growth (Table 6.5). Some of these species may also be used successfully in intensive agroforestry systems of the regions.

Table 6.5 Plant species suitable for rehabilitation of sandy plains or interdunal plain in Thar Desert.

Rainfall zone (mm)	Trees	Shrubs/creepers	Creepers/Grasses
150-300	*Acacia tortilis, Prosopis juliflora, P. cineraria, A. senegal, Capparis decidua, Hardwickia binata, Tamarix aphylla*	*Haloxylan salicornicum, Leptadenia pyrotech-nica, Aerva persica, A. pseudotomentosa, Zizyphus nummularia,*	*Citrullus colosynthis, Lasiurus sindicus, Panicum turgidum*
300-400	*A. tortilis, Faidherbia albida, Albizia lebbeck, Azadirachta indica, P. juliflora, P. cineraria, Tecomella undulata, Parkinsonia aculeata, Colophospermum mopane, Cordia rothii, Zizyphus mauritiana*	*Acacia jacquemontii, Z. nummularia, H. salicornicum, L. pyrotechnica, A. persica, A. pseudotomentosa Dichrostachys glomerata*	*C. colosynthis Cenchrus ciliaris, C. setigerus, L. sindicus, Desmostachya bipinnata, Saccharum munja*
400-550	*Ailanthus excelsa, Albizia lebbek, A. tortilis, A. senegal, Dalbargia sissoo, Emblica officinalis, P. cineraria, P. juliflora T. undulata, C. mopane, Z. mauritiana,*	*A. jacquemontii, Cassia auriculata, D. glomerata*	*C. ciliaris, C. setigerus, S. munja, D. bipinnata, P. antidotale*

Likewise the riverine corridor appears more productive than the surrounding desert, and supports the idea that it may act as a refuge or as a channel for the ingress of peri-desert species. However, species diversity of plants is not higher within the river corridor; rather, it is driven by rainfall and the accompanying increase in annual plants following a rain occurs (Free et al., 2013). Shallow soil areas are also common but found mostly in the eastern and south-eastern part of the arid western Rajasthan. These are consisting of a shallow sandy loam soil having a depth of 30-45 cm, below which there is a calcareous nodules and/or ‘Kankar hard pan’ layer. This area requires special attentions for better root growth and establishment of the planted seedlings. The choice of tree species for shallow soil areas is relatively less and can be categorized based on the rainfall, i.e. <250 mm rainfall and > 250 mm rainfall annually (Table 6.6).

Table 6.6 Species suitable for rehabilitation of shallow soil areas in Rajasthan.

Category I (< 250 mm rainfall zone)	Category II (> 250 mm rainfall zone)
Acacia tortilis	*Azadirachta indica*
Acacia leucophloea	*Dichrostachys nutans*
Hardwickia binata	*Hardwickia binata*
Prosopis juliflora	*Prosopis juliflora*

Category I (< 250 mm rainfall zone)	Category II (> 250 mm rainfall zone)
Prosopis alba	*Acacia nilotica*
Grewia tenax	*Acacia senegal*
Zizyphus nummularia	*Zizyphus nummularia*
Cordia rothi	*Holoptelia integrifolia*
Capparis decidua	*Eucalyptus camaldulensis*
Salvadora oleoides	*Pongamia pinnata*
Lycium barbarum	*Indigofera argentea*
	Cadaba fruiticosa
	Mimosa hamata

3.2.2 Mulch and compost

Mulch is used as a temporary measure to help with the establishment and growth of the planted vegetation, but mulch alone will not protect from eroding or establish vegetative cover (Howell, 1999). Mulch can be organic (e.g., compost, grass clippings, straw, bark, leaf litter) or inorganic (e.g., stone) (Sotir and Fischenich, 2001). Mulch can be applied in various ways, including spreading it over the entire surface, over sown seeds, or around the individual plants under afforestation. Mulch helps to keep soil cool and moist and enhances growth and early establishment of shrub and tree seedlings (Gupta, 1995; Howell, 1999). The approaches of using straw/live checkerboards and revegetation has been successful and effective for controlling mobile dunes and rehabilitating desert ecosystems (Singh and Rathod, 2002; Whitford, 2002; Li et al., 2004). A good option for armoring sown grass seed is to mulch the entire site with chopped plant material or brushwood cleared from the site. Sand mulches are also used around plants that allow water to infiltrate rapidly to the depth of the sand and resist capillary movement back up to the surface. If the underlying soil has a high water-holding capacity, the water will remain there until it is taken up by the plants (Singh, 2004b). Sand and gravel mulches have also been used throughout the ages to mitigate the evaporation loss of water and to stabilize soil temperatures as well. Ancient Indian farmers in the desert region have used sand and gravel as mulches for centuries. The Hopis and their ancestors used sand and gravel mulches to grow their crops in the arid regions of the Colorado Plateau. The sand, with its small pore spaces, held the water while the gravel, with its large pore spaces, allowed water to freely penetrate to the sand below and provide both an insulating layer and a heat sink to moderate the temperatures in subsurface layer (Louge et al., 2013).

3.2.3 Grass seeding

Major area of the Thar Desert is unprotected and overgrazed that contribute significantly to aeolian dust load in the atmosphere, with possible adverse feedback to the regional climate. The soil transport rate (kg m^{-1} day^{-1}) is observed almost three times higher in overgrazed area as compared to the controlled grazing area of *Lasiurus sindicus* grass. In this wind-eroded aeolian sediments decreased with increase in grass height from the surface (Mertia et al., 2009). This indicates that grasses have more effective role in protecting soils from both water and wind erosion (Shah, 2008). To increase grass cover, grass seeding is one of the most common methods, but it will be ideal to use a mixture of creeping and clump forming grasses and herbs. Creeping grasses form a continuous root system, or mat. Clump forming grasses leave gaps between the plants that can be vulnerable to erosion, but they can grow large with deep roots (Hearn and Weeks, 1997). Seed mixtures normally include grasses that germinate rapidly and provide immediate short-term protection, and slower-growing perennial grasses that provide long-term protection. Though optimum seed mix depends on the soil types, site characteristics, and climatic conditions (Schor and Gray, 2007), but it is recommended to consider use of native seed varieties.

3.2.4 Plantation

Selection of tree and shrub species for afforestation should match with local conditions, including soil types, specific site problems and climate and should be of superior quality. For this at least six to ten tree and shrub species should be selected with an array of plant species supported by quality planting materials of these species. Though bare dunes are devoid of vegetation, but land with existing grass like *Dactyloctenium sindicum*, *Cenchrus ciliaris* etc. as observed in inter-dunal areas are poor choice for a successful plantation unless the soil is plowed and disked for at least one year before planting to improve soil condition and water storage and reduce competitive effects (Singh, 2004a & b). Competitive effects of vegetation growing in semi-stabilized dunes should also be minimized. Planting of seedlings should be restricted to monsoon months, when sand loss can be minimized by use of mulch or other sand stabilizing methods (Miller et al., 2014). Before planting, lay out of the rows for proper location and spacing is must. Farmyard manure at the rate of 5 kg per pit along with termiticide/insecticide can be mixed with soil used for refilling the pits in all types of habitats/landforms. Initial dose of 10-20 g of single super phosphate may help establishment of seedlings and ameliorate soil stress conditions (Singh and Singh, 2011a). However, protection against biotic interferences is must at the start of the rehabilitation work.

- In the restoration of dunes, the adult neighbours available may be maintained/ retained as such to protect seedlings from the adverse climatic conditions (Singh et al., 2003b). During plantation a pit size of 45 cm × 45 cm × 45 cm can be excavated and uppermost soil could be scraped to fill the pit along with farmyard manure at the rate of 5 kg per pit. After planting, initial irrigation (in absence of rain) and sand/organic mulching is necessary.
- In sandy plain areas, planting tree seedlings can be done in a pit size of 60 cm × 60 cm × 60 cm and a saucer shape basin of one meter diameter around pits is made to harvest rain water and for proper establishment of the seedlings. However, different *in situ* micro-catchments for rain water harvesting may also be tried for better results and productivity of the planted seedlings. These micro-catchments are ring pits, trench-cum-mound, trench and mounds, saucers of 3 m diameter and checker board design etc (Gupta, 1995).

- Soils having a depth of 30-45 cm underlain with calcareous nodules and/or ‘Kankar pan’ underneath needs relatively bigger size pits i.e., 60 cm × 60 cm × 60 cm for better root growth and establishment of the seedlings. In absence of such operations, the roots of growing tree may coil once they reach to the depth of the "Kankar pan" and in turn their growth is retarded. And in absence of proper root development, there may be chances of mortality when irrigation will be withdrawn.

3.2.5 Water availability and irrigation

The presence of water is vital for plant growth. As rain is scarce in desert areas, other sources of water should be envisaged. Irrigation can play a significant role in arresting desertification through its effect in promoting the establishment and growth of vegetation one use under wind erosion or sand drift control. Groundwater resources, rain and dew water harvesting and wastewater use should be considered in this regard. In the highly sandy and dune covered areas, the drip system of irrigation could be effectively used for raising tree/horticultural crop. It has been observed to economies water and increase the production of *Lasiurus sindicus* in the extreme western part of Rajasthan. However, excessive use of irrigation water particularly in depressions with hardpans, leads to rise of water table and increases salinity. In dry climates it may be necessary to provide supplemental irrigation after planting. The number of watering and the amount of water applied depends upon climate, species, and the soils. For example, in an area of sandy loam which receives 150 to 200 mm of rainfall and has a dry season of 9 months, about 7 to 8 (the higher number of irrigation will be in Jaisalmer, Barmer, Bikaner, Ganganagar, Nagaur and northern part of Jodhpur, Falodi to IGNP) irrigation in first year @ 15 liters of water, 4 to 5 irrigation in 2nd year (@ 30 liters and 3 irrigation in 3rd year) @ 30 liters of water for each seedling is probably sufficient to assure survival, effective use of nutrients and to encourage growth. But for proper establishment and growth of the planted seedlings, it is important to provide a good soaking once a week initially for a month. Light watering encourages root growth too near the surface making the plant susceptible to drought. Thus it will be more appropriate to increase quantity of irrigation water by reducing frequency of irrigation (Bala et al., 2003). Contour furrows, trenches or other cultural treatments are some strategies of rainwater harvesting that will facilitate survival and growth of the planted seedlings in relatively high rainfall areas.

3.2.6 Site maintenance

There is need to protect seedlings from grass and weed competition until the seedlings are well above the height of grass and weeds particularly during monsoon period. Intensive root competition from *Dactyloctenium sindicum* and other competitive grasses impede tree growth for years, even after trees crowns have been grown taller than the grass (Singh, 2004b). Many plantations are damaged from wild as well as domestic animals. These are preventable by erecting fence, which may be expensive. Inspection of the planted seedlings required several times for signs of insect and disease problems or water stress. The reasons for such types of stresses should be searched upon and care should be taken to ease them out. The work of planning, ordering trees and getting the trees in the ground is wasted if one is not committed to controlling weeds and watering the plants for at least five years. For the purpose of effective control of sand drift under biological control measures the most important are (i) irrigation to maintain soil moisture, (ii) weed removal, (iii) causality replacement, and (iv) plantation caring from pests and diseases.

4. WIND EROSION CONTROL AND LIVELIHOOD CONNECTIONS

Wind erosion control by vegetative barriers of tree sticks favourably affect soil and water conservation and growth and yield (27.6% higher grain yield) of pearlmillet. Application of vegetative barriers of tree sticks recorded +7.5 cm soil deposition while control plot recorded soil erosion to the extent of removal of -5.7 cm soil surface (Poonia and Singh, 2006). Strip cropping of legumes with pasture grass (1:3 ratio) reduces soil loss (20.5 tons ha^{-1}) in comparison to the bare field (48 tons ha^{-1}). The loss of soil organic carbon and total nitrogen was to the level of 44 to 48 kg ha^{-1} and 3.0 to 3.2 kg ha^{-1}, respectively in bare soil left after sole cropping (Soni et al., 2007). In contrast, a pasture and afforestation encourage sediment deposition, providing a net gain of soil organic carbon and total nitrogen (Raji and Oguwole, 2006). Planting 'Aloes' or thorn less cactus (*Opuntia ficus-indica*) also improve the effectiveness of grass reseeding for rangeland restoration, exceeding the benefits gained from the more common strategy of using the branch together with economic value of these plants (King and Stanton, 2008; Gebretsadik et al., 2013). The major functions of cactus pear reported are food, livestock feed, cash income, environmental protection, fence, fire wood, cochineal production and bee forage, whereas the dry matter yield of the different cultivars of *Opuntia ficus-indica* ranged between 12.9 and 13.7 tons ha^{-1} (Gebretsadik et al., 2013).

Production from *A. tortilis, P. juliflora* and *Calligonum polygonoides* at the age of 50 months have been recorded as 5.2 tons ha^{-1}, 7.00 tons ha^{-1} and 7.15 tons ha^{-1} fuel wood, respectively. *C. polygonoides* produced the highest biomass in form of fuel wood utilizing minimum amount of soil water (Singh and Rathod, 2002). Likewise, fresh biomass of *C. angustifolia* plants was highest with *C. polygonoides* and lowest with *A. tortilis*. *Cassia angustifolia* produced dry leaves of 0.76 tons ha^{-1} y^{-1} with *A. tortilis*, 0.96 tons ha^{-1} y^{-1} with *P. juliflora* and 1.39 tons ha^{-1} y^{-1} with *C. polygonoides*. Considering the economic return from *C. angustifolia* leaves, Rs 16720 ha^{-1} y^{-1} could be obtained from the plots in which *C. polygonoides* is integrated with *C. angustifolia* as compared to Rs 9120 ha^{-1} y^{-1} from the plots in which *A. tortilis* was integrated (Singh et al., 2003a). *Cenchrus ciliaris* produced green fodder of 1.22 tons ha^{-1} $year^{-1}$ with *A. tortilis*, 1.58 tons ha^{-1} $year^{-1}$ with *P. juliflora* and 2.23 tons ha^{-1} $year^{-1}$ with *C. polygonoides* (Singh and Rathod, 2002). Besides, there is increase of income and creation of employment opportunities and alleviation of poverty of local communities. The environmental well-beings are:

- Reduction in volumes of dust and sand into the atmosphere and polluting the surrounding areas due to mild to severe sand storms.
- Benefits of carbon sequestration, biodiversity enhancement, soil and climate conditions, and the value of associated forest products (Singh and Rathod, 2002; Amiotti et al., 2013).

- By conserving and enhancing soil carbon stock there will be removal of CO_2 from atmosphere and minimization of GHG emissions from the soil.
- Positive effects of planted trees on the decrease of soil erosion and sand drift.

5. ACTION AHEAD

In highly degraded areas, establishment of indigenous species is relatively slow and requires even introduction of exotics like Acacias. For example Rajasthan's Forest Department has responded by initiating and implementing desertification control programmes in which stabilization of sand dunes have been done by planting *Acacia tortilis* trees in monocultures. In general plantations too, the percentage of *Acacia tortilis* is not less than 70 percent. Though it has done the work for which it was planted, but over-grazing, temperature increase and tree demise results in many dunes shift again, i.e. reactivation of sand drift (Singh and Rathod, 2002). This leads to the deposition of sand on agricultural land and threatens the life and livelihoods of communities residing nearby. In a restoration strategy, starting from shifting sand dunes and aligning all the sites in chronological order Miyasaka et al. (2014) observed that the planting of trees progressed vegetation restoration faster than livestock exclusion and the planting of shrubs. The planting of trees restored shifting sand dunes to the same level of fixed sand dunes after 25 years. Restoring shifting sand dunes to a near-stable state characterized by *Cleistogenes squarrosa* takes about thirty-five years. The sequential turnover in species composition move along the upward topographic gradient throughout the restoration trajectory, indicating that vegetation restoration on sand dunes is promoted by a process where diaspores establish and spread upward from interdune lowland.

Though, many dune fields undergoes alternating periods of mobilization and stabilization in response to changes in wind power and rainfall, but disturbances associated with land use appeared to be a dominant factor contributing to the activation of stabilized vegetated dunes in drylands. The reduction in human activities such as grazing and farming may lead to stabilization of once active dune fields. Changes in grass cover, grass community composition, and seed bank can serve as indicators of whether the system has irreversibly shifted from a vegetated to a bare dune state (Bhattachan et al., 2014). There is need to explore the possibility of revegetating the open area or the gaps generated or even replace the originally planted exotics by introducing the indigenous trees or cover crop in a sequential manner. Planting of multiple layers of indigenous species consisting of creepers like *Citrullus colosynthesis*, grass like *Lasiurus sindicus*, shrubs like *Calligonum polygonides* and trees like *Acacia senegal*, *Prosopis cineraria*, *Tecomella undulata* or *Salvadora oleoides* etc. However, most of these species are high light-demanding and hence kept beyond the canopy of the existing trees or bushes. As cover crops, castor (*Ricinus communis*) and Sonamukhi (*Cassia angustifolia*) could also be tried dibbling the seeds. The expected benefits will only be visible after three to six years when the plants are mature. For example, the grass species *Lasiurus sindicus*, when used as fodder, could provide up to 6,660 INR (Rs) per hectare and from the third year onwards together with the tree *Acacia senegal*, when used for fuel wood, could provide 10,000 INR per hectare.

6. CONCLUSION AND RECOMMENDATIONS

Erosion is a serious problem of environmental degradation in the regions with contrasting seasonal climate and increased human activities in the desert fringes. Over-exploitation of vegetation for fodder and fuelwood, the two basic needs of life for the desert people, is damaging the desert ecosystem and enhancing desertification. These degraded lands however have tremendous resilience for regeneration when the influence of biotic factors is removed.

Sandy plains and various forms of sand dunes generated from wind action are not only observed in arid region but in wet and humid areas also creating devastating impacts (Alghamdi and Al-Kahtani, 2005). However, the transition between active and stabilized dunes is controlled mainly by wind speed and aridity (Barchyn and Hugenholtz, 2012). While, enhancing sand deposition and sand transport, reducing the supply of sand upwind and deflecting the moving sand to other sides are the methods to tackle the problem of wind erosion, the methods of sand drift control that are employed singly or in combination are (i) transposing, (ii) planting, (iii) paving, (iv) paneling, (v) fencing, and (vi) use of oil.

Though geotextiles supported by seed sowing of different species could be effective, but biological method of sand dune stabilization is more effective and long lasting as compared to the chemical and physical methods. Use of fast growing exotic species of tree and grasses from isoclimatic regions appeared beneficial under effective protection and caring for the initial phases of sand drift control. Promoting regeneration and/or planting indigenous trees, shrubs and grasses however, have proved highly successful towards the control of desertification and ecological restoration of the sandy areas.

The association of *C. angusifolia* as the surface vegetation is best to control sand drift effectively, whereas integration of grass is promised for fodder production along with the sand drift control. *C. polygonoides* is the best neighbour with better soil water status underneath and highest facilitating influence on the associated species. Besides, the benefits of carbon sequestration of 3.72 tons ha^{-1} with *A. tortilis*, 5.24 tons ha^{-1} with *P. juliflora* and 5.66 tons ha^{-1} with *Calligonum polygonoides* could also be achieved within 4-5 years through plantation in addition to the other environmental benefits like microclimate amelioration, soil improvement and sheltering the habitations.

Because of availability of pasturelands and sacred groves, the Western Rajasthan holds a big potential for development into a rangeland. The highly nutritive fodder grasses *Lasiurus sindicus*, *Cenchrus ciliaris*, *C. setigerus* and *Cymbopogon jwarancusa* etc are well adapted to the region and should be utilized in restoring these degraded community lands.

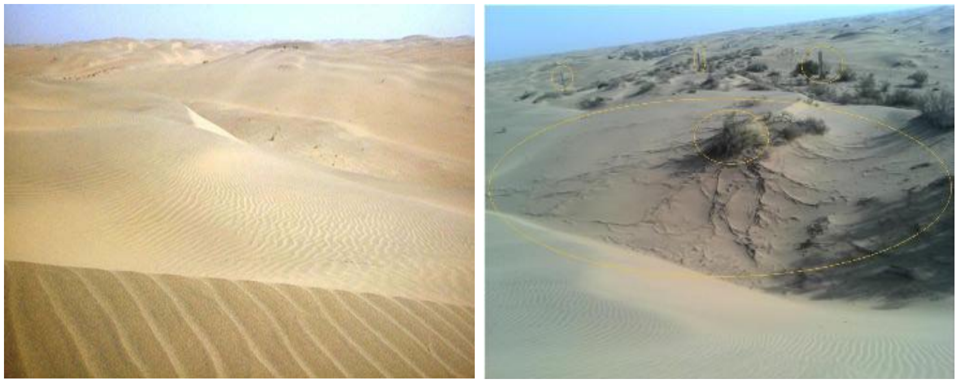


Plate 6.1 Moving dune (left) and *Calligonum polygonoides* roots (right) exposed due to wind erosion

Plate 6.2 *Calligonum polygonoides* regenerated by seeds sowing along the micro-windbreaks (left) and micro-windbreak of *Cassia angustifolia* in Chekerboard (right) with a planted seedling in the centre.

Plate 6.3 Surface vegetation (left) *Cassia angustifolia* with *Calligonum polygonoides*, and (right) *Cenchrus ciliaris* root stock with *C. polygonoides.*

7

RECLAMATION AND MANAGEMENT OF SALT-AFFECTED, WATERLOGGED AND EFFLUENT INFLICTED SOILS

The salt-affected and waterlogged areas accounted for about 4.2% and 3.5% of the total geographical area of India. Naturally soil salinity or sodicity are associated with aridity. Secondary salinization is associated with waterlogging, over-irrigation and irrigation with water of high salt content. Release of immobilized salts already present in the soils, atmospheric salt dispositions, weathering of soil minerals and use of fertilizers are other factors responsible for increased salinity. Chemical, physical and biological means of measure are adopted for reclamation of salt-affected lands. Different types of amendments are used to minimize the salt, sodium, and/or magnesium concentration from the plant root zone through leaching. Application of gypsum or calcium rich salts, sulfur, rice husk and composts of varying origins and slow release fertilizers improves saline-sodic soils. Though better supported by other measure, biological reclamation appears more effective for stabilization of soil quality and eco-restoration of salt-affected soils. This chapter describes extent and distribution of salt affected, water logged and effluent or wastewater affected soils, their characteristics together with reclamation of such areas by selecting appropriate vegetations of varying tolerance levels toward salinity, alkalinity, water-logging and effluent quality.

1. INTRODUCTION

Soil salinity is considered the major stress among the stresses in plant worldwide (Ladeiro, 2012). Total area under salt-affected soils in the world constitutes about 800 million hectares which includes 397 and 434 million hectares of saline and sodic soils, respectively (Kheyrodin, 2014). Salt-induced land degradation is common in arid and semi-arid regions where rainfall is too low to maintain a regular percolation of rainwater through the soil and irrigation is practiced without a natural or artificial drainage system. Such irrigation practices without drainage management leads to accumulation of salts in the root zone, affecting several soil properties and plant productivity adversely (Warrence et al., 2003; Amira and Qados, 2011). About 75 countries are within the sovereign borders of salt-affected soils occupying more than 20% of the global irrigated area (Ghassemi et al., 1995) and the trend is increasing with time (Metternicht and Zinck, 2003). The extent of land degradation due to chemical deterioration and water logging in India is about 4.2% and 3.5%, respectively. Salinization is a type of chemical deterioration and is the result of poor management of irrigation schemes. Irrigation with high salt content water with little attention to the drainage leads to a rapid salinization of the soils mainly in arid and semi-arid regions. Additionally salinization also occurs when seawater or fossil saline ground water intrudes the ground water reserves of good quality and happens sometimes in coastal regions with an excessive use of ground water. A third type of salinization occurs where human activities lead to an increase in evapo-transpiration of soil moisture on salt-containing parent material or with saline ground water. Waterlogging is another physical type of land deterioration and includes flooding by river water and submergence by rain water caused by human intervention in natural drainage systems (Oldeman et al., 1991).

Salinity and water logging adversely affect irrigated dry lands, and in several narrow irrigated valleys in the coastal regions (Chitale, 1991; Kaiser et al., 2013; Mishra et al., 1996; Sharma and Mondal, 2006). Though limited but quantification of social and economic impacts of these degradations reveal that the most affected farmers supplement their low on-farm income with off-farm economic activities (Zekri et al., 2010), whereas farmers in severely affected areas move to nearby cities in search of livelihood (Ali et al., 2001; Bala et al., 2004). In the Indo-Gangetic basin, the yield losses for wheat, rice, sugarcane and cotton grown on salt-affected lands estimated to 40%, 45%, 48%, and 63%, respectively, whereas employment losses predicted to 50 to 80 man-days ha^{-1} along with 20-40% increase in human health problems and 15-50% increase in animal health problems (Tripathi, 2009). A simple extrapolation at the global level, the annual cost of salt-induced land degradation in irrigated areas has been estimated to about US$ 27.3 billion because of lost crop production (Qadir et al., 2014).

2. SALT AFFECTED SOILS

Salt-affected soils differ from normal arable soils in respect of two important properties, the amount of soluble salts and the soil reaction. The major dissolved mineral salts are Na^{+} (sodium), Ca^{+2} (calcium), Mg^{+2} (magnesium), and K^{+} (potassium) cations and Cl^{-} (chloride), SO_4^{-2} (sulfate), HCO_3^{-} (bicarbonate), CO_3^{-2} (carbonate), and NO_3^{-} (nitrate) anions. Excess soluble salts adversely influence soil behaviour by changing its physico-chemical properties, which in turn have a strong bearing on the activity of plant roots and growth. From the management point of view salt-affected soils are categorized into: saline, alkaline and saline-alkali soils (Yadav, 1980). Saline soils are characterized as non-sodic containing sufficient soluble salts. Alkali soils are characterized by elevated levels of sodium ions and exhibit structural problems as a result of certain physical processes like slaking, swelling and dispersion of clay, and specific conditions, i.e. surface crusting and hard-setting. With properties overlapping of both saline and alkali, saline-alkali soils are characterized by elevated levels of soluble salts and sodium ions both.

2.1 Distribution of salt affected soils

The distribution of saline or alkali soils is relatively more extensive in the arid and semi-arid regions (Owens, 2001). Salts released during weathering of earth crust, move both vertically and horizontally with the runoff water. Because of low rainfall, high potential evapo-transpiration (PET) and slow drainage system in arid regions salts do not move to a long distance but accumulate in soils and ground water. The increased salt concentration may be antagonistic for the woody perennials, which have greater tolerance to these stresses than the annual crops. Utilization of these salt affected areas is necessary owing to increasing demand for fodder, fuel and other minor produce. However, high level of salinity and sodicity are serious problems and are going to affect crop productivity adversely. They require specific approaches for their reclamation and management to maintain long term productivity (Radford, 2014).

The salinity, sodicity and coastal salinity has degraded about 1.71 million ha, 3.79 million ha and 1.25 million ha lands, respectively making a total of 6·75 million ha in India under this category (Singh, 2009a). Out of this, about 2.60 million ha area is in north-western region of India that covers Rajasthan (0.38 m ha) and Gujarat (2.22 m ha). In Rajasthan, the soils with primary soil salinity are encountered in the natural saline depressions like the Pachpadra, Didwana, Sambhar, and few others covering about 2.1% area of the State. Besides these, occurrences of saline lands are seen in the far flood plain of river Ghaggar and in part of the Luni river basin. However, small pockets of salt affected soils lie scattered not only in arid region but also in semi-arid region of Rajasthan. All arid districts of Rajasthan have mainly inland salt affected soil with sodium chloride and sulphate as the dominant salts (Plate 7.1). Different categories of salt affected soil in Rajasthan are: (i) Natural saline soils; (ii) Relict saline soils; (iii) Secondary salinized soils due to high water table; and (iv) Secondary salinized soils due to highly saline water used for irrigation (Kolarkar et al., 1980). A rapid rise in water table because of seepage of IGNP canal and intensive irrigation in command area of Rajasthan however, is also augmenting the proportion of salt affected area (Kalra and Joshi, 1997; Tewari et al., 1997). In Gujarat, both inland and coastal salt affected soils are distributed in Kachchh, Patan, Surendranagar, Banaskantha, Jamnagar, Porbander, Junagarh, Bhavnagar, Ahemdabad, Bharuch and Surat districts.

2.2 Characteristics of salt affected soils

Soil salinity and alkalinity are technically expressed in terms of pH, electric conductivity (EC), exchangeable Sodium percentage (ESP) and/ or Sodium Absorption Ratio (SAR). Both alkali and the saline soils differ in their physical and chemical characteristics (Table 7.1) and thus nature of constraints, i.e. depending upon the severity of the salt accumulation, for plant growth (Table 7.2). Due to excessive amount of neutral salts, saline soils remain generally in satisfactory physical condition and show good permeability. However, high water table coupled with poor quality ground water particularly near the canal and other water courses leads to excessive salt accumulation that hinder the drainage. Under excessive salinity plant growth is adversely affected because of osmotic imbalance and disorder of nutrient availability marked by either deficiency or toxicity (Yadav, 2006). Characterization of salt-affected lands helps determine to adopt restoration options in a given context or region. Saline soils are distinguished from the sodic soils because of dominance of neutral salts of chlorides and sulphates of sodium. Salinity is expressed in a number of ways, i.e. mol per liter and milligrams per liter or parts per million, and is measured in terms of electrical conductivity (EC) as decisiemens per meter (dSm^{-1}) or millimhos per centimeter ($mmhos\ cm^{-1}$). Alkali soils are characterized by an excess of Na^+ ions in relation to calcium and magnesium. The exchangeable sodium percentage (ESP) is milli equivalent of exchangeable sodium per 100 g soil divided by milliequivalent cation exchange capacity per 100 g soil multiplied by 100 as whole. ESP equals:

$$= \frac{\text{Exchangeable } Na^+ \text{ (me/100 g soil)}}{\text{Cation exchange capacity (me / 100 g soil)}} \times 100$$

Sodium adsorption ratio (SAR) is concentrations of Sodium ions divided by square root of half of the total concentrations of Calcium and Magnesium in millimol per litre.

$$\mathrm{SAR} = Na^+ / \sqrt{(Ca + Mg)^{++}/2}$$

Table 7.1 Properties of saline, alkaline and waterlogged soils in relation to plant survival and growth. (Source: Marcar et al., 1999).

Properties	Saline	Alkaline	Waterlogged
ECe	>4 dS/m	<4 dS/m	n.a.
ESP*	<15	>15	n.a.
pH	<8.2	>8.2	
Physical appearance	White efflorescent crust	Salt encrustation with black colour near organic matter spots	-
Major product	Dominance of Na, Ca, Mg, Cl and SO_4 ions	Dominance of Na, CO_3, HCO_3 ions	Anaerobic respiration
Physical structure	Flocculated	Dispersed	Variable: low O_2 concentrations
Soil water	Osmotically-induced water stress likely	Reduced access to subsoil moisture because of impeding layers	Excess supply water stress likely
Required nutrients	Imbalance	Imbalance	Imbalance
Gypsum availability	Naturally present	Gypsum usually absent	-
Others	Often high Na: Ca ratio	High Na:Ca ratio, Calcium carbonate concretions usually present at 1-1.5 m depth	n.a.

ECe = electrical conductivity of water extracted from a saturated soil paste; n.a. = not applicable, ESP = exchangeable sodium percentage. * = under Australian conditions, sodic soils have ESP> 6

Table 7.2 Characteristics of salt affected soils based on severity classes.

Type of soils	Severity class	pH	EC (dS/m)	ESP
Saline soil	Medium	< 8.5	4-8 (2-4)	<15 (<5)
	High	< 8.5	8-16 (4-8)	<15 (<5)
	Very high	< 8.5	>16 (>8)	<15 (<5)
Alkali soil	Medium	8.5-9.0	<4 (<2)	15-40 (5-10)
	High	9.0-10.0	<4 (<2)	40-60 (10-20)
	Very high	>10	<4 (<2)	>60 (>20)
Saline-Sodic soil	Medium	8.5-9.0	4-8 (2-4)	15-40 (5-10)
	High	9.0-10.0	8-16 (4-8)	40-60 (10-20)
	Very high	>10	>16 (>8)	>60 (>20)

Figures in parenthesis represent the threshold values for Vertisols

2.3 Salts accumulation and soil properties

Salinity promotes soil flocculation, whereas sodicity promotes soil dispersion. The relationship between soil salinity and its flocculating effects, and sodicity and its dispersive effects influence whether or not soil will stay aggregated or become dispersed under various salinity and sodicity combinations. Water either by irrigation or rainfall flows into the spaces between clay particles. If the salinity of the applied water is low than the soil salinity, it results in swelling and dispersion of clay particles. In contrast, irrigation water with higher salinity than the soil leads the particles to stay together and maintain soil structure. However, the main concerns related to the relationship between salinity and sodicity of irrigation water are the effects on soil infiltration rates and hydraulic conductivities. The ratio of salinity (EC) to sodicity (SAR) determines the effects of salts and sodium on the soils. The combination of salinity and sodicity of soils is measured by the swelling factor, which is the amount, a soil is likely to swell with different combinations of salinity and sodicity. The swelling factor indicates whether sodium-induced dispersion or salinity-induced flocculation will more greatly affect soil physical properties (Itami and Fujitami, 2005). Excess accumulation of salts in the surface horizons are mainly due to the following reasons:

- Secondary salinization associated with waterlogging.
- High salt content of irrigation water.
- Release of immobilized salts already precipitated in soils.
- Atmospheric salt dispositions as in coastal areas.
- Weathering of soil minerals.
- Use of fertilizers.

The relative significance of each source in contributing soluble salts to the root zone depends on the natural drainage conditions, soil properties, irrigation water quality, management practices and distance from the coast line. Soluble salts are either neutral in their reaction (e.g. chlorides and sulfates of sodium, calcium and magnesium) or are the sodium salts of carbonate and bicarbonates capable of producing alkalinity.

2.4 Productivity losses in salt-affected lands

Salt affected soils are normally uncultivated, uninhabited bare lands with poor quality that suffer from different stresses. These soils are generally not conducive for regeneration of many types of vegetation. Salts occur naturally in the soil and in irrigation water, whereas additional salts are added through fertilizer application. Though barren, the salt affected soils are potentially productive lands. Through irrigation, some of the salts leach to groundwater or are carried away in agricultural wastewater to saline sinks. If not removed, the salts build up in the soil continue over time, and too high concentrations of accumulated salts in soil reduce the ability of crops and plants to take up water and leads to lower yields. Saline water irrigation increases exchangeable Na^+, K^+, Ca^{2+}, Mg^{2+}, and soil pH, whereas soil salinization and removal of salt can also damage the ecosystem farther a field.

The growth of most crop plants is adversely affected because of impairment of physical conditions, disorder in nutrient availability and suppression of biological activity due to pH going up to 11 and exchangeable sodium up to 90 or so. The soluble salts contain preponderance of sodium carbonates and bicarbonates capable of alkaline hydrolysis, thereby saturating the absorbing complex with sodium. Swelling of dispersed clay may be considered as the main mechanism responsible for clogging of pore space in alkali soils, thereby restricting their ability to conduct water and air for decreasing their infiltration rate, hydraulic conductivity and moisture transmission characteristics (Itami and Fujitami, 2005).

3. SALTLAND VEGETATIONS

Plants that survive and reproduce in the environments with salt concentration greater than 200 milli Mol of NaCl (~20 dSm^{-1}) are referred to as halophytes, which constitute about 1% of the world's flora (Flowers and Colmer, 2008). Halophytes are the plants capable of completing their life cycle under highly saline (NaCl) conditions and have capacity of increased productivity with increasing salt levels and grow better under salinity condition than under fresh water conditions (Yensen, 2008; Roy et al., 2012). Several halophyte species including grasses, shrubs, and trees remove the salt from different kinds of salt-affected soils through salt exclusion, excretion, or accumulation by their morphological, anatomical and physiological adaptation in their organelle level and cellular level (Table 7.3).

Vegetation growing in saline depression in Rajasthan have been classified into true halophytes, facultative halophytes and transitional halophytes (Sen and Rajpurohit, 1978). True halophytes are *Suaeda fruticosa*, *Cressa cretica*, *Aeluropus lagopoides*, *Salsola baryosama*, *Haloxylan recurvum*, *Zygophylum simplex* etc. Facultative halophytes are *Trianthema triquerta*, *Launia nudicaulis*, *Tamarix dioca*, *Eragrostis ciliaris*, *E. pilossa*, *Salvadora persica* and *Cleome barchycarpa*, which are halophytes but can grow in non-saline area also, whereas the plants like *Pulicaria wightiana*, *Euphorbia granulata* and *Indigophera cordifolia* are mainly non-saline but can grow in saline area also. The transitional halophytes are those which grow only on the transitions of saline and non-saline area like *Haloxylan salicornicum*, *Sporobolus helvolus* and *S. marginatus* etc.

Table 7.3 Walter classification of halophytes.

Types of halophytes	Characteristics and examples
Salt excluding	Root system of these plants possesses an ultrafiltration mechanism leading to establishment of such species as the dominant component of the mangrove vegetation. Example are *Rhizophora mucronata*, *Ceriops candolleana*, *Bruguiera gymnorrhiza*, *Kandelia candel* etc.
Salt excreting	These plants regulate internal salt levels through foliar glands. *Avicennia officinalis*, *Avicennia alba*, *Avicennia marina*, *Aegiceros corniculatum,* and *Acanthus ilicifolius* are some examples of this category.
Salt accumulating	These plants accumulate high concentrations of salt in their cells and tissues and overcome salt toxicity by developing succulence. *Sonneratia apetala*, *Sonneratia acida*, *Sonneratia alba*, *Limnitzera racemosa*, *Excoecaria agallocha*, *Salvadora persica*, *Sesuvium portulacastrum*, *Suaeda nudiflora,* and *Pentatropis sianshoides* are some examples of this category

Various mechanisms are involved by which vegetation of saltlands makes themselves adaptable to this environment. This includes ion compartmentalisation, osmolyte production, germination responses, osmotic adaptation, succulence, selective transport and uptake of ions, enzyme responses, salt excretion, and genetic control (Koyro et al., 2011). Salt excretion is one mechanism that prevents excessive concentrations of salts building up in photosynthetic tissues (Arya et al., 2011; Hasanuzzaman et al., 2013). Halophytes possessing multicellular salt glands and salt hairs are common in many halophytes such as *Cressa* (Convolvulaceae), *Frankenia* (Frankeniaceae), *Spartina*, *Chloris*, and *Aeluropus* (Poaceae), *Atriplex* (Chenopodiaceae), *Statice*, *Limonium*, *Plumbago*, and *Armeria* (Plumbaginaceae), *Glaux* (Primulaceae), *Tamarix* and *Reamuria* (Tamaricaceae), and some mangrove species like *Avicennia*, *Aegialitis*, *Aegiceras,* and *Acanthus* (Arya et al., 2011; Hasanuzzaman et al., 2013). Accumulation of compatible solutes, i.e. carbohydrates, GB, polyols, and Pro, is also a basic strategy for the protection and survival of halophytes under salt stress (Parida and Das, 2005; Lee et al., 2008) and protect plants against stress by cellular osmotic adjustment, detoxification of ROS, protection of membrane integrity, and stabilization of enzymes and proteins (Ashraf and Foolad, 2007). Increased salinity is also associated with decrease in auxin, cytokinin, gibberellins and SA in the plant tissues and an increase in ABA and jasmonic acid (JA). Such changes in hormone levels in plant tissue are thought to be an initial process controlling growth reduction due to salinity. Thus NaCl-induced reduction in the plant growth can be mitigated by application of plant growth regulators (Javid et al., 2011).

Use of sulphur inoculated Thiobacillus has been observed more efficient than gypsum in the reduction of the exchangeable sodium of the soil and promoting leaching of salts, especially sodium (Stamford et al., 2002). Sulphur inoculated with Thiobacillus reduces the EC of the soil saturation extract to levels below that adopted in soil classification of sodic or saline sodic. Relatively greater tolerance to salinity in *Leucena leucocephala* and more resistant to acidity in Mimosa spp. are more promoted by sulphur inoculated with Thiobacillus (Stamford et al., 2002). Likewise, the tolerance of liquorice (*Glycyrrhiza glabra*) to sodicity has also been observed due to presence of a strain of Mesorhizobium (CCNWGX 035) enhancing tolerance to NaCl, pH and temperature (Ge-Hong et al., 2008; Dagar et al., 2015).

4. SALTLANDS RECLAMATION

Reversing salt-induced land degradation naturally would require several years. However, interim salinity management strategies could provide a pathway for effective remediation and demonstrate the importance of reversing land degradation and rewards of investing in sustainable land management. Further, increasing societal need of fuel wood and fodder also leads to planting of salt tolerant trees and shrubs on salt affected soil with additional benefits of mitigating climate change. Rehabilitation includes control of extension of salt affected soils, its reclamation, stabilization and eco-restoration for social benefits. The rehabilitation of salt lands is common through chemical means and engineering approaches, whereas extension of salt affected soils is controlled by utilizing the resource on sustainable basis. Amongst different technologies utilized to reclaim saline-alkaline soils, adoption of leaching has been found least costly and could result in an incremental output of 14 quintals per hectare (Chinnappa, 2005). Green manuring has been observed to be another effective technology and could enhance crop yields on saline as well as waterlogged soils. Adoption of salt-resistant crop varieties is also profitable for small and marginal farmers. Instead of leaving their lands fallow due to their inability to adopt capital-intensive technologies, they can adopt them for land reclamation and higher returns. For a comprehensive afforestation program under rehabilitation of saltlands, there is need of special considerations, which include:

- Identification of the nature of salt problem.
- Assessment of availability and quality of irrigation water.
- Selection of suitable tree species.
- Choice of pitting and planting methods for alkali and saline soils.
- Soil and water management.
- Physical and social fencing during initial years.

While chemical reclamation requires different types of amendments for different soils, the biological reclamation is more important for stabilization of soil quality and eco-restoration. All these are associated with cost in minimizing the concentrations of salt, i.e. sodium or magnesium levels of salt affected soils and is governed by the presence of compacted layer in subsoil, which is required to be broken to leach the salts from the root zone (Hassan et al., 2013). Other factors affecting the cost of land restoration include the quality and quantity of water available for leaching the salts (Murtaza, 2013); the quality and depth of groundwater (Vyshpolsky et al., 2008); the crops to be grown during and after soil amelioration and their market value (Kushiev et al., 2005; Lamers et al., 2008); the topographic features of the land (Hassan et al., 2013); and the climatic conditions as soils under hot and arid climate would need more water and time to reach a specific level of remediation as compared to those under cold and humid climate. The cost of restoration usually increases with increase in the level of salinization (Murtaza, 2013). For example, a moderately saline soil would require less investment to bring it back to a productive state than a highly saline soil under similar conditions. Similarly, the quantity and related cost of a calcium source, such as gypsum, increase with the level of sodium in alkali soils or magnesium in magnesium-affected soils (Vyshpolsky et al., 2008). Selection of salt tolerant plants and crops is very important for cultivation of salt affected soils. Salt-tolerant plants have the capacity to grow using land and water unsuitable for conventional crops producing food, fuel, fodder, fiber, resin, essential oils, and pharmaceutical products (Ladeiro, 2012). Various amendments using gypsum, sulfur, farmyard manure or small dose of fertilizer are also important to ameliorate soil conditions and help enhance plant growth (Yadav, 1980; Ali and Ashlam, 2005).

4.1 Choice of species

Though limited but various tree or shrub species can grow in areas affected by salt and can play an important role in reducing the effects of salinity (Yadav and Singh, 1970). Planting new trees also helps to beautify areas of land with minimal productive use and provides habitat for native wildlife and natural insect predators. Trees help in reducing the wind flow over bare salt areas and their roots help bind the soil, and this reduces further erosion of the site. However, for obtaining maximum production from saline land, it is essential to select the correct species, land-preparation, planting techniques and tree-growing systems. Species choice depends on a range of soil and climatic factors, including degree of soil-salinity, and whether wood and/or non-wood products are desired by the local people or villagers. For example, species like: Mesquit (*Prosopis juliflora*), Kikar (*Acacia nilotica*), Sesbania (*Sesbania aegyptica*), Casuarina (*Casuarina equisetifolia*), Eucalypts (*Eucalyptus camaldulensis*), Siris (*Albizia lebbeck*), Parkinsonia (*Parkinsonia aculeata*), Leucaena (*Leucaena leucocephala*) and Karanj (*Derris indica*) are suitable energy plantation species; whereas species like *A. nilotica*, *C. equisetifolia*, *A. lebbeck*, *E. camaldulensis*, Arjun (*Terminalia arjuna*), Neem (*Azadirachta indica*), Jamun (*Syzygium cumini*), Khezri (*Prosopis cineraria*), *P. juliflora*, Imli (*Tamarindus indica*), Farash (*Tamarix aphylla*), Jungle jalebi (*Pethecellobium dulce*), etc. are suitable small timber and non-wood forest product species. Many species like Guava (*Pisidium guajava*), Aamla (*Phallyanthus emblica*), Ber (*Zizyphus mauritiana*), Date-Palm (*Pheonix dactylifera*), Phalsa (*Grewia subinae*) are different fruit-species and can be considered (Dagar et al., 2001). Besides many grass and shrubs species can suitably be introduced to hasten the reclamation process, and improved productivity. Grasses are more tolerant to alkali environment compared to most field crops. Karnal grass, Rhodes grass, Bermuda grass, and para grass are highly tolerant to alkali conditions and can withstand ESP up to 80-90. The grasses like Bermuda grass can be grown in soils with EC_3 up to 18 dSm^{-1}. Other promising grasses for rehabilitation of saline soil are *Aeluropus lagopoides*, *Chloris barbata*, *Echinocloa colonum*, *Dicanthium annulatum*, *Sporobolus helvolus*, *Phragmites* spp. and Sida spp. For this soil profile modification can be highly effective in leaching salts. For minimizing soil aggregate destruction and of maintaining a leveled floor, minimum-till deep chiseling, followed by the use of sand-topdressing and minimum-till shallow chisels for maintenance may prove to be more desirable than conventional ripping, especially in soil types consisting of silty-clay loam (Miyamoto and Nesbitt, 2011).

4.1.1 Species for Saline Lands Afforestation

Trees or shrubs producing fuel wood or fodder are rated better for salty soils afforestation rather than the timber species. Thus in addition to salt tolerance, socio-economic conditions and the ameliorative role of trees should also be given due consideration in selecting species for plantation of salt soils. Though there are inter- and intragenic variations in salt tolerance of forest tree species, the tolerances level also vary with the growth stages. For example, significant differences have also been observed in the species of Eucalypts and the provenances of *Eucalyptus camaldulensis* for their salt tolerance behaviour (Mahmood et al., 2009; Kurosawa et al., 2012). Numerous tree species have been evaluated for their tolerance to saline conditions, but some species have been rated better than the others (Table 7.4).

Table 7.4 Saline soil tolerant species for their use in afforestation.

Salinity level	Tree species
Moderately tolerant (ECe 10-15 dSm^{-1})	*Acacia leucocephala, Azadirachta indica, Casuarina cunninghamiana, Eucalyptus tereticornis, Acacia catechu, A. eburnean, Terminalia arjuna, Samanea saman, Albizzia procera, Borassus flabellifera, Prosopis cineraria, Dendrocalamus strictus, Butea monosperma, Feronia limonia, Leucaena leucocephala, Tamarindus indica, Guazuma ulmifolia, Ailanthus excelsa, Dichrostachys cinerea, Balanites roxburghii, Maytenus emerginata, Dalbergia sissoo, Carissa carandus, Melia azedarach,* etc.
Tolerant (ECe 15-25 dSm^{-1})	*Acacia ampliceps, A. nilotica, A. tortilis, Casuarina equisetifolia, Casuarina glauca, Casuarina obesa, Callistemon lanceolatus, Eucalyptus camaldulensis, Albizzia lebbeck, Pongamia pinnata, Crescentia alata, Capparis decidua* etc.
Highly tolerant (ECe 25 to 35 dSm^{-1})	**For inland saline soils**: *Prosopis juliflora, Salvadora persica, S. oleoides, Tamarix articulata, Tamarix troupii, Tamarix ericoides, Acacia farnesiana, Acacia cyanophylla, Parkinsonia aculeata, Salsola baryosoma, Atriplex* spp., *Suaeda* spp., *Kochia indica, Aeleuropus lagopoides* etc.
	For coastal regions: Mangrove (*Avicennia, Rhizophora, Ceriops, Aegiceras, Cynometra, Excoecaria, Heritiera, Lumnitzera, Nypa, Phoenix, Scyphiphora, Sonneratia, Xylocarpus), Barringtonia asiatica, Cordia subcordata, Clerodendrum inerme, Dolichandrone spathacea, Hernandia peltata, Hibiscus tiliaceous, Pandanus* spp., *Pongamia pinnata, Terminalia catappa, Thespesia populnea, Ochrosia oppositipholia, Scaevola taccada, Cerbera manghas, Calophyllum inophyllum, Ficus retusa, Syzygium samarangense, Manilkara littoralis, Arthrocnemum indicum, Salicornia brachiata* etc.

Source: Modified from Dagar et al. (2005).

A fairly broad range of reasonably salt tolerant trees and shrubs can be grown on these sites. However, planting of salt tolerant, non-halophytes may have a number of advantages over halophytes, as this group of plants is good source of fodder and fuel, and improves the saline soil through recycling of organic matter as well. There is a wide variation in genus, species and provenances of forest tree species in levels in their performance on saline soil. Most willow varieties are able to tolerate moderately saline conditions ($EC_e \leq 5.0$ dS m^{-1}). Some varieties (Alpha, India, Owasco, Tully Champion, and 01X-268-015) show no reduction in growth with severe salinity ($EC_e \leq 8.0$ dS m^{-1}). Some willow varieties are quite salt-tolerant and suitable for establishment on salt-affected soils (Hangs et al., 2011). Among the ten-year old plantation of various species *Terminalia arjuna, Prosopis juliflora, Pongamia pinnata* and *Pithecellobium dulce* showed 100% survival, whereas *Prosopis alba* attained 50% survival. *Eucalyptus tereticornis* attained height of 9.3 m followed by *Casuarina equisetifolia* with 8.2 m, whereas minimum plant stature was observed in *Cassia siamea* (Singh et al., 2011a). Here *Prosopis juliflora* attained maximum diameter at stump height, crown diameter, lopped biomass, and litter fall at all the growth stages producing aerial biomass of 70.27 Mg ha^{-1} followed by *Acacia nilotica* with 63.09 Mg ha^{-1} and *Casuarina equisetifolia* with 53.11 Mg ha^{-1}.

Salt tolerant grasses can persist on very saline sites with ECe of 8-15 dSm^{-1}, including couch (*Elymus repens*). A number of salt tolerant eucalypts can also be successfully grown on these sites. The area of high salinity (16-25 dSm^{-1}) is patchy in nature and shows vegetation like sea barley grass and other highly salt tolerant ground covers. Several *Melaleuca* species and Acacias can be established at the higher salinity levels within this range, whilst salt bush, Casuarinas and eucalypts can be established on areas at the lower end of the range. While choosing plants for such sites, the provenance is as critical as the species. Various clones specially adapted to high salt levels can also be developed. For severely saline sites (25 dSm^{-1}), which are usually bare and are typically waterlogged during the winter with development of salt crust during summer, planting trees alone is seldom sufficient to overcome salinity problems. Mechanical works to better drain the area, in conjunction with reduced grazing to allow increased grass growth, is critical. Tree planting, however, can be an important part of a comprehensive approach to reclaim these lands. Some of the vegetation like *Suaeda fruiticosa* grows on such soils, whereas grasses like species of *Sporobolus* and *Chloris* genus come over some elevated areas. Samphire (*Haloscarcia* spp.) that grows as a small groundcover on salt lakes in Western Australia can also survive. A few exceptionally tolerant shrubs of the *Melaleuca* family can be established.

4.1.2 Species for Alkali Soils Afforestation

The species consistently performing better under alkali conditions of soils or irrigation waters have been presented in Table 7.5. However, application of some ameliorative measures improves plant survival and growth. For example plantation of *Prosopis juliflora* in sodic soils of semi arid region in Haryana showed positive influence of gypsum application on survival (Singh et al., 1989). Mix tree plantation ameliorate the soil at faster rate as compared to monoculture indicated by planting *Populus deltoids* at a spacing of 4m × 4 m, *Syzygium cuminii* and *Dalbergia sissoo* in between poplar tree are useful with enhanced reduction in the salt concentration in the soil (Chaturvedi et al., 1986). Tree density in a plantation is also a critical factor. For example, *P. juliflora* planted at spacing of 1m × 1 m and 1m × 2 m under irrigated conditions and application of 15 tons per ha gypsum, produced above ground biomass of 39 kg/tree at a density of 5,000 plants/ha and 32.2 kg/tree at a density of 10,000 plants/ha after 7 years (Singh and Abrol, 1986). However, considering the carrying capacity, the tree density in salt affected soil should not be more than 400 trees per hectare (Bhumbla, 1986). Soil amendment with gypsum at

100% gypsum requirement and 3 kg FYM enhanced growth equivalent to that obtained using the amendments applied in the auger hole technique (Gill et al., 1993; Arya et al., 2005). *Acacia ampliceps* grow well under saline environment, but its maximum growth was observed under low to medium salinity patches (4-12 dSm^{-1}) with survival percentage 80-90 (Arya et al., 2005), but a reduction in the percent survival of *A. ampliceps* up to 50 has been reported at salinity level of 12-16 dSm^{-1} (Ashraf et al., 2006). However, *A. ampliceps* has also been observed surviving and growing very well at highly saline eroded black soil and gave sufficient biomass.

Table 7.5 Species tolerant to varying levels of alkalinity for their use under afforestation.

Soil pH_2 down to 1.2 m	Species
>10	*Acacia nilofica, Butea monosperma, Casuarina equisetifolia, Prosopis juljflora, Prosopis cineraria*
9.0 to 10.0	*Aegle marmelos, Achras japota, Albizia lebbeck, Carissa carandas, Cassia siamea, Eucalyptus tereticornis, Feronia limonia, Pongamia pinnata, Phoenix dactyljfera, Psidium guajava, Sesbania sesban, Tamarix articulata, Terminaiia arjuna, Zizyphus mauritiana, Zizyphus jujuba*
8.6-9.0	*Azardirachta indica, Dalbergia sissoo, Emblica officianalis, Grevalia robusta, Hardwickia binnata, Kigelia pinnata, Morus alba, Moringa oleifera, Mangifera indica, Pyds communis, Populus delteoides, Punica granatum, Prunus persica, Tectona grandis, Syzygium cumuni, Vilis vinifera*

4.2 Plantation and management practices

Growing trees on sodic soils requires modification in the root-environment by (i) amending the chemical nature of soil for optimum growth of roots, leaching of salts and maximum retention of soil-moisture; (ii) breaking the hard pan by perforation so that vertical growth of roots should be in place; and (iii) proper maintenance of soil-fertility by applying fertilizers and manure. The technique adopted for afforestation of sodic soils is mainly depend upon site and soil conditions, species to be planted and the purpose of the plantation. Considering this development of sodic soils for afforestation involves the following components:

4.2.1. Site Preparation

For successful plantation of trees for timber production and orchard establishment, one should dig pits of size 90 cm × 90 cm × 90 cm. In these pits, hard $CaCO_3$ layer should be broken with the help of mechanical auger, at least to a depth of 180 cm. The diameter of the post hole may vary from 15 to 30 cm. Shallow pits of sizes 60 cm × 60 cm × 60 cm or 45 cm × 45 cm × 45 cm can be employed for energy-plantation, especially where *Prosopis juliflora* is going to be planted. Breaking of hard layer through mechanical auger however is a must for proper growth of all other plant-species (Gill and Abrol, 1985).

4.2.2 Refilling pits/auger Holes

After digging of pits, it is necessary that these pits should be filled back with appropriate mixture as soon as possible. Points needing consideration here are: (i) addition of salt through loose salt-rich surface-soil and/or addition through wind; (ii) rainwater may fill the pits with salt-rich surface run-off from adjoining areas and thus increase the concentration of toxic soluble salts, like carbonate and bicarbonate of Sodium, which are harmful for the roots. The stagnated or pit filled run-off water should be drained out and the fine clay deposited inside the pits should be scraped out before refilling; (iii) after a number of rains, it is difficult to mix amendment, farm-yard manure (FYM) and rice-husk (RH) with sticky sodic soil and properly fill back the pit; and (iv) If the pits are filled before the rainy season then the rainwater can be used for dissolution of amendment and leaching of salts from the pit. While refilling the postholes, soils should be properly packed, so as to avoid serious settling down at later stages, which can affect the establishment of seedlings. After filling the pit, a raised earthen bund should be made around it (with the amended soil), so as to prevent the entry of salt-rich run-off water into the pit. Additions of gypsum and pyrite in the filling mixture of the planting holes show pronounced effect on the survival and growth of tree species. Many studies (Sandhu and Abrol, 1981; Yadav, 1981; Gill and Abrol, 1985; Singh and Abrol, 1986) conducted on the mixture for filling the planting hole suggest the following combinations:

- Shallow pit with 3 kg gypsum + 3 kg FYM + 3 kg Rice husk;
- Deep pit with 5 kg gypsum + 5 kg FYM + 5 kg Rice husk; and
- Deep pit for fruit tree with 10 kg gypsum + 10 kg FYM + 5 kg Rice husk.

Auger hole technique

It helps facilitate rooting through the hard sub-surface layers, which involves the digging of pits (20-25 cm diameter and 100-130 cm deep) with tractor mounted diggers. These pits are refilled with a mixture of the original alkali (excavated) soil together with 3 kg gypsum and 8 kg farm yard manure (FYM), before 3 month old tree seedlings are planted in these pits. Approximately 20 g zinc sulphate and 10 g BHC powder are also mixed in the filling mixture. Four irrigations are given after planting at an interval of 4-5 days during the first month. Planting is generally carried out from July to September, and this technique results in >90% survival on highly alkaline soils where nothing else could be produced. In a field trial, growth and biomass production after 6 years was significantly higher when planted by this augerhole technique than by the traditional pit and trench planting methods.

In a polybag technique, where polybag carrying the seedling was removed from the base as well as whole of the polybag was retained as such under field plantation with soil of Ec > 12 dSm^{-1}, showed percentage survival of 52.85% for the seedlings of *A. nilotica, Eucalyptus tereticornis, Dalbergia sissoo, Ailanthus excelsa, Azadirachta indica* and *Prosopis cineraria* (Bimlendra and Toky, 2006). *Dalbergia sissoo* and *Eucalyptus tereticornis* attained maximum growth and biomass in the field after six months. *P. cineraria* had the highest root: shoot ratio. This is adaptive mechanism for survival in harsh environmental conditions. This technique assured survival even in tree species which are reported to be sensitive to salts such as *D. sissoo* and *A. indica*, while the survival and growth of other salt tolerant tree species viz. *P. cineraria* and *A. nilotica* were enhanced.

4.2.3 Soil Amendments

For the soil amendment many different methods are used as physical amelioration (deep ploughing, sub-soiling, sanding, profile inversion), chemical amelioration (amending of soil with various amendments like gypsum, calcium chloride, limestone, sulphuric acid, sulphur, iron sulphate) and electro-reclamation (treatment with electric current). Gypsum is the most commonly used amendment due to its availability at low cost. Joachim et al. (2007) pointed the beneficial effect of combined use of farm yard manure and gypsum/ Calcium chloride on the reclamation of sodic soils, where these chemicals directly supply soluble calcium for the replacement of exchangeable sodium. Likewise, sulphuric acid or sulphur that indirectly through chemical or biological action, make the relatively insoluble calcium carbonate available for replacement of sodium (Sibbet, 1995). The quantity of sulphur required is depending upon the soil and climatic conditions. To reduce soil pH of 8 to 6.5, about 1.25 to 2.5 tons of sulphur and 5 to 7.5 tons of organic matter per hectare will be required for cropping. The incorporation of molasses, rice husk and cow dung decreases soil EC, pH and SAR (Hussain et al., 1998) and increases the yield (Prapagar et al., 2012). Addition of organic amendments in the form of straw like rice husk compost, water hyacinth compost, green manures of *Sesbania aculeata*, decomposed composts and plant root action all help dissolve the calcium compounds found in most soils and improves soil properties for plant growth (Stanley, 2008; Gul et al., 2014; Abdel-Fatah, 2012). The most effective, hydrotechnical amelioration methods, are based on the removal of exchange and soluble sodium and changing the ionic composition of soils by added chemicals with parallel leaching of sodium salts out of the soil profile. Use of coal powder has also been observed effective in growing alfalfa in saline soils (Raychev et al., 2001).

4.2.4. Irrigation

Because of low rainfall, irrigation during initial stages of development and growth is essential for tree seedlings raised on such problematic soils. Depending upon the climatic conditions and distribution and frequency of rainfall, the irrigation should be applied at least once in 7 days in the first three months and then once in a month for at least one year. Even at the latter stages of growth, protective irrigation is required particularly in sodic soils (Ahmed and Qamar, 2003). Frequency of irrigation should be more in shallow pits, as compared to the deeper pits. As the surface of soil contains high concentration of salts, flood-method of irrigation should be avoided in the first year of planting. Spot-irrigation with the help of containers/pipes will be more useful. At later stages, irrigation can be done through channels joining the various pits. However, to avoid salts accumulation on the ridges of the channels connecting the pits, application of gypsum in the channel and on the ridges can be of great help. Wherever possible, physical removal of salts, especially in the first year, can be useful.

4.2.5 Improved Drainage

A common factor in salt-affected areas is prolonged periods of saturated soils. It is this double combination of salt and water logging that is particularly damaging to plant growth. Plants can withstand a much higher soil salt concentration if the soil around the roots is well drained. Deep ripping the soil of the site greatly improves water infiltration that helps reduce the concentration of salt in surface layers. It may also reduce ponding of surface water. Ridge mounds provide a well drained area of soil for young seedlings to grow during the critical first year (Arya and Tewari, 2009). Tree growth and survival are maximized where the mound is more than half a metre above natural the soil level and where double mounds are formed (Fig 7.1). This enables trees to be planted in a slight depression that catches rainwater but still keeps initial root growth above the saturated soil profile. Additional deep furrows alongside the mounds will drain the site better and may further boost tree growth. Ridge mounds constructed on a grade can also help to channel water away from the affected areas. However, care must be taken to avoid creating additional erosion problems.

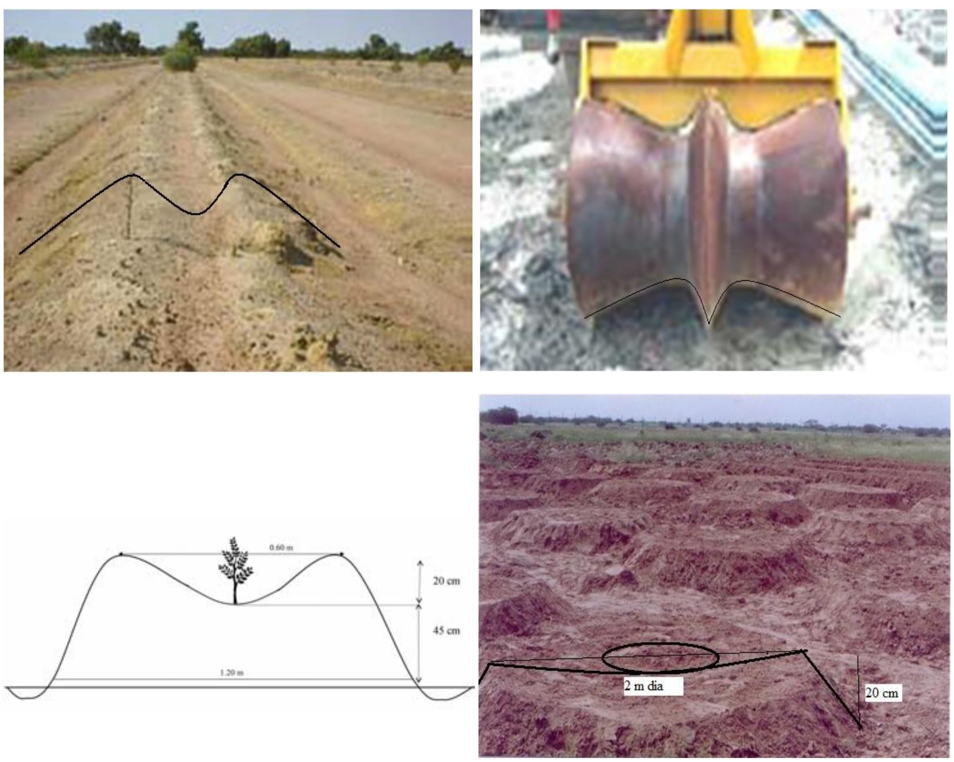


Figure 7.1 Double ridge mound or 'v' notch mound and the press-wheel used for its construction. This design is used in saline soil conditions where temporary leaching of soil salt is necessary for establishment of seedlings or seeds. Circular dish mounds for plantation in saline/ water logged areas (right lower).

Double ridge mounds or V-notch mounds are bunds of 0.50-0.60 m broad at top and 1.2 m at bottom. The height of the bund is about 0.50-0.75 m high with ridges of 20 cm high on both sides (Mullan and White, 2002, Fig 7.1c). Likewise circular dish mound is raised to a height of 20 cm in a circle of 2.0 m diameter. Survival of *Eucalyptus camaldulensis* and *E. largiflorens* have been observed to increase with increasing mound height. In the double-ridge mounds, the improvement was from 35% in 0.25-m-high mounds to 49–59% in 0.50 m, 0.75 m and 1.0 m high mounds (Ritson and Pettit, 1992). Double ridge mound has also been observed best for *Atriplex lentiformis*, *A. stocksii* and *A. amnicola* whereas circular dish mound is best for *A. lentiformis* (Arya, 2009; Arya et al., 2010). Root development has been observed along the ridges in Double ridge mounds and in all direction in case of circular dish mound (Fig 7.1d). Gypsum application enhances the growth and yield of *A. ampliceps* by 2-fold biomass on deeper and shallow alkali soils at the age of five years (Arya and Lohara, 2008). *Suaeda nudiflora* and *Atriplex stocksii* found on mud flats along sea coast or in saline soils in Gujarat also show high survival rate and growth. Biomass production is highest on circular dish mound both for *S. nudiflora* (2.25 tons ha^{-1}) and *A. lentiformis* (1.30 tons ha^{-1}) after 36 months (Arya and Lohara, 2006). Circular dish mound supported with gypsum and 9 g N is beneficial for *Colophospermum mopane* with better growth and biomass. Its roots penetrate the $CaCO_3$ kanker pan further enhancing its utility (Arya and Lohara, 2008; Singh and Rathod, 2006b).

4.2.6 Reduced Evaporation

Organic mulching around young planted seedlings reduces surface evaporation and salt concentration. This also boosts tree survival and growth. Various materials are also used that include straw, spoilt hay, grass clippings, stable sweepings, old animal manure, tree mulch, woodchips, newspapers, old carpet and rags, available farming byproducts can be used as mulch for saline soil reclamation (Kaswala et al., 2012; Bezborodov et al., 2010; Zhang and Wang, 2013). It is essential to establish a sustainable practice that will enable low-lying saltlands to become productive and improving soil health and biology which assists in the overall improvement of these ecosystems (Maomao et al., 2014). By improving the overall health of the system and the associated soil conditions, the once unproductive land will increase in value, and in turn assist in the restoration of neighbouring remnant and riparian zones through better nutrient catchment and reduced erosion and runoff of salts, nutrients and topsoil due to poor soil structure and low in organic matter. Effects of drip irrigation just below the mulches on the improvement of saline-alkaline soil and cotton yield indicates that the salt leaching effect is bad with irrigation of 400 mm and good with irrigation of 525-600 mm, whereas 675 mm of irrigation appeared wastage in water resource (Wang et al., 2014). Non-linear relationship was observed among seed cotton yield, lint cotton yield, water utilization efficiency (WUE) and irrigation amount, where optimal irrigation of 475-564 mm was obtained. With initial soil salt content of 2.55%, the suitable irrigation for cottons with drip irrigation under mulch in saline-alkaline soils was 525 -564 mm and use of mulch provide support in raising the WUE of drip irrigation.

4.2.7 Use of Fertilizers

Fertilizer like single superphosphate or di-ammonium sulphate which increases acidity in soil and maintains fertility of soil impoverished by leaching and cropping appears beneficial in saltland reclamation. Work at the Central Soil Salinity Research Institute, Karnal suggests that crops on alkali soils generally needs 20-25% more nitrogenous fertilizer than those on normal calcareous soil (Abrol and Gupta, 1990). Doddema et al. (1986) has reported a decrease in ammonium and nitrate in soil and plants *Arthrocnemum fruticosum* in parallel with increasing salinity in a saline area in Jordan. Nitrite is only found in the roots and always in very low quantities (Singh, 1998). Application of phosphorus and zinc aids growth of plant in saline soils. Gobarah et al. (2006) has reported that foliar spraying with zinc levels has a significant effect on growth and yield of groundnut and also enhances uptake and N, P and K and their concentrations in barley plants (AbdEl-Hady, 2007). Sodium concentration of tissues decreases with increasing Zn rate and its uptake of P and K concentrations and their uptake by barley plants. Application of nitrogen along with gypsum (gypsum + 9g N) enhances the growth and biomass of *Salvadora persica* as compared to application of nitrogen only (Arya et al., 2005). In another study, all plant characters of *Salvadora oleoides*, *Prosopis cineraria*, *Capparis decidua* and *Tamarix aphylla* grown at five salinity levels (0.65, 5.8, 10.69, 20.71 and 30.4 mS cm^{-1}) and two levels of fertilizer (control and with addition of 100 kg N ha^{-1} and 60 kg P ha^{-1}) have been observed decreasing with increasing salinity levels, but enhances with increasing fertility (Sharif and Khan, 2009). Here ECe value at which dry matter production is reduced to 50% as compared to un-fertilized control plants is highest for *S. oleoides* followed by *P. cineraria*, *T. aphylla* and *C. decidua* under low fertility as well as at supplemental fertilizers. However, addition of fertilizers alleviate the adverse effects of salinity and support plant growth.

5. WATERLOGGED SOILS

Clearing of native vegetation results in rising groundwater tables and mobilize the stored salt causing adverse impacts to farmland, infrastructure, water resources, and biodiversity in many parts of the world. Introduction of canal irrigation in dry areas underlain with brackish groundwater has led to rising water table and consequent water logging and salinity problems (Mandal and Sharma, 2011). An area is said to be waterlogged when the surplus water stagnates due to poor drainage or when the shallow water table rises to an extent that soil pores in the root zone of a crop become saturated, resulting in restriction of the normal circulation of the air, decline in the level of oxygen and increase in the level of carbon dioxide (Plate 7.2). The actual depth of water table, when it starts affecting the yield of the crops adversely, may vary over a wide range from zero for rice to about 1.5 meters for other crops. Area with water table within 2 meters of the land surface in waterlogged. The areas with water table between 2 to 3 meters below land surface are potential areas for waterlogging, whereas the areas are safe when the water table is below 3 meters of the land surface. Recent technical and economic research has emphasized how difficult it will be to establish sufficient perennial species to get control of rising groundwater tables. Wherever water tables are already shallow, the options for farmers are salt-tolerant plants or engineering (e.g. deep open drains). There are a number of good practices for development of new and better options for plant-based management of salinity (Pannell and Ewing, 2006). In India, 823 numbers of schemes covering nine states excluding Rajasthan were approved for reclaiming 122532.00 ha waterlogged area costing Rs 1953.9 million, out of which an area of 78278.00 ha is reported to be reclaimed till March, 2013 (http://wrmin.nic.in/forms/list.aspx?lid=414).

5.1 Reclamation of water logged Areas

Various measures to check waterlogging include constructing drains, installing pumps to lift water, laying pipes beneath the ground under sub-surface drainage, management of water under irrigation and use of crops and trees tolerant to waterlogging.

5.1.1 Proper Drainage System

Subsurface drainage is an effective tool to combat the twin problem of waterlogging and salinity and thus to protect capital investment in irrigated agriculture and increase its sustainability (Gupta, 2002). Subsurface drainage systems consisting of open and pipe drains with drain spacing varying between 45 and 150 m and drain depth between 0.90 and 1.20 m, installed in farmers' fields, enhanced crop yields significantly, e.g. rice with 69%, cotton with 64%, sugarcane with 54% and wheat with 136%. Such increase was because of lowering of water table and soil salinity levels by 25% and 50%, respectively than in the non-drained fields (Ritzema et al., 2008). However, drain depth and range depends upon agro-climatic and soil conditions. For example an average drain depth of 1.2 m, with a range from 1 to 1.5 m have been found adoptable considering the gravity drainage requirement and flat land in Chambal Canal Command area of Rajasthan (Bhattacharya and Michael, 2003). Thus, farmers should have adequate surface drainage facilities to remove excess water from their fields. The surface runoff and subsoil drainage of water should be relatively high, particularly during rainy season so that water should not retain on soil surface.

5.1.2 Using Tube Wells

A network of tube wells is an ideal device for the dual purpose of lowering the water table and for providing supplemental irrigation. Tube wells have the capability to draw out of the earth large quantities of water continuously and are a good technique to reclaim water logged areas (Malmberg, 1975). However, pumping causes widespread changes in the chemical quality of ground water by changing the rate and direction of flow, inducing infiltration from canals, and mixing of indigenous waters of different chemical quality.

5.1.3 Lining of Canals

Continuous seepage from canals causes serious water logging accompanied with salt accumulation, converting a once fertile land into a huge waste and spoil (Hooja et al., 1997). Suitably designed concrete lining of canals and other water channels is provided to check the seepage from a canal (Swamee et al., 2000). It helps not only in controlling water logging but also in saving useful irrigation water.

5.1.4 Effective Water Management

Since the overall availability of groundwater is limited, the chance of minimizing productivity losses by applying more groundwater does not appear to be feasible. The only option is to reduce irrigation intensity and to arrive at an optimal mix of irrigated and rain-fed areas. The farmers and practitioners should be educated about water management and use of excessive irrigation water for cultivation of certain crops should be avoided. Modern irrigation techniques like drip irrigation should be adopted.

5.1.5 Tolerant Crops

Plants adapted to waterlogged conditions have mechanisms to cope with the stresses like aerenchyma formation, increased availability of soluble sugars, greater activity of glycolytic pathway and fermentation enzymes, and involvement of antioxidant defense mechanism to deal with post hypoxia/anoxia oxidative stress (Jackson and Colmer, 2005; Sairam et al., 2008). Gaseous plant hormone ethylene also plays an important role in modifying plant response to oxygen deficiency. Crops like, Brassica spp., rice, oats, waterchestnut, *Colocasia* and medicinal plant Acorus and *Helianthus tuberosus* etc are the preferred species for water logged areas. The catfish and waterchest integrated technology has potential to derive about Rs.60, 000-70,000/ha net return per annum (Parida, 2011).

5.1.6. Tolerant Trees

Tree species such as *Acacia nilotica*, *A. tortilis*, *Casuarina glauca* and *C. obesa* have been rated moderately tolerant to waterlogged saline soils (Dagar and Tomar, 2002). It has been observed that by way of furrow planting technique, it is possible to keep salt concentrations relatively low in the rooting zone of tree saplings such that they are able to escape the adverse effect of high salinity. Tree species like *Acacia farnesiana*, *Parkinsonia aculeata*, *Prosopis juliflora*, *Salvadora persica*, *S. oleoides* and *Tamarix* sp. could be rated the most promising which could be grown satisfactorily on waterlogged saline soils with ECe > 25 dSm^{-1} in their active root zone. Thus use of bio-drainage is envisaged as a benign and cost effective technology to lower the rising saline water table so as to take it well below (>1.5 m) the root zone of the crop plants.

5.2 Species and site suitability

Selection of tree species for water table control essentially depends upon their transpiration potential and uptakes water through deep and extensive root system, planting technique and basic amendments. Studies conducted on one year old plants of six species of *Eucalyptus* indicated that weekly transpiration rate ranged from 2.5 to 11.5 g of water per day per 100 cm^2 of leaf area (Anonymous, 1984). *Eucalyptus* plantation is able to reclaim waterlogged saline soils in canal command areas of IGNP, i.e. western Rajasthan, where five years old trees of *Eucalyptus* spp. could lower the water table by 85 cm with an average transpiration rate of 50 litre per day per plant (Bala et al., 2014). Thus *Eucalyptus* has very high potential for transpiration of water (Table 7.6) and has emerged as most suitable tree species for bio-drainage under such condition (Toky, 1992; Rani et al., 2010; Singh et al., 2014b, Anonymous, 2014).

Table 7.6 Effect of different levels of irrigation on the rater of transpiration (mmol H_2O per sq. m) of *D. sissoo, E. camaldulensis* and *A. nilotica* seedlings. Values are mean ± Standard Deviation.

Tree species	Year	Irrigation level				
		20 mm	14 mm	10 mm	8 mm	Live saving
D.sissoo	Ist	3.01±1.06	2.62±0.90	2.06±0.68	1.75±0.56	1.48±0.59
	IInd	1.91±0.96	1.59±0.86	1.25±0.64	1.09±0.57	0.70±0.44
E.camaldulensis	Ist	2.65±0.69	2.32±0.57	1.70±0.49	1.34±0.38	0.79±0.10
	IInd	2.49±0.71	2.18±0.56	1.54±0.28	1.25±0.14	0.77±0.15
A. nilotica	Ist	2.57±0.69	2.36±0.57	1.56±0.42	1.22±0.22	0.87±0.16
	IInd	2.53±0.73	2.29±0.54	1.67+0.47	1.29±0.35	0.86±0.29

Source: Singh et al. (2014b).

Although water table response to revegetation is governed by many factors, trees have the greatest potential for lowering the rising water tables. Eucalypts, Casuarinas, *Bambusa arundinacea*, *Tamarix* spp., Lucerne etc. are some species which have high biodraining ability from moist soils (Chhabra and Thakur, 1998; Zang et al., 1999; Stirzaker et al., 1999; Cramer et al., 1999). Comparative performance indicates more water use and greater decline in water table underneath *Eucalyptus camaldulensis* compared to *Casuarina glauca* plantation (Roy Chowdhury et al., 2011). Thus, selection of the species can accordingly be done depending upon environmental conditions and site characteristics (Table 7.7). To maximize the effectiveness of trees and shrubs in reducing the recharge to groundwater following points need consideration:

- Planting should occur on the recharge areas of local aquifer systems and where area is steep and dissected, characterized by weathered and fractured rock with shallow soils (less than 5 m) or where the soils are deep, sandy and permeable.
- Location of the planting area has access to relatively fresh groundwater (George et al., 1999).
- As most dryland salinity occurs in the 400 to 600 mm/yr rainfall zone, the choice of species is based both on water uptake and economic viability.
- Trees and shrubs should be planted in a design to maximize water usage while minimizing the area under plantation, i.e. high density.
- About 30 to 50% of the landscape should be revegetated within intermediate and regional scale systems.
- Groundwater salinity should be <7.5 dS m^{-1} in water discharge zone. Plantings should be done on the lower slopes above or away from seeps and/or scalds and management techniques, i.e. fencing to control grazing,

mulching and fertilization etc should be used to assist in the establishment of plant cover.

- Combining tree and shrub planting with other vegetation/agronomic and engineering measures should also be considered for effective control of rising water table.
- Planting should be designed to meet other objectives such as biodiversity conservation or carbon sequestration for reduction in greenhouse gas emissions.

Table 7.7 Tree species for waterlogged saline soils with ECe in dSm^{-1} down below 0.3 m.

ECe (dS/m)	Firewood/timber/fmit species
20-30	*Acacia farnesiana, Prosopis juliflora, Pithecellobium dulce, Parkinsonia aculeata, Tamarix aphylla*
14-20	*Acacia nilotica, Acacia penaatula, Acacia tortilis, Casuarina glauca, Casuarina obese, Casuarina equisetifolia, Eucalyptus camaldulensis, Feronia limonia, Leucaena leucocephala, Zizyphus jujuba*
10-14	*Callistemon lanceolatus, Casuarina cunninghamiana, Eucalyptus tereticornis, Terminalia arjuna*
5-10	*Albizzia caribea, Dalbergia sissoo, Emblica, officianalis, Guazuma ulmifolia, Punica granatum, Pongamia pinnata, Samanea saman*
<5	*Acacia auriculiformis, Acacia deami, Acacia catechu, Syzygium cumini, Salix spp., Tamarindus indica*

5.3 Planting design

When planted in large numbers in the recharge areas of catchments trees can reduce the amount of water entering the system. Over time, this can help in lowering water table further down the slope. Trees established around the edge of a water-logged, salt-affected area help lower the water level sufficiently to help prevent the further spread of the problem (Ram et al., 2007). However, the interaction of salinity stress and lack of oxygen in the root zone under waterlogged conditions makes it difficult to establish the tolerance limit of a species. *Acacia auriculiformis*, *Terminalia arjuna*, *Tamarix articulata* and *Casuarina equisetifolia* can tolerate saline conditions without high water table, where *Prosopis juliflora*, *Tamarix articulata* and *Casuarina equisetifolia* can tolerate high salinity and high water table both (Tomar and Gupta, 1985).

Tall seedlings (plants) are generally preferred to transplant on mounds of suitable dimensions so that complete submerging during rainy season can be avoided. Planting on soil ridge (raised bund) is most suitable than planting on flat land to provide sufficient soil depth for root growth and aeration (Plate 7.2d). The height of ridge varies from 0.50 to 1.0 m depending upon the soil condition. Afforestation of Eucalyptus or Casuarina on flat land with pits or auger holes having soil mixed with gypsum or FYM supported by single super phosphate and granular insecticide gives satisfactory growth in waterlogged area (Tiwari and Mathur, 1983; Abrol and Sandhu, 1980). Studies on plantation of *Eucalyptus* on waterlogged and saline-alkali soil indicated highest growth rate and survival of the seedlings on raised bunds (ridges) covered with polythene sheet and soil having pyrite (Hira and Thind, 1986). The experimental observations indicate that the survival and growth of tree species are markedly improved with furrow planting when compared with sub-surface and ridge-trench planting methods in saline water logged area of semiarid region (Tomar et al., 1998). The furrow technique provides favorable niches for plant survival and growth and was also the most economical for such soils compared to ridge-trench and subsurface. *Prosopis juliflora*, *Tamarix* spp., *Casuarina glauca*, *Acacia farnesiana*, *A. nilotica*, *A. tortilis*, and *Parkinsonia aculeata* have been found most promising species for these saline soils. *Casuarina glauca* and *Salvadora oleoides* survived even prolonged stagnation of floodwaters for 9 months. The biomass of *Prosopis juliflora* and *Casuarina glauca* have been recorded highest (98 tons per ha and 96 tons per ha), followed by *Acacia nilotica* (52 - 67 tons per ha) and *A. tortilis* (41 tons per ha) when planted with subsurface or furrow techniques under saline waterlogged soils (Tomar et al., 1998).

Ridge plantation of *Eucalyptus tereticornis* (Mysure gum) clone in waterlogged area have been observed reducing the levels of groundwater table underneath the strip-plantation by 0.85 m in 3 years (Ram et al., 2007; Ram et al., 2011). Here ridge-to-ridge distance was 66 m and each ridge was 0.5 m high, 2.6 m wide at the base and 2.0 m wide at the top. The strip–plantation contained two rows of trees at a spacing of 1m x 1m, resulting in a density of 300 plants ha^{-1}. The annual rate of transpiration by 240 surviving trees per ha was 268 mm per annum against the mean annual rainfall of 212 mm. Likewise, plantation of *Eucalyptus camaldulensis*, *E. fastigata*, *E. rudis* and *Corymbia tessellaris* on raised bunds, improved vegetation cover with simultaneous decrease in water table in waterlogged area of IGNP command area in the Indian desert (Bala et al., 2014). Performance of *E. rudis* was best with respect to growth, biomass, transpiration rate and overall bio-drainage potential. *E. rudis* maintained uniform transpiration and photosynthesis rate throughout the year. Ground water level receded by 145 cm in *E. rudis* plot compared to 90 cm, 70 cm and 60 cm in *C. tessellaris*, *E. camaldulensis* and *E. fastigata*, respectively within a period of four and half year. Soil organic carbon, electrical conductivity, NH_4 and NO_3-N were high in *E. rudis* and low in *E. fastigata*. *E. rudis* had high potential to be used as an efficient bio-drainage species in canal command waterlogged area of Indian desert (Fig 7.2). Apart from the planted species, *Prosopis juliflora*, *Tamarix dioca* and *Saccharum munja* also have come up in the area with recession of ground water table as natural succession and contributed significantly for further lowering of ground water table and increasing productivity.

A field bund plantation of *Callistemon lanceolatus*, *Eucalyptus tereticornis* clone-3, *E. tereticornis* clone-10, *E. tereticonis* clone -130, *Eucalyptus* hybrid clone (*E. tereticornis* × *E. camaldulensis*), *Melia azedarach*, *Pongamia pinnata*, *Prospis juliflora*, *Tamarix aphylla* and *Terminalia arjuna* on an abandoned waterlogged area (water table up to 2 m) in strip of about 60 m apart from each other showed variable effects on the ground water table (Toky et al., 2011). In this field bunds were 2.9 m broad at base, 2.6 m broad at top, 0.45 m in height and extend to a length of 150 m from north to south. Two rows of trees were planted on each bund with a row to row distance of 1.3 m. Plant to plant distance was 1.5 m in *Eucalyptus* and 3 m in other species. Height, DBH, foliage development and survival were maximum in 4 *Eucalyptus* clones as well as in *P. juliflora* and *T. arjuna* over past 6 years. A cone of depression of water table immediately beneath each strip plantation was noted as compared with no depression in the control. Depression was to the maximum magnitude beneath strips of *Eucalyptus* spp. (80-97 mm), *Prosopis juliflora* (82 mm) and *Tamarix aphylla* (79 mm). An overall 20 cm decline in water table was observed on entire site during this period making it arable. Thus prudent strip plantation trees raised on farmer's field bunds lowers saline water table remediating degraded arable land and proves a low cost, high return, socially acceptable and environmentally friendly technique. However, a constraining situation exists in the areas where the groundwater is sweet and is being subjected to over-exploitation for irrigation and other purposes, resulting in a steep fall in the ground water table. In such a situation, monoculture of high bio-drainage potential species like *Eucalyptus* may add to the ecological disaster by further contributing to water-table decline. Replacement of fast biodrainers like *Eucalyptus* with slow biodrainers could be a better option in this condition.

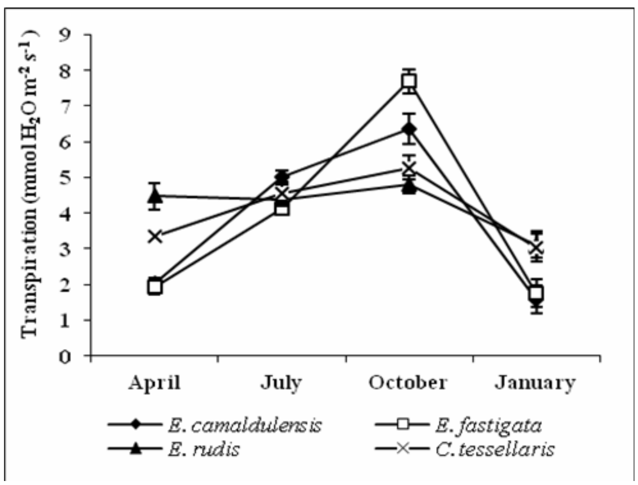


Figure 7.2. Temporal changes in rate of transpiration in different tree species in a waterlogged area of IGNP. Source: Bala et al. (2014).

6. UTILIZATION OF EEFLUENTS

Disposal of ever increasing wastewater causes major ecological and public health problems and requires removal of hazardous compounds/salts before land/water disposal (Chhonkar et al., 2000; Vohla et al., 2009; Irshad et al., 2015). Though deteriorating the ground water quality and promoting human health hazards in the nearby area, the stagnated wastewater is becoming wetlands at many places supporting many flora and fauna (Plate 7.3). Land disposal of effluents has become a widely applied method for their treatments (Hopmanns et al., 1990; Barton et al., 2005) and a source of water and nutrients too particularly in case of municipal effluent. There is need to modify the environment to suit the available plants or change of species to suit the existing environment- the major approaches to improve and sustain land productivity in a saline environment (Singh and Bhati, 2003a; 2005). Management options for land disposal of wastewater include treatment of effluent itself or soil amendments to ameliorate sodicity and salinity levels (Ahamed and Kashif, 2014).

The approaches relevant to wastewater management (Kumar et al., 1998) under Indian conditions are: (i) conservation of various resources, viz., energy, raw materials and water; (ii) adoption of more efficient processes of manufacturing for better resource utilization; (iii) water use minimization strategies; and (iv) reduction in quantity and quality of wastewater requiring treatment. Gypsum is reported for its beneficial effects in terms of soil sodicity amelioration and influence on crop production/seedling growth (Qadir et al., 1998; Haisheng et al., 2008). Likewise, the ash generated as a by-product of combustion of fuel-wood, has potential to be used as a fertilizer in forest systems (Singh et al., 2000; Augusto et al., 2008), as the wood ash is a source of potassium, calcium, magnesium, and other trace minerals (Pitman, 2006) and supposed to be beneficial in soil improvement and plant growth. Land application of municipal effluent enriches soil organic matter and other nutrients for plant growth (Mitra and Gupta, 1999), improves environmental quality of the suburban area and reduces ground water pollution (Stewart and Flin, 1984).

6.1 Quality of wastewater

Not less than seventeen types of heavily polluting industries have been identified by CPCB in India. These are cement, thermal power plant, distilleries, sugar, fertilizer, integrated iron and steel, oil refineries, pulp and paper, petrochemicals, pesticides, tanneries, basic drugs and pharmaceuticals, textile including dye and dye intermediates, caustic soda, zinc smelter, copper smelter and aluminum smelter (Antil, 2012). These industries discharge their effluents into city sewage system, nearby water bodies or adjoining agricultural lands. The composition of some of the effluents from different type of industries is quite variable (Table 7.8). Effluents of Zn melter, iron rolling mills and paper mills are highly acidic with pH <5.0. The effluents of oil refinery, paper mill, distillery and sugar mill are rich in organic carbon ranging from 820 to 28350 mg L^{-1}. There are toxic metals in some of the effluents released from these industries (Table 7.8). Thus, the composition of the industrial effluents varied according to the nature of process for manufacturing and the raw material used (Narwal et al., 1993; Totawat, 1993; Zalawadia et al., 1997; Singh et al, 2009b). The textile industry is one of the major industries in the world that provides employment with no required special skills and play a major role in the economy of many countries (Singh and Bhati, 2003b). Synthetic fibres are dyed using disperse dyes, basic dyes and direct dyes. The textile industry utilizes various chemicals and large amount of water during the production process. About 200 liters of water is used to produce 1 kg of textile. The water is mainly used for application of chemicals onto the fibers and rinsing of the final products. The waste water produced during this process contains large amount of dyes and chemicals containing trace metals such as Cr, As, Cu and Zn which are capable of harming the environment and human health (Ghaly et al., 2014).

Table 7.8 Physico-chemical characteristics of some of the industrial effluents in India.

Parametrs	Industrial effluents								
	Oil refinery	**Paper mill**	**Distillery**	**Cycle industry**	**Spent wash**	**Zn smelter**	**Textile**	**Iron rolling mills**	**Sewage**
pH	6.9	4.8	7.1	7.1	7.2	3.5	9.5	1.4	7.80
EC (dS m^{-1})	0.5	1.2	13.0	4.8	29.0	7.7	4.30	7.86	0.93
COD (mgL^{-1})	850	1350	28350	23	2225	-	300	74,830	190
N (mgL^{-1})	140	168	42	84	1200	-	139.5	1.50	12.5
K (mgL^{-1})	0.1	0.5	1576	163	6681	-	40	3	32
Ca (mgL^{-1})	-	-	-	-	-	-	28	26	256
Mg (mgL^{-1})	-	-	-	-	-	-	6	7	156
Fe (mgL^{-1})	80	240	459	92	61	0.7	0	320	3.64
Mn (mgL^{-1})	7.8	16.4	37.9	15	4	-	0	280	0.32
Cu (mgL^{-1})	4.0	10.9	19. 3	64.0	0.8	13.0	0	91	0.26
Zn (mgL^{-1})	30.0	6.4	37.9	2.4	1.2	-	0	375	0.48
Pb (mgL^{-1})	1.0	3.8	8.7	-	0.7	-	-	-	-
Ni (mgL^{-1})	3.0	4.2	6.6	30.0	0.7	-	-	-	-
Cd (mgL^{-1})	0.1	0.2	0.3	5.4	0.06	0.02	-	-	-

Source: (Antil, 2012; Narwal et al., 1992; Totawat, 1993; Zalawadia et al., 1997; Singh and Bhati, 2003a; Singh et al., 2009b; Chowdhury et al., 2015).

6.2 Species suitability for afforestation

Some species grow naturally in the wastewater disposed areas like *Phragmities australis*, *Tamarix* spp., *Prosopis juliflora*, *Parkinsonea aculeata*, *Salvadora persica*, *Sesbania aculeata*, *Typha angustata*, *Echnochloa* spp., *Chloris barbata*, *Heliotropium curassavicum*, *Paspalum verginetum*, *Aeluropus lagopoides* indicate their tolerance towards the quality of water. Sewage irrigation have been reported to have positive effect on crop yield and higher yields of vegetable crops are obtained when irrigated with untreated sewage water compared to irrigation with canal water (Mahida, 1981; Shafiq-ur-Rehman, 2010). However, utilization of such wastewater in growing tree appears more beneficial rather than its use in growing vegetable, which has direct link with food chain. The responses of *Acacia nilotica*, *Casurina equisetifolia*, *Terminalia arjuna* and *Syzygium cumini* have been observed fairly better towards the tannery effluent water, where survival of these species were 99%, 96%, 99.5% and 97.7%, respectively in Kanpur area of Uttar Pradesh. In an experiment conducted on the use of textile effluent, *P. juliflora* performed the best, whereas *A. nilotoca* and *A. lebbeck* were the unsuitable species. Survival of *A. indica* was highest followed by *P. juliflora*. Soil treated with wood ash performed best followed by soil treated with gypsum (Singh et al., 1997; Singh and Rathod, 1999; Singh et al., 2000, 2009b). Irrigation with textile effluent enhances soil pH, EC and Na concentration but decreases Mg, Cu, Fe, Mn and Zn concentration resulting in leaf chlorosis and defoliation, whereas irrigation with municipal effluent and a mixture of textile and municipal effluent had positive influence on soil Mg and micronutrient concentration and the seedlings were without any adverse effect (Singh and Bhati 2003 a,b). Though varied in performance towards different types of effluents released from the industries, some of the species are listed in Table 7.9. Among these Eucalypts, Acacias and Casuarinas are better performers providing substantial amount of biomass in the form of fuel wood and fodder (Singh, 2002).

Table 7.9 Species tested against different types of industrial and municipal effluent disposal.

Type of Effluent	Species	Reference
Municipal sewage	*Casuarina Equisetifolia, Acacia nilotica, Azadirachta indica, Robinia pseudoacacia, Swietenia mahagoni; Acacia saligna*, *Albizia lebbeck*, *Melia azedarach*, *Taxodium disticum*, *Tipuana speciosa*	Kumar and Reddy (2010); Farooq et al. (2010); Singh et al. (2009b); Tabari and Salehi (2009); Ali et al., (2011); Hassan et al. (2002)
Textile industry	*A. nilotica*, *Dalbergia sissoo*, *Eucalyptus camaldulensis*, *Prosopis juliflora*, *Parkinsonia aculeata*, *Acacia tortilis*, *Azadirachta indica*	Kanekar et al. (1993); Singh and Bhati (2003a, b; 2008); Singh et al. (2010b; 2014a); Shah et al. (2010)
Dairy-farm effluent	*Eucalyptus saligna*, *Eucalyptus nitens*, *Salix kinuyanagi*	Roygard et al. (2001)
Dye industry	*Delonix regia*, *Albizzia amara*, *Acacia auriculiformis*	Rajan et al. (2011)
Paper industry	*Swietenia macrophylla, Khaya senegalensis, Acacia auriculiformis*	Suriyanarayanan et al. (2012)
Tannery industry	*Terminalia arjuna, S. cumini, Casuarina equisetifolia, A. indica, Thespesia populnea*	Manikonandan et al. (2016)

6.3 Effluent utilization and productivity

The use of waste water in growing woodlots is a viable option for the economic disposal of waste water (Neilson et al., 1989; Singh and Bhati, 2005). Moreover, wastewater from municipal origin is rich in organic matter and also contains appreciable amounts of macro and micro-nutrients (Gupta et al., 1998; Singh et al., 2010b). Accordingly nutrient levels of soil are expected to improve considerably using continuous irrigation with municipal waste water. Utilization of wastewater mixed with harmful heavy metals under plantations lead to decrease the toxicity, because of a developed rooting system in the plant (Karpiscak et al., 1996) and as such, play the important and fundamental role for the environmental protection. In a lysimetric study, application of municipal effluent at ½ PET (potential evapotranspiration T_1) and canal water at 1PET (T_4) produced same biomass at the age of 2 and 3 years when water requirement of plant was less- saving of half of the quantity of canal water for drinking purposes. Height and collar diameter for the 36 months old seedlings indicates that seedlings of T_3 treatment (sewage application at 2PET) attained greater height in all the three species. *E. camaldulensis* the seedlings irrigated with sewage at ½ PET attained the minimum height, whereas in *A. nilotica* and *D. sissoo* seedlings irrigated with canal water at 1PET attained the minimum height. Collar diameter was equivalent in the both sewage irrigated and canal water irrigated at ½ and 1 PET, respectively in *E. camaldulensis* whereas it was greater in canal water irrigation at 1 PET in case of *A. nilotica* and *D. sissoo*. Collar diameter was significantly high (by 16%, 25% and 42%, respectively) for the seedling irrigated with sewage water at 2PET compared to canal water irrigated seedlings at 1PET (Table 7.10).

Table 7.10 Effect of different levels of municipal effluent on height and collar diameter of trees seedlings at different age (Source: Singh, 2002).

	E. camaldulensis			***A. nilotica***			***D. sissoo***		
Months	**3**	**36**	**48**	**3**	**36**	**48**	**3**	**36**	**48**
Height (cm)									
T_1	37	490	500	33	320	340	50	335	365
T_2	38	520	560	36	310	350	49	355	400
T_3	38	575	640	39	380	415	50	380	415
T_4	36	500	515	43	330	335	50	330	375
Collar diameter (cm)									
T_1	0.5	7.7	7.90	0.4	6.2	6.20	0.5	7.0	7.40
T_2	0.5	7.9	8.60	0.5	6.7	6.70	0.4	7.8	8.00
T_3	0.5	8.9	10.00	0.4	8.0	8.50	0.5	10.	10.90
T_4	0.5	7.6	7.85	0.6	6.4	6.50	0.4	7.2	7.40

However, one cannot ignore that the use of wastewater for irrigation purposes damage the ecosystem because of high concentration toxic substances and heavy metals. The major benefit in most cases is likely to be the value of the fresh water exchange for high-value urban or industrial use. This could lessen the cost of municipal authorities of seeking their supplies through more expensive means. In addition, reuse prevents untreated wastewater discharge to coastal and groundwater systems with ecosystem and tourism benefits. Depending on the local situation, there could also be benefits to farmers if they can avoid some of the costs of pumping groundwater, while the nutrient present in the wastewater could save some of the expense on fertilizer. Relatively more benefits can be obtained in dry areas, where scarcity of water is increasingly high and soil is deficient in water holding capacity and the nutrients availability.

7 BENEFITS OF RECLAIMATION

7.1 Improvement in soil properties

The extensive roots system of different species open the soil, increase air exchange, organic matter and hydraulic conductivity, and decrease the rhizosphere pH as a result of root exudates stimulated biological activity and releases plant nutrients. Foliage deposition on the soil also increases organic matter, humus and mulching decreases evaporation and improves the physical properties of the soil (Arya et al., 2005; Holligton et al., 2001; Singh et al., 1989a). Improvement in saline or alkali soils due to vegetation is advantageous in several ways like (i) no financial outlay for chemical amendments, (ii) benefits from crops grown during amelioration, (iii) promotion of soil aggregate stability and creation of macropores that improve soil hydraulic properties and root proliferation, (iv) greater plant-nutrient availability in soil after phytoremediation, (v) more uniform and greater zone of amelioration in terms of soil depth, and (vi) environmental considerations in terms of carbon sequestration in the post amelioration soil (Boyko, 1966; Qadir et al., 2007). For example *Suaeda fruticosa* accumulate sodium and other salts and leaves of this plant contain 9.06% salt on a fresh weight basis (Chaudhri et al., 1964). The luxuriantly growing halophytes *Suaeda maritime* and *Sesuvium portulacastrum* exhibit greater accumulation of salts (504 and 474 kg of NaCl, respectively from the saline land from 1 ha in 4-month time) in their tissues as well as higher reduction of salts in the soil medium (Ravindran et al., 2007). Zahran and Abdel Wahid (1992) has made an attempt to reclaim poorly drained soils using *Juncus rigidus* and *J. acutus* and has reported that the EC of soil with a 50% saturation decrease from 33 to 22 dSm^{-1} in a single growth period. Amshot grass (*Echinochloa stagnina*), *Arthrocnemum indicum*, *Suaeda fruticosa* and *Sesuvium portulacastrum* reduce exchangeable sodium percent and EC (Helalia et al., 1992; Rabhi et al., 2008; Rabhi et al., 2010). *Phylanthus amarus* is found to be well adapted to variety of soils, at soil pH ranging from alkaline to neutral and acidic conditions and has shown preference for calcareous well drained and light textured soil (Tewari et al., 2001). While *Suaeda salsa* produces about 20 tons dry weight ha^{-1} containing 3-4 tons of salt (Ke-Fu, 1991), *Portulaca oleracea* accumulates 497 kg ha^{-1} with biomass production of 3948 kg ha^{-1} (Hamidov et al., 2007). Nasir (2009) conducted a field study to investigate the effects of growing three types of salt accumulator halophyte species namely *Tamarix aphylla*, *Atriplex nummularia* and *A. halimus*, where these halophytic species decreased the soil salinity at the end of the experiment.

The physical, chemical and biological properties of salt-affected soils improve gradually after establishment and growth of vegetation. Akhter et al. (2003) evaluated the phytoremediation performance of salt-tolerant species *Leptochloa fusca* and observed that soil salinity, sodicity, and pH decreased exponentially by growing this grass as a result of leaching of salts from surface (0–20 cm) to lower depths (>100 cm). Concentrations of soluble cations (Na^+, K^+, Ca^{2+}, and Mg^{2+}) and anions (Cl^-, SO_4^{2-}, and HCO_3^-) were reduced through to greater soil depths. The decline in soil pH was attributed to release of CO_2 by grass roots and solubilization of $CaCO_3$. De Souza et al. (2012) reported *Atriplex nummularia* as a very potential halophyte that sustains under water-stressed condition of sodic or saline soil. They concluded that the growth patterns and anatomical changes shown by the halophyte *A. nummularia* grown under different soil moisture conditions can contribute significantly to the management of soil and water in semiarid regions. The roots of salt-tolerant trees penetrate deeper soil layer and improve permeability, which facilitate salt leaching. Through absorption, the trees are also able to exclude salts. In alkali soils, the ameliorative effects of 20-year-old plantations appeares in the order of *Prosopis juliflora*>*Acacia nilotica*>*Terminalia arjuna*>*Albizzia lebbeck*> *Eucalyptus tereticornis* (Dagar et al., 2005). In this maximum reduction in ESP and pH is observed under *Tamarix articulata*, followed by *Prosopis juliflora* and *Acacia nilotica* in seven-year-old plantations. When raised with saline irrigation, *Tamarix* *articulata* shows a 0.23% increase in organic carbon in its soil surface layer; *Prosopis juliflora* 0.26%; and *A. nilotica* 0.10%. Shirazi et al. (2006) has observed maximum zinc, copper and iron contents in *Acacia nilotica* as compared to *Acacia ampliceps* and *Acacia stenophylla* growing under saline environment. Sodium accumulation in plant negatively relate with nitrogen, phosphorus, copper, zinc, maganese and iron. The high nutritive values in foliage of native acacia indicate that *Acacia nilotica* can play an important role in improving the fertility of the soil (Singh et al., 2014a). Likewise, improvement in soil physico-chemical properties and available N, P, and K under 6-10 years old multipurpose tree species plantation has also been observed than natural fallow, where soil bulk density reduced and porosity and infiltration rate enhanced under the plantations of *Prosopis juliflora, Acacia nilotica,* and *Casuarina equisetifolia, Dalbergia sissoo* and *Eucalyptus tereticornis* (Mishra et al., 2006; Singh et al., 2011a).

7.2 Enhanced production

Improved production systems including horticultural, pastoral, agri-horticultural, silvi-pastoral, silvi-cultural, agroforestry are the components of integrated farming system in bio-saline agriculture. Judicious use of the reclaimed lands for different production purposes and restoration of quality of soil through people's participation in rehabilitative work is the way to get out of problem of salt affected soil in developing countries (Biswas and Biswas, 2014). *Prosopis juliflora-Leptochloa fusca* silvipastoral model was observed to be excellent for fuelwood and forage production and for the amelioration of high pH soils. *Leptochloa fusca* in association with *P. juliflora* planted at a spacing of 3 m x 5 m produced 46.5 tons per ha green fodder in 15 cuttings over a 50 month period without the use of fertilizers or soil amendments. In addition about 80 tons per ha air dried wood was also produced by the *P. juliflora* after 6 years (Singh, 2006). This system, when followed for little more than four years, reclaims alkali soils to such an extent that normal agriculture crops like *Trifolium alexandrinum* and *T. resupinatum* can be grown successfully (Dagar et al., 2005). Likewise, silvipastoral system involving *A. nilotica, Eucalyptus tereticornis* and *Parkinsonia aculeata* on ridges and *L. fusca* grass in the trenches have been found quiet successful (Dagar, 2009). Afforestation with soil amendments improves soil properties and promotes vegetation colonisation resulting in increased number of vegetation including salt tolerant grasses (Arya et al., 2005), which could be used for growing *Cenchrus setigerus* (a highly palatable non salt tolerant grass) latter (Arya et al., 2011).

Quite often fuel wood is obtained from salt-tolerant trees and shrubs that meet the fuel wood requirement of more than a billion people in developing countries. Such fuelwood species are of Prosopis, Tamarix, Salsola, Acacia, Suaeda, Kochia, Capparis, Casuarina, Pithecellobium, Parkinsonia and Salvadora genuses. Besides, species like *Dalbergia sissoo*, *Pongamia pinnata*, *Populus euphratica* and *Tamarix* spp. could provide good-quality wood. In coastal areas too, the mangroves species of Rhizophora, Ceriops, Avicennia and Aegiceras are good fuel woods and contribute to charcoal production also (Ladeiro, 2012). Strip plantations of Eucalypts under waterlogged area sequestered 15.5 tons carbon per ha during the first rotation of 5 years and 4 months, whereas wheat yield in the interspaces of strip plantations enhanced 3.4 times that in adjacent waterlogged areas without plantation (Ram et al., 2011). Seeds of various halophytes like *Suaeda fruiticosa*, *Arthrocnemum macrostachyum*, *Salicornia bigelovii*, *S. brachiata*, *Halogeton glomeratus*, *Kochia scoparia*, and *Haloxylon stocksii* possess a sufficient quantity of high quality edible oil with unsaturation ranging from 70–80%. Seeds of *Salvadora oleoides* and *S. persica* contain 40–50% fat and are a good source of lauric acid.

Experiments conducted at ND University of Agriculture and Technology, Faizabad and CSSRI, Karnal indicate that many fruit plants can be grown in alkali soils by adopting proper site preparation techniques and by using appropriate doses of organic and inorganic amendments. These fruit species are: *Zizyphus mauritiana* (Ber), *Psydium guajava* (Guava), *Punica granatum* (Pomegranate) and *Syzygium cumini* (Jamun). After a sufficient time, the agricultural crops can also be grown in the form of agri-horticultural system, where fruit trees components will be *Emblica officinalis* (amla), *Carrissa carandas* (karonda), *S. cumini*, *P. guajava*, *Z. mauritiana* and *P. granatum*. These fruit trees are sodicity tolerant but do not tolerate water stagnation and frost (Minhas et al., 2005). Likewise, medicinal and aromatic plants can also be grown and are attractive and remunerative options for crop diversification in sodic soils. The continuous growing of some aromatic grasses like palmarosa (*Cymbopogon martinii*), lemongrass (*Cymbopogon flexuosus*) and vetiver (*Vetiveria zizanioides*) reduces the sodicity and improves the physico-chemical properties of the sodic soil because of biological action of grass roots (http://www.vetiver.com/INR_sodic.htm).

Medicinal and aromatic crops also offer attractive and remunerative option for crop diversification while reclaiming salt affected soils (Dagar et al., 2004). Utilization of salt affected wasteland and land affected by sodic/saline irrigation water have a potential to sustain the aromatic crops viz. palmarosa (*Cymbopogon martini*), lemon grass (*Cymbopogon flexuosus*), vetiver (*Vetiveria zizanioides*) and German chamomile (*Matricaria chamomila*) and medicinal crops like periwinkle (*Catharanthus roseus*), ergot of rye (*Claviceps purpurea*), Egyptian henbane (*Hyoscyamus muticus*) and isabgol (*Plantago ovata*) have been found promising for cultivation under salt affected condition. In most of the crops, essential oil yield and quality of oil and content of principal ingredients in medicinal plants are not affected by salinity or alkalinity (Patra and Singh, 1995; Anwar et al., 2001; Cedmap, 2001). Cultivation of *Cymbopogon martinii*, *Cymbopogon flexuosus* and citronella java (*Cymbopogon winterianus*) enhances soil available N also as compared to the initial values (Singh et al., 2004a). Likewise, *Brassica* spp., waterchestnut, *Colocasia* and medicinal plant Acorus and *Helianthus tuberosus* etc are the preferred species for water logged areas.

8. CONCLUSION AND RECOMMENDATIONS

Increased extent and severity of salt-affected and waterlogged areas lead to land degradation in dry lands. In most of the cases secondary salinization is associated with waterlogging, when over-irrigated with water of high salt content. Release of immobilized salts already present in the soils, atmospheric salt dispositions, weathering of soil minerals and use of fertilizers are other factors responsible for increased salinity as a field problem. Most of the measures adopted to reclaim salt-affected lands are amendments for different soils, and are associated with minimizing the salt, sodium, and/or magnesium concentration from the plant root zone. Though better supported by other measure, biological reclamation appears more important from stabilization of soil quality and eco-restoration. Despite the importance of salt concentration in shaping the composition of plant communities, our knowledge about how different species respond physiologically to variable salinity and alkalinity levels is limited, particularly physiological and biochemical mechanisms of halophytes.

- Because of varying tolerance among the species toward stresses like salinity, alkalinity, water-logging and effluent quality, selection of species is the prime, but it should also depend upon the site quality and environmental conditions.
- Various amendments to remediate salt affected soils are leaching of salts/sodium through drainage, use of gypsum or calcium rich salts, sulfur, rice husk and composts of cowdung or leaflitter together with slow release fertilizer are beneficial under afforestation.
- Pits with broken subsurface layer are effective in alkaline soils, but raised bunds are effective by providing sufficient rooting environment. However, it increases the water requirement and similar stresses hence could be avoided in arid climate where water availability is not there for a longer period in a year.
- Raised bund plantation is more effective in the waterlogged area with surface stagnation, where high density mixed plantation could be promoted.
- Findings on the phytoremediation of salt affected soils indicate that some halophytes harvest salt from the soil at significantly high level and hence become a cost-effective and environmentally sound technology in this direction.
- There is need to find out and select the plants having capability to remove the maximum quantity of salts by way of producing higher biomass with some economic value. Further, the selected plant species should tolerate high salt concentration.
- Diversification of halophytes to remediate soil salinity could be more beneficial in accumulating the salt in a cost-effective way. Identification of novel genes with high salt tolerance and biomass yield characteristics and the subsequent development of transgenic plants with superior remediation features would be topic of future research.
- Long-term strategies to restore waterlogged area could involve at least 40 to 50% area of the catchment encompassing the range of issues arising from the changes in the water table rather than concentrating on just one aspect, such as replanting trees.
- Plant based options will need to combine with other options too making better use of the land affected by waterlogging and salinity.

- Use of treated municipal effluent in irrigations can be an overflowing resource from the nutrient elements required for plants.
- It is noted sometimes that the nutrient contents in the municipal effluent is more than needed by plants. In such a condition a diverse community of plants including trees, shrubs and grasses could be a better option for efficient utilization of effluent with increased biomass production per unit area.
- Huge amount of municipal effluent produced in the cities of dry areas can be used (preferably after treatment) for accomplishment of plantation projects and for development of rural and urban green spaces and green belts around the city and for reduction of air pollution and mitigate climate change.

Plate 7.1 Saline land of Talchhaper sanctuary with *Suaeda fruiticosa*/*Spoprobolus diander* in Rajasthan (left) and saline-alkaline land of Little Rann of Kutch in Gujarat with isolated bush (right).

Plate 7.2 Problem of water logging at 1357 RD, IGNP, tree mortality due to development of salinity in water logged areas in Hanumangarh, Rajasthan and rehabilitation of waterlogged area.

Plate 7.3 Discharge of effluent, stagnation in Jojri river near Jodhpur, vegetation like *Phragmites* spp., *Tamarix* spp. etc and the associated problems and effluent utilization in growing trees.

8

QUALITY SEEDS AND NURSERY MANAGEMENT

Importance of good quality seedlings has grown massively because of increased demand for both public and private plantations. Nursery developed seedlings should not be only of good quality but strong enough also to adapt to and resist the exposure to harsh environmental conditions of the dry areas. First step in improving quality of planting material is quality seeds collected from correct species superior in phenotypic characters, i.e. from seed stands or candidate plus trees. Seeds should be healthy and free of pathogens and insect pests. Suitably stored at cool dry places in case of delayed sowing could be tested for viability and germination percentage, which can be enhanced further applying seed treatment techniques. Making conducive environment to start nursery operations at the right time, all necessary materials at site and resolving negative effects of the technical and social factors responsible for a successful nursery operation are some acts favoring development of quality planting materials. This chapter deals with criteria of selecting trees and developing seed production areas, methods of seed collection and storage, testing seed germination and its improvement methods, soil mixture used in beds or containers, time of seed sowing, seed sowing and pricking of germinants and enhancing seedling quality by applying effective doses of water and nutrients together with control of diseases and pests.

1. INTRODUCTION

Productivity and economics of plantation and the environmental services provided by it depends upon the quality of planting material (Maltoni et al., 2010). The importance of good quality seedlings has also grown massively because of increased demand of healthy seedlings for both supplies to the public and use in large scale plantation (Suri and Mohan, 2011). Teak (*Tectona grandis*) is principal timber species in India, whereas plantations of Eucalypt (i.e., *Eucalyptus teriticornis* and *E. grandis*) were initiated to meet the pulpwood raw material requirements. Plantation of *Bombax cieba* was to supply matchwood to the small scale industries, but is taking momentum for plywood industries also. *Acacia auriculiformis* was propagated as a fuel wood tree but is now being used in pulp factories. Likewise, species like Acacia (*Acacia tortilis*), Albizia (*Paraserianthes falcataria*), Pinus (*Pinus* spp.), Prosopis (*Prosopis juliflora*), silver oak (*Grevillea robusta*), and wattle (*Acacia mearnsii*) plantations were also introduced to meet the local needs and improve environmental conditions (Chundamannil, 2001). Reducing the effects of changing climatic conditions and its mitigation are of more concern to most of the afforestation programmes. Because of harsh environmental conditions like erratic rainfall, infertile soils, high alkalinity and salinity, waterlogging, excessive biotic pressure and so on, increasing vegetation under natural regeneration or direct seed sowing are likely to be unsuccessful. Though there are varying degrees of merits and demerits, but nursery raised seedlings of appropriate quality can be a relatively better option particularly in areas, which are full of adversities, i.e. dry areas.

Experimental evidences show that field survival and productivity are related to the quality of planting materials (O'Reilly et al., 2002; Maltoni et al., 2010; Papanastasi et al., 2012). Despite of this fact quality of the planting materials observed in general are poor and their field performance is also not up to the mark. Though plant population per unit area and crop homogeneity are the major factors in improving productivity, but plant health, the insertion of seeds, the type of fertilizer, the number and dose of fertilizer, the suitability of the tool and the work material, the type of soil, the frequency of fertilizer application, working procedures, weed control, pest control, fertilization technology, and the fertilization of seeds are priority factors with the biggest impact as a determinant of farm productivity enhancement (Hidayati et al., 2014). Non-availability of quality seeds and lack of proper nursery planning and management appears to be the major drawback in this regard. In some of the cases bulk seeds of poor quality are purchased from non-reliable sources under hurry resulting in poor quality planting material. Low quality seedlings when planted in field and exposed to varying site conditions like sun burning, drought, grazing animals, insects, diseases, fire etc. fail to provide desired results (Mahmud et al., 2005). Thus planting materials must be strong enough to adapt and resist the exposure to a harsh environment immediately after transplanting in field. Improvements can be sought by advance nursery planning, so that the seed of the correct species superior in phenotypic character and other necessary materials are available to start operations at the right time. In addition, better nursery practices should also be adopted to develop and maintain quality seedlings. Many factors including both technical and social factors are responsible for a successful nursery operation. Appropriate site for a nursery is the most important decision affecting the efficient production of good quality seedlings. The vital issues needing consideration while selecting a nursery site are:

- Choice of species.
- Number of plants to be produced each year.
- Types and size of the seedlings.
- Expected life of the nursery operation.
- Location of the plantations site.
- Villages with social response.

2 SEED COLLECTION AND STORAGE

High quality seed is central to the success of plantations. The forest tree seed sources in many developing countries in general are in very poor quality resulting in low productivity of the plantations. For this mass production of genetically improved seeds is must. It should be followed with necessary testing of seed and source material. Short term strategies include development of seed stands and their conversion to seed production areas for quick supply of quality seed. The long-term strategies include selection of candidate plus trees, establishment of seed orchards, laying out of progeny trials, selection of elite trees, establishment of second generation seed orchards etc. It takes, however, a long time to provide quality seed material.

2.1 Choice of species

The tree species selected for afforestation must be compatible with the management goals and biologically suited to the planting site. Some important tree species of north-western India are *Tecomella undulata*, *Acacia nilotica*, *Prosopis cineraria*, *Azadirachta indica, Salvadora* spp., *Zizyphus* spp., *Cordia myxa* etc. Some exotics like *Acacia tortilis*, *Eucalyptus camaldulensis* etc., are also considered under afforestation in some of the selected sites (Stanturf et al., 2013; Bala et al., 2014). However, selection of a species or a combination of species must be finalized after determining the potential advantages and limitations of the planting site. Points to be considered in selecting suitable species are:

- Source of seeds.
- Site quality, especially soil factors.
- Climatic suitability.
- Potential growth rate on the site.
- Requirements of light.
- Potential competition problems at the site.
- Potential insects and disease problems.
- Market value of the plants and plantation.
- Compatibility within the group of species.
- Multipurpose value, i.e. timber, wildlife, erosion control and aesthetic values.
- Individual tree species characteristics.

2.2 Seed sources

Seed source is often overlooked but it is critical component in a successful afforestation program. By selecting appropriate seed sources one can improve the overall productivity of the plantation since the trees will be adapted to the environment of the planting site. Appropriate seed source selection also reduces catastrophic plantation losses due to poorly adapted genetic material (Prakash et al., 2001a & b; Lyngdoh et al., 2014). Poorly adapted seed sources can survive and grow for many years, until an environmental event, such as an early frost or extremely cold winter, results in catastrophic losses. Further, local seed sources have been observed as most appropriate unless proven otherwise through genetic testing. Tree improvement efforts continue to examine seed source performance of a region, whereas advanced tree improvement practices include the establishment of seed production areas to facilitate the collection of seed from quality native stands, the establishment of progeny tests where individual families are tested and selected for high performance, and seed orchards for the production of high quality seed with superior genetic potential (Dogra, 1989).

Seed production area is a phenologically superior stand made up of vigorously growing healthy trees, upgraded by thinning to remove poorer phenotype and treated and managed to cause abundant seed production (Emmanuel et al., 2002). Because of culling operation to remove the selected phenotypically inferior ones, it is also called as negative selection (Sivakuma et al., 2011). For example, a 20 hectares seed stand of *Acacia tortilis* planted in 1978 at 0-20RD Gharsana Distributory Gharsana in Rajasthan was converted into seed production area after inter-comparing various other seed stands (Table 8.1). Out of 3850 trees, 1350 tree culled and 2500 tree retained after scoring each tree in the stand and ranking them in descending order. After culling average height, clear bole and girth at breast height was shifted in higher side by 0.44, 0.58, and 0.54 cm, respectively. This is also selected from the existing best plantations or proven provenances of *T. undulata*, *A. nilotica*, *P. cineraria* and *Acacia tortilis* (Sharma et al., 2002; Katwal et al., 2003; Mishra and Bohra, 2011). Seeds collected from SPA show an improvement in seed mass (weight) and germination percentile with genetic gain of about 5 to l0 percent (Chaudhury et al., 2001a & b).

Table 8.1 Seed production areas in Rajasthan and Gujarat states of India.

State	Species	Location	Seed Zone	Area (ha)
Rajasthan	*E. camaldulensis*	0-7 Sangeeta distributory Suratgarh, Hanumangarh	RJ-II	10.00
	Acacia nilotica	Mandera Beed, Bharatpur	RJ-II	15.00
	Acacia nilotica	0-22, GM, Gharsana, Ganganagar	Zu-v	20.00
	Dalbergia sissoo	40-55 RD, NDR, Hanumangarh	RJ.V	20.00
	Dalbergia sissoo	Shahpura, Jaipur East	RJ-II	10.00
Gujarat	*Acacia nilotica*	Pavagarh, Godhara	GU-III	10.00
	Acacia nilotica	Gusar, (Panam Project), Site I & II, Godhara	GU-III	25.00
	Tectona grandis	Limbani, Chhota Udaipur	GU-III	10.00
	Tectona grandis	Chikhli, Dangs South	GU-I	20.00
	Tectona grandis	Dumka, Lalwada, Baria	GU-III	10.00
	Tectona grandis	Saathakashi, Vura	GU-I	5.00
	Tectona grandis	Parmera, Valsad	GU-I	20.00
	Tectona grandis	Achhala, Godhra	GU-III	20.00

Source: Chaudhury et al. (2001a & b).

2.2.1 Selection of candidate plus trees

Plus trees are the superior phenotypes in height, diameter at breast height, clear bole, etc. selected from a natural forest or plantation. Though selection criteria for candidate plus trees (CPTs) vary from species to species and type of produce one requires, but many of the basic characteristics remain the same. In general the individuals having diseases, dead branches, or attacked by any pathogen and pests are rejected in the initial stage of selection. For timber purposes major characteristics considered for the CPT selection are straightness, cylindrical bole, non-forking, non-twisting bole, free from buttresses and flutes and minimum taper (Chauhan and Gera, nil). Further, the selected tree should dominate in the height and girth compared to its surrounding trees of the same species and age. This is the first step of any long term tree improvement programme for producing genetically superior seeds on mass scale (Emmanuel, 2001). Candidate plus trees of some important species namely *Tecomella undulata*, *Acacia nilotica*, *Prosopis cineraria*, *Acacia tortilis* have been selected in western India to enhance quality seed production and their use in future genetic programme (Katwal et al., 2003).

A number of candidate plus trees (CPTs) of *Tecomella undulata, Acacia nilotica*, *Dalbergia sissoo*, *E. cmaldulensis* and *Tectona grandis* are available in different region (Table 8.2). These CPTs have been selected based on phenological parameters and tested through progeny trials (Anonymous, 2013). The existing progeny trial of *Tecomella undulata* is performing better with 87% survival at AFRI Jodhpur as compared to Bikaner trial with 58% survival at the age of 51 months. The progeny of CPT-23 and CPT-45 (Chohatan and Baytu) gave best growth at Jodhpur and Bikaner, respectively and minimum was of progenies of CPT-4 and CPT-8. In international Neem provenance trial, performance of Annur (India) and Gatti Subramanyam (India) provenances were best at Jodhpur and at Jaipur, respectively (Emmanuel, 2001). For oil and azadirachtin content, Shivpuri (0.93 percent) was found best for azadirachtin and North Bilaspur (46 percent) for oil content among the 39 provenances (Emmanuel and Tomar, 2003).

Table 8.2 Selected candidate plus trees of different tree species in Rajasthan, Gujarat and Punjab, India.

SNo.	Name of species	Number of trees	State	Seed Zone
1.	*Acacia nilotica*	40	Rajasthan	RJ.V
	Acacia nilotica	10	Rajasthan	RJ-II
2.	*Acacia nilotica* (farmer's field)	25	Rajasthan	RJ-II M &IV
3.	*Acacia nilotica*	15	Gujarat	GU-IV
	Acacia nilotica	10	Gujarat	GU-VI
4.	*Dalbergia sissoo*	40	Rajasthan	RJ.V
	Dalbergia sissoo	10	Rajasthan	RJ.II
5.	*E. camaldulensis*	30	Rajasthan	RJ.V
6.	*Tectona grandis*	13	Rajasthan	RJ.V
7.	*Tectona grandis*	50	Gujarat	GU-III
8.	*E. camaldulensis*	20	Punjab	PU-I
	Total	263		

Source: Anonymous (2013).

2.2.2 Seed Orchards

A seed orchard is a plantation of selected clones or progenies which is isolated or managed to avoid or reduce the pollination from outside sources and are managed to ensure easily harvestable seeds. In fact it is an output system for genetically improved material (Sweet, 1995). Though it is long term quality seed production programme, but the expected genetic gain from such orchards ranges between 30 and 40 percent. This is advantageous in providing quality seeds for future plantations. Seed orchards are of two types like:

1. Seedling seed orchard
2. Clonal seed orchard

2.2.2.1 ***Seedling Seed Orchard:*** Seedling seed orchards are raised from the seeds collected from superior phenotypes. The seedlings planted from this material are rough, where inferior trees are removed leaving the best trees of best families for seed production. Seedling seed orchards and progeny trials have been established at different localities after collecting the materials from the CPTs selected in different seed Zones (Table 8.3). These materials can be tried to enhance the quantity of forest produce (Emmanuel et al., 2002).

Table 8.3 The Seedling Seed Orchards cum Progeny Trials in Rajasthan.

SNo.	Species	Site location	Area (ha)	Year of planting	Seed Zone
1.	*Acacia nilotica*	Govindpura, Jaipur	10.00	1997-98	RJ-II
2.	*Acacia nilotica*	IGNP, Banda, Anupgarh	10.00	1998-99	RJ-V
3.	*Dalbergia sissoo*	Govindpura, Jaipur	15	1997-98	RJ-II
4.	*Dalbergia sissoo*	IGNP,34RD, Sangeeta Distributory	4	1998-99	RJ-V
5.	*E. camaldulensis*	Govindpura, Jaipur, Rajasthan	7	1996-97	RJ-II
6.	*E. camaldulensis*	IGNP,34RD, Sangeeta distributory	2	1998-99	RJ-V
7.	*E. camaldulensis*	Army Area, Jodhpur	7	1996-97	RJ-V

Source: Emmanuel et al. (2002).

2.2.2.2 ***Clonal seed orchard:*** A clonal seed orchard is composed of vegetatively propagated trees established primarily from the clonal material of superior phenotype for the production of seed of proven genetic quality (Sreekanth and Balasundaran, 2013). More than 1000 ha of CSOs have been established in India with 450 ha in Maharashtra, 240 ha in Madhya Pradesh, 120 ha in Karnataka, 92 ha in Andhra Pradesh, 35 ha in Kerala, 30 ha in Orissa and Tamil Nadu, and 25 ha in Arunachal Pradesh (Katwal, 2005). Clonal seed orchards of different tree species established (Table 7.4) in Rajasthan and Gujarat should be utilized for collecting seeds and utilization in rehabilitation of degraded dry areas (Emmanuel et al., 2002).

2.3 Seed collection and time

The method of seed collection depends on the terrain, spacing between trees, species and age of tree and management of the seed stand also. The easiest and cheapest method of fruit/seed collection is from felled trees particularly in western countries. A properly trained climbing team can make cost effective collections and this method appears more appropriate. However, one should know the time and dates for seed collection. In some years, fruits ripen earlier than usual, whereas in other years they may ripen later. In general, fruits tend to ripen later in the west than in the east, and later in higher altitude area also. A number of species shows variations in flowering and fruiting throughout the year, though high number of species observed flowering and fruiting during the period of rainfall. Likewise, many species produce fruit in a very short period of time (1–3 months). Therefore, information on the flowering and fruiting phenology of native trees is very much useful to plan seed collection and mass seedling production in the nursery (Sulistyawati et al., 2012).

Table 8.4 Established clonal seed orchard in Rajasthan and Gujarat forest area.

SNo.	Species	Site location	Area (ha)	Year of planting	Seed Zone
1.	*Dalbergia sissoo*	Govindpura, Jaipur, Rajasthan	7.00	1996-97	RJ-II
2.	*Dalbergia sissoo*	Machh, Rajpipla, Gujarat	2.00	1997-98	GU-II
3.	*Dalbergia sissoo*	Fulwadi, Rajpipla, Gujarat	2.00	1998-99	GU-II
4.	*Tectona grandis*	Machh, Rajpipla, Gujarat	4	1997-98	GU-II
5.	*Tectona grandis*	Fulwadi, Rajpipla, Gujarat	6	1998-99	GU-II
6.	*E. camaldulensis*	Govindpura, Jaipur, Rajasthan	8.00	1999-00	RJ-II

Source: Emmanuel et al. (2002).

The ripe pods/fruits should be collected by hand plucking or by shaking the pod bearing branches or may be beaten off the tree with a stick after sweeping the ground clearly. If fruits are collected too early, the seeds may be immature and weak. If collection is delayed, the seed may be eaten by birds, or attacked by insects or fungi. Fleshy fruits should be picked just as they turn from green to their ripe colour (Annexure 8.1). Since the time of season may vary from year to year, it will be more appropriate to monitor change in colour of the fruit as it change between yellowish green to yellowish brown in case of *Gmelina arborea* (Saralch and Singh, 2013). A wide variation in seed germination and seedling growth are also observed. Seeds from green-yellow fruits of *Azadirachta indica* and purple fruits of *Salvadora persica* exhibits lowest mean germination time and highest germination value (Prakash et al., 2001b; Kumar and Mishra, 2007b). After collection, the pods should then be sun dried on a concrete floor, canvas sheets or cloth sacks until split open.

Fruits or seeds should not be collected from unhealthy or insect infested trees. Fruits that have fallen to the ground should be avoided for this reason, though they may sometimes be suitable for collection. Time schedule for seed collection is another essential issue. If possible, selected trees should be monitored regularly to check on seed ripeness and availability. Tree species have definite seed year, when there is always bumper seed production and seed quality is better also. In lean years also seed production is always there. Following a preplanned schedule one can succeed in timely collection of good quality seeds (Annexure 8.1). For example, the seeds collected directly from tree branch of *Azadirachta indica* showed significantly higher germination percentage, mean germination time and germination value from fruit collected from ground (Kumar and Mishra, 2007c). Changes in physico-chemical properties of Neem oil during storage affect seed germination and growth and abnormalities in developing seedlings (Kumar, 2007). All age classes showed similar pattern in reduction or increase in physico-chemical properties of oil obtained after storage. Age class >30 years observed the best for oil production but their seeds lost viability rapidly as compared to others because of faster rate in rancidity of oil inside the cotyledons. However, no germination was recorded after 65 days of storage at ambient room temperature in all age classes of *A. indica* trees.

2.4 Cleaning and storage of seeds

Blowing or winnowing after trampling with feet or beating the dry pods inside a sack speed up seed separation. The pods/fruits which do not easily split should be opened manually or mechanically. There is a large variation in seed size, weight and dimensions of seeds collected from different tree species as well as individual candidate plus trees of a species. Cleaning and separation of *Eucalyptus camaldulensis* seeds can be done by using sieve of 600 micron size (Mishra et al., 1997). Floatation test are also applied to separate viable seeds from the empty ones. Bulk seeds of *Commiphora wightii* show very poor germination percentage (10%). Germination improves to 45% when tested after discarding the floaters seeds (Kumar et al., 2012). There are four types of seeds in *C. wightii* based on the colours like black, dark brown, off-white and white. Out of this dark brown/black seeds are viable ones and the seeds are non dormant and germinate readily without any pre-treatment.

Seed storage behaviour refers to the capacity of seeds to survive desiccation (Delahaie et al., 2013). Roberts (1973) classified these seeds according to their physiological behaviour, i.e. orthodox and recalcitrant. Orthodox seeds are those that could be dried to low moisture content and tolerate freezing temperatures. These seeds can be dried without damage to low moisture contents. Over a wide range of storage environments their longevity increases with reductions in both moisture content and temperature, in a quantifiable and predictable way. Orthodox seeds include most grain and legume types. The recalcitrant seeds do not undergo a period of maturation drying during their development, and as a consequence, they are shed from the parent plant at high water content. Since these seeds are sensitive to desiccation and generally also to chilling, they cannot be stored under the conditions that facilitate storage of orthodox seeds. However, the critical moisture level for survival varies among species. Some examples are *Camellia sinensis* (tea), *Hevea brasiliensis* (rubber), *Cocos nucifera* etc. Intermediate seeds are more tolerant to desiccation than recalcitrants, though that tolerance is much more limited than is the case with orthodox seeds, and they generally lose viability more rapidly at low temperature. They do not conform to all the criteria defining orthodox seeds, especially in respect of the quantification and predictability of the relations between longevity and both drying and cooling.

Mature, heavy and healthy and well dried seeds should be stored in a dry and cool environment and at sub freezing temperature. For improved storability, seed moisture and storage temperature must be kept low and controlled. After drying seeds properly seed should be stored in tin cans, metal boxes, glass jars, or plastic bags or container with lids that can be sealed. Following precautions should be taken during seed storage:

- Seeds should be checked that the surfaces of the seeds should dry and each seed lot should be free from insects and fungal infection.
- Containers should be clean and airtight.
- Container should only be opened when necessary.
- A light dusting with a low toxicity insecticide may be necessary if seeds are to be stored for a year.

Azadirachta indica can be stored under ambient room temperature in a sealed 200µ polythene bag and kept in an airtight plastic container after depulping and drying under shade untill it reaches equilibrium moisture content of 7% (Kumar and Mishra, 2009a). If the seeds are to be sown immediately after processing (i.e. within a few days), one needs to put them into a cloth bag and keep cool until used. Use of sealed container such as a polythene bag, glass jar or tin should be avoided, as the seeds are usually moist and will quickly get warm and mouldy. Freshly collected *A. indica* fruits are extracted by four different methods and are tested for their viability, storability and seedling performance (Kumar et al., 2007; 2009). Thoroughly washed fruit and dried seeds under shade to reach equilibrium moisture content (7%) exhibit significantly higher germination percentage (97.5%) and germination value (62.36) and lowest (9.20 days) mean germination time during storage than fruits soaked for 24 hr in fresh water, depulped up to 50% and depulped as whole fruit. Thoroughly washed fruit show greater germination percentage followed by 50% depulped and-whole fruit depulped after 30 and 60 days of storage, respectively (Kumar et al., 2009).

2.5 Seed pre treatment

Many species have seeds that germinate quickly when sown after processing or storage. Some species however, take several months to germinate unless they are treated properly. Such seeds are said to be dormant. Most of the desert perennials including *Aeluropus lagopoides*, *Teucrium oliverianum* and *Convolvulus oxyphyllus* etc. do not germinate easily and uniformly because of the dormancy effects (Zaman et al., 2011). There are several ways of pre-sowing treatments to overcome dormancy, depending on the species. Some species become dormant only when the fruits are fully ripe. If they are collected just before changing from green to their ripe colour, the seeds will germinate quickly in the nursery even sown immediately. However, if they are left until the fruits are ripe, they will take a longer time to germinate. There is variation in germination between scarified and unscarified seeds and seed coat also shows dormancy effects on germination and seedling growth (Krishan and Toky, 1994). Provenances of *Acacia nilotica* showed better germination (16-92% in unscarified vs. 68-100% in scarified seeds) and growth for scarified seeds. The variations were random and did not show relationship with the latitude of the origin seed source (Krishan and Toky, 1994).

Seed pretreatments also have effects on seed germination (Raghav and Kasera, 2012). Effects of treating seeds with KNO_3 has been observed significant (but decreased with increasing concentration from 5 ppm to 20 ppm) for *Commiphora* *wightii* (Lal and Kasera, 2012). It was best under scarification by nicking (39.5%) for *Capparis decidua,* which exhibited only 1% and 10.5% germination under without scarification and scarification with 99.8% conc H_2SO_4 for 3 minutes (Kumar and Mishra, 2008). *Capparis decidua* seeds treated with 50 and 100 ppm GA_3 showed a gradual increase in germination percent 49.5% and 52%, respectively. It enhanced further when seeds were scarified by nicking prior to treatment. At 200 ppm, the germination increased significantly to 74.57%. However, higher concentrations like 400, 700 and 1000 ppm failed to increase germination rather decline it. The seeds scarified by sulphuric acid before application of GA_3 gave 21.5% germination (Kumar and Mishra, 2008). Chilling seeds for two weeks or chilling with GA_3 (25.5%) had no improvement in seed germination over control and GA_3 alone, respectively. However, seeds scarified before chilling reduced germination to 19.0%. Seeds scarification and treatment with GA_3 both prior to chilling provided 54.07% germination. The seeds treated with 200 ppm GA_3 took 9.52 days against 21.93 days for untreated seeds for germination. A combination of nicking and large seeds shows 100% germination in *Albizia lebbeck*, whereas hot water treatment produces only 67.5% germination (Missanjo et al., 2013).

2.5.1 Water Soaking Treatment

Seeds of many species like *Albizia lebbeck, Acacia senegal* etc germinate much more quickly and uniformly if they are soaked in warm water for a few days before sowing. Use of chemical like GA3 improves the germination (Zaman et al., 2011). For this every day change in water is necessary, but use of very cold water should be avoided. A study on the influence of chemicals pretreatment like Urea and Diammonium phosphate (1% each), Potassium dihydrogen phosphate (KH_2PO_4), Potassium Nitrate (KNO_3), Potassium Chloride (KCl), Indole-3-Acetic Acid (IAA), Indole-3-Butyric Acid (IBA), Gibberellic Acid (GA_3), Naphthalene Acetic Acid (NAA), 6-Benzlaminaopurine (6-BAP) and Kinetin (100µg ml^{-1} each) for 12 h, on germination and seedling performance of *Azadirachta indica* indicates non-significant or negative effect on germination percentage, germination value (GV) and mean germination time (MGT) over water soaked control (Kumar and Mishra, 2009a).

2.5.2 Hot Water Treatment

Another way of treating hard-coated seeds is by using hot water, i.e. *Acacia senegal* (Sanyang et al., 2008). The seeds are poured into a large quantity of water that has just gone off the boil, and left in it for several minutes - the time depending on the species. The hot water is then poured off, and replaced by cool water, in which the seeds are allowed to soak for 24 hours. This method must be applied carefully, and the proper timing observed, so as not to kill the seed.

2.5.3 Cold and Moist Treatment

Most of *Acacias* and *Prosopis* species have hard seed coat. These seeds require soaking in cold water for 24 hours or mechanical breaking of seed coat or acid scarification for 5 to 15 minutes for better germination (Arya et al., 1995). Seeds of

Rauvolfia serpentina treated with concentrated sulphuric acid (H_2SO_4) for 5 minutes and then washed with normal running tap water gave 57% germination as the best performance (RFD, 2008). Concentrated sulphuric acid (H_2SO_4) treatment of *Ougeinia oojeinensis* (Tanas), *Thespesia populnea* (Paras papal) and *Caeseria tomentosa* (Munjal) seeds for 30 minutes and then washing out of the acid under running tap water for 15 minutes also give best results, i.e. 93% germination within two weeks. Effects of acid treatment on seed germination of *Acacia nilotica*, *Albizia lebbek*, *A. procera* and *Prosopis cineraria* indicate that treatment with conc. HNO_3 for 30 minutes increases seed germination from 24 percent to 47 percent in *A. nilotica*, and 37 percent to 63 percent in *A. procera*. Treatments with conc. H_2SO_4 show an adverse effect on these species, but enhance germination of *P. cineraria* and *A. lebbek*. HNO_3, in general and improve seed germination in all the species (Bimlendra and Toky, 1993).

3. SEED TESTING AND GERMINATIONS

Seed testing is the science of evaluating the planting value of the seeds. By testing the seeds one can assess the quality attributes of the seed lots which have to be offered for sale and minimizing the risk of planting low quality seeds. Seed viability is one of the major factors, which determines germination percentage so that the sowing density can be known and time and input cost of nursery could be saved. However, seed germination and its vigour depend upon various physico-chemical properties of seeds. Seed size and their weight and dimensions vary with seeds collected from individual candidate plus trees that grow at different locations influencing germination percentage (Mishra et al., 1997; Shukla et al., 2000b; Prakash et al., 2001b). Number of seeds per gram and percent germination varies from tree to tree. The lowest number of seeds were observed for the tree at Lunkaransar (1690±50 pure seeds per gram) and highest at Kola (1920±30). However, germination percent was lowest in Pilibanga (41±4%) and highest in the seeds collected from Sangeeta Distributary, Suratgarh (83±5%). Seed germination at 30±1°C was completed within 6 days of incubation and no pretreatment was required. Effects of seed size parameters like length, breadth, thickness and weight have also been observed in seed germination and seedling performance of many species like *Acacia nilotica* subsp. *indica, Albizia lebbeck*, *Caesalpinia sappan, Pongamia pinnata* etc (Krishan and Toky, 1996a; Kumar and Toky, 1996; Sunil et al., 2009; Mariappan et al., 2014). Seed germination and seedling growth varies between the sites also, but latitude or longitude of the original seed source does not indicate any effects (Krishan and Toky, 1996b). For both *A. nilotoca* and *P. cineraria*, south Indian provenances showed lower germination as compared to North Indian provenances (Krishan and Toky, 1996b; Arya et al., 1995). Seed germination of *A. lebbeck* varied from 5-95% among the provenances, where maximum seed germination of 94% was recorded in Jabalpur followed by Mehsana (79%) and Hisar (73%) provenances (Kumar and Toky, 1996). The study of Kumar and Mishra (2009b) showed insignificant differences in respect of seed and seedling performance of freshly collected seed from physiologically superior and inferior trees of *Azadirachta indica*. However, seeds of inferior trees declined significantly in performance as compared to superior trees after 30 and 60 days of storage and indicated rapid seed deterioration in storage (P_{50}, 172 days) as compared to superiors (P_{50}, 271 days). Seedlings raised from stored seeds of superior and inferior trees showed no effect on seedling performance. However, application of nutritional treatments like Nutron, Hexameal, FYM or NPK increases harvest index of planted seedlings of *P. cineraria* (Prakash et al., 2003; Shukla et al., 2000; Shukla and Kasera, 2003).

Study on seed size, germination and seedling performance of *Azadirachta indica* suggests that any size grade of freshly collected seeds can be sown, but in case of delayed sowing small or medium size seeds can be preferred for sowing to get better seedling and seedling performance. The study of Kumar (2007) by grading neem seeds into larger seeds (size 8 mm or >8 mm), medium seeds (size <8 mm and >6 mm) and small seeds (size <6 mm) indicates that grading does not influence germination percentage both as fresh and after 35 days of storage, but larger size fresh seeds show significantly higher MGT as compared to medium and small size seeds. Number of leaves, vigour index, maximum volume index and minimum sturdiness quotient observed higher in small size seeds followed by medium and larger size seeds. Small and medium seeds showed higher volume index, quality index and minimum sturdiness quotient after 35 days of storage. Vigour index decreases with increased duration of storage in all type of seeds. However, small and medium size seeds showed higher vigour index followed by larger size seeds after 35 days of storage.

Types of substratum, orientation of seeds, sowing depth and storage temperatures also have important bearing on the percentage germination of tree or shrubs seeds (Mishra et al., 1998; Kasera et al., 2003b). Orientation of seed in the germinating trays does not have any significant effect on the germination percentage of neem seeds. Though removal of endocarp has no effect on the percentage germination of neem seeds but it decreases the germination period from 7 days to 5 days. Lowering of temperature (<20°C) enhances percentage germination of stored seeds of Neem as compared to the seeds stored at 35±4°C (Mishra et al., 1998; RFD, 2008).

Seed germination particularly under field conditions is also influenced by soil salinity and alkalinity. In a study, seed germination and seedling growth of *Acacia nilotica*, *Albizia lebbek*, *Pithecellobium dulce* and *Prosopis juliflora* decreased with increase in alkalinities due to Sodium carbonate and sodium bicarbonate (Srinivasu and Toky, 1996). The seed germination and seedling growth is observed up to pH 10.0 in *A. lebbek* and *P. dulce,* while it continue up to pH 11.0 in the remaining two species.

3.1 Seed sampling and testing

Seeds supplied by an organization are clearly mentioned with about its viability percentage. Seed testing explains about merits of seeds under collection, correctness of handling procedures and potential seedlings available for regeneration. Quality seeds are generally true to species or a cultivar capable of high germination, free from diseases and insects, free from mixture and other seeds and inert material. The germination and purity of seed are determined by conducting a seed test on a small representative sample drawn from the seed lot. It provides information to meet the legal standards determining seed quality and establishes the rate of sowing. The procedures followed in seed testing are provided below:

3.1.1 Seed Sampling

Seed analysis begins with the sampling of the seed lot. The seed testing rules (AOSA, 1996; ISTA, 1996) provide guidelines on how one can draw samples from a seed lot so that the sample is representative of the entire seed lot. It means any tests conducted on the sample will accurately estimate the mean value of the lot quality (Morrison, 1999). Sampling can be done with the hand or with a seed probe known as a Trier. If there is only 1 container, primary samples should be taken until there are 5 primary samples. In case of more than 1 container of seed lot, samples from each container should also be tested, i.e. at least 1 probe from each container. In case of more than 5 containers, 5 of the containers plus 10% of the remaining ones should be sampled, but there is no need to sample more than 30 containers. All of the primary samples are then placed together to make up the composite sample. Sampling by hand (by inserting the open hand into the seeds) is necessary when the seeds will not flow into the probe because of their size, shape, or surface texture. The seeds are then placed in a second container to form the composite sample. At least 5 handfuls must be taken, and all levels must be sampled. When the hand cannot be inserted into the seedlot, the seeds can be poured from one container into a second, stopping at a minimum of 5 evenly spaced intervals and removing a handful of the seeds for the composite sample. This composite sample is mixed and then divided to obtain a sub-sample. This procedure is very important and must be done correctly for the results to be accurate. The composite sample can be mixed either mechanically or by hand. Hand mixing can be replaced by mixing with either a soil divider or a gamet divider to save time. The cleared out seed is then divided in half, then quarters, eighths, and so forth, to obtain the correct weight for the subsample, which must be twice as large as the minimum amount for the purity test (AOSA, 1996) otherwise an amount containing 2,500 seeds should be taken. This amount can be estimated by counting out 100 seeds and multiplying their weight by 25.

3.1.2 Moisture Tests

Moisture testing is essential immediately when the seeds arrive at the seed laboratory. Once a sample container is opened and work begins, the seeds will likely gain or lose moisture. This test is made on 2 sub-samples containing 3 - 5 g of whole seeds. These two samples are placed in containers with lids and weighed to determine the moist weight. Then the samples are placed in a forced-draft drying oven for 16 to 18 hours at 105 ± 2°C in an oven after removing the lids (ISTA 1996). The samples are then placed in a desiccator for 20 minutes before weighing a second time to determine the dry weight. The lids are placed on the cans while cooling and weighing. The loss of weight indicates moisture content in the un-dried sample represented in percentage moisture. Moisture content can be computed using following formula:

$$\% \text{ Moisture contnet } = \frac{\text{Wet weight} - \text{Dry weight}}{\text{Wet weight}} \times 100$$

3.1.3 Purity Analysis

In general sample is separated into three components, i.e. pure seeds, other seed, and inert matter. The percentage of each part is determined by weight. Seeds of all species and each kind of inert matter present are identified as far as possible and if required for reporting, their percentages by weight are determined. For this transmitted light, sieves and blowers are used to separate the component parts of the working sample. The blower is used for uniform blowing method. In general, seeds of noxious weed are mixed with the main seedlots and requires purity test. Sometime random amplified polymorphic DNA (RAPD) markers are also used for evaluating seed purity in commercial cultivars (Crockett et al., 2000). Each species has its own specified minimum weight, which has been determined to contain about 2,500 seeds. The mixing and dividing should be done in the same way as described in the sampling procedure for drawing the submitted sample from the composite sample. It is necessary to obtain very close to the minimum weight because analyst does not want to examine more seeds than necessary, and the accuracy of the test is evaluated using tolerance tables developed based on these minimum weights. According to ISTA, purity values report percentages of pure seeds, other seeds, and inert materials. Percent purity can be calculated using following formula:

$$\% \text{ Purity } = \frac{\text{Weight of clean seed}}{\text{Weight of total seed}} \times 100$$

Noxious weed examination is a specialized purity scrutiny. It is not a test traditionally associated with forest seeds but may become more common as the commercial exchange of native plants increases. A noxious weed is a highly aggressive competitor or a plant with other highly objectionable characteristics, such as being poisonous. It is so offensive it has been put on a noxious weed list compiled by an individual state or the federal government. A noxious weed examination is made solely to identify the number of noxious weed seeds found in the sample (Karrfalt, 2008). The sample size for a noxious weed examination is 25,000 seeds. The following formula can be used to calculate the number of seeds in a unit weight of seeds:

Weight of seeds × purity (%) × No. of seeds per unit weight

For example: 1 kg of seeds at 95% purity with 25,000 seeds per kg seed lot. It will become: 1 kg x 0.95 x 25,000 pure seeds/kg = 23,750 pure seeds.

3.1.4 Seed Weight Determination

Seed germination also varies with seed weight (Tripathi and Khan, 1990). The number of seeds per unit weight is determined on the pure-seed fraction from the purity test. It is made by counting out about 8 replicates of 100 seeds and weighing them to the same precision as the weights for the purity test. The coefficient of variation of these 8 values is computed. The coefficient should not be greater than 6 for chaffy seeds or greater than 4 for all other seeds. If not an additional 8 replications need to be counted and weighed and combined with the first 8 weights. All 16 weights are then used to compute the mean. Any weight diverging from the mean by more than 2 standard deviations is discarded and the remaining weights are used to compute the number of seeds per unit weight.

3.1.5 Germination Testing

Germination is the number of normal seedlings produced from 100 pure seeds expressed as a percentage. The germination test is conducted on the pure-seed fraction from the purity test using 4 replications of 100 seeds either in a container or a tray. If fewer than 400 seeds are available, then the number of seeds per replication should be reduced so that an equal number of seeds are present in each of the 4 replications. Seeds are then hand-planted using sand, sand and perlite mixtures, potting mixtures, soil, and various papers like blue blotters, white blotters, or crepe-cellulose papers. Germination tests are run in cabinets or rooms that meet exacting requirements for temperature and light control in order to make accurate and repeatable estimates. Temperature of chamber depends on the species and is determined by experiments, as many species do well at an alternating 20 and 30°C. For this, the chamber is held for 16 hours at 20°C and for the remaining 8 hours at 30°C. Sources of light should be blue and/or red light but not far red light as far red light inhibits germination. Cool white flourescent lamps are most commonly used. The combination that supports the highest percentage of germination in the most reasonable time is the one that is adopted in the rules for testing. Dormancy in seeds, if any, must be overcome in order to conduct the germination test, just as when trying to grow seedlings. Accuracy of germination test is tested in duplicates, quadruplicates or more samples. Variation between the samples serves as an indication of the reliability of the results. The average germination of all replications represents the result of the test. However, allowable differences (%) should not exceed greater than 10%, 12% and 15% when germination percentages are >90%, 80-90% and <80%, respectively. In case of exceeding these limits, the test should be repeated again. Results of re-test and concurrent tests made by different methods should be averaged, provided the results are within the tolerance limit. Otherwise the higher results are reported. The allowable tolerance limits between germination tests are:

Range of germination (%)	Allowable tolerance (%)
97 - 100	4
95-96	5
90-94	6
80-89	7
70-79	8
60-69	9
Below 60	10

3.1.6 Germinative Energy

In general, 1-2 seeds germinate per day, increasing to a maximum and then falling off as few sluggish seeds continue to sprout after the bulk of the sample has finished. The time required to reach the highest germination percent in a test is termed energy period and the percentage of seeds germinating in this time is 'germinative energy'.

3.2 Seed vigour and viability

Various measurements (Ranal and de-Santana, 2006) on seed germinations are the germinability, germination time, coefficient of uniformity of germination (CUG), coefficient of variation of the germination time (CVt), germination rate (mean rate, weighted mean rate), coefficient of velocity, germination rate of George, Timson's index, GV or Czabator's index; Throneberry and Smith's method and its adaptations, including Maguire's rate; ERI or emergence rate index, germination index and its modifications etc. All these germination measurements are applied to evaluate seed germination and seedling emergence (Dorneles et al., 2005).

3.2.1 Seed Vigour

The vigour test predicts the general ability of a seedlot to germinate normally over a range of adverse conditions. Its purpose is to differentiate seedlots with essentially equal germination, according to their ability to germinate well. The most common vigour tests in agriculture are the cold test, the accelerated aging test, the conductivity test, and the tetrazolium test. In addition to these, speed of germination as expressed in a number of formulas has been put forward for use in forestry as a vigour test. The faster a seedlot completes germination or reaches its peak the more vigorous it is said to be. The simplest indicator is days to 90% of total. For example, if the final germination is 88%, the indicator would be how many days it takes to reach 79% germination. A lot that reaches 79% in 12 days would be more vigorous than one that takes 16 days.

The **cold test** is done by planting the seed in damp soil and then holding the germination tray at 10°C for 7 days. This test mimics the cool damp conditions of soil in early spring. At the end of the period, the germination trays are transferred to the appropriate temperature for germination. The higher the percentage of germination, the more vigorous the seed is said to be. The **accelerated aging** test is conducted with the stress of high temperature and moisture. A defined amount of seeds is placed in a small box with a screen tray that suspends the seeds over a reservoir of water. These boxes are then placed in an aging chamber at 40 to 43°C for 72 to 288 hours, depending on the species. At the end of the period the seeds are planted and tested for germination under the standard conditions. The **electrical conductivity test** is widely used in agriculture but has not been adopted as routine practice. In this, seeds are soaked individually or in bulk, where the deteriorated or dead seeds leak electrolytes more readily than high-vigour seeds. Greater the leakage higher will be the electrical conductivity. **Tetrazolium staining** is also tried to test vigour test (Van Waes and Debergh, 1986). Because of the highly subjective nature and great amount of experience requirement, it has never been widely used as a vigour test particularly in forest species.

Czabators factor (1962) has been developed for use with southern pines, combines the maximum daily average germination (called the peak value) and the average daily germination at the end of the test to form one statistic (germination value). The germination is counted frequently, at least every third day, and the cumulative germination on each day is divided by the number of days that the test was run in order to compute the mean daily germination for that particular day. For example, the cumulative germination on day 22 is 88 and the mean daily germination is 4 means daily germination increases until the period of maximum germination has ended and then decreases. The germination value is computed by multiplying the peak value by the mean daily germination. Lots that have higher germination values are generally considered more vigorous.

3.2.2 Germination Velocity Index

This is the best way of expressing seed vigour. Under this every count is recorded in germination test and by adding the quotients of these new germinants germination velocity index (GVI) values are computed using the formula of Woodstock (1976):

$$GVI = N_1/1 + N_2/2 + N_3/3 \ldots\ldots N_n/N$$

Where N_1, N_2, N_3 and N_n are the numbers of new germinants on day 1, 2 ……N following the start of germination tests. Higher is the value, more is the vigour of seed lot (Raizada and Raghubanshi, 2010).

3.2.3 Seedling Vigour Index

Seed vigour is a property that determines potential for fast and uniform emergence, and development of seedlings under a wide range of field conditions (AOSA, 2002). While GVI indicates the fastness of germination, seedling vigour index indicates the speed of subsequent growth of the germinants. Seed vigour is an important component of seed quality and satisfactory levels are necessary in addition to traditional quality criteria of moisture, purity, germination and seed health to obtain optimum plant stand and high production of the crops (Sivakumar and Wani, 2013). Seedling vigour index (SVI) is determined using the formula of Abdul- Baki and Anderson (1973):

SVI (%) = Σ Seedling germination (%) × Height of seedling or wet (fresh) weight of seedling or Dry weight of the seedling/100

3.2.4 Chemical Staining for Viability

The tetrazolium staining procedure is useful in estimating the viability of dormant seeds, especially those having high dormancy (Van Waes and Debergh, 1986). This test involves soaking the seed first in water to fully imbibe the seed and soften it for cutting. A moistened seed takes up the stain more rapidly. A variety of methods are used to open the seeds without damaging to the embryonic axis- the axis of radical and the plumule. Usually forceps and sharp single-edged razor blades are used to cut and open the seeds. The solution used to make a tetrazolium (TZ) test is made by dissolving 2, 3, 5-triphenol tetrazolium chloride in a phosphate buffer of pH 7.4. The colourless solution is taken up by the prepared seeds and then reacted with respiratory enzymes (i.e., dehydrogenases) to form an insoluble light pink (magenta) precipitate. Tissues that are alive and respiring take stain and those that are not alive do not take stain. The TZ test should be completed in 4 to 48 hours.

3.2.5 Excised Embryo Testing

It is done on the embryo after its removal from the seed. In this embryo is freed from the restriction of the seed coat and nutritive tissues. By this one germination that takes many months occurs within 10 to 14 days (Heit, 1955). The ashes (*Fraxinus* L.), maples (*Acer* L.), and cherries and plums (*Prunus* L.) are some of the genera that are tested by this method. Because the embryos are very vulnerable to infection once excised, the test must be done under strictly clean (axenic) conditions with extra care about contamination. If good embryos easily mould, then cleaning procedures must be reviewed for effectiveness and the work area examined for sources of microbial contamination. The procedures for excising the embryos are similar to those used in preparing seeds for tetrazolium. However, embryo must be removed intact without any significant injury or broken apart. The main advantage of this method over the TZ test is that the evaluation is less subjective; the growing embryo is actually observed in most cases leading to a direct reading on the growth potential of the seed lot.

3.2.5 X-ray radiography

X-ray radiography provides a rapid and accurate analysis of the internal structure of seeds, identifying empty, insect-damaged, or poorly developed seeds and help judging maturity, determining seed quality and detecting mechanical injury (Machado and Cícero, 2003). Seed work is usually done with x-rays in the range of 10 to 30 kvp (that is, kilovolt potential), which is the amount of penetrating power of the X-rays. The exact kilovolt potential depends on the equipment and the seeds in question. Trial and error is necessary to find the best combination. X-ray inspection cabinets are manufactured that operate in this very low kilovolt potential range for examining small items such as seeds (Ramakrishnan et al., 2012). They are designed for total protection of the operators, with complete lead shielding and safety interlocks on the door. X-ray radiography has proven useful for studying the seeds from many wild species, which often can be empty or poorly formed (Leadem, 1984). Some laboratories test every lot of seeds they receive with X-rays and get a good initial evaluation. X-ray radiography can be of great value in evaluating germination test results, because it is much faster than cutting open seeds that failed to germinate.

4. NURSERY PRACTICES AND MANAGEMENT

Establishment of nursery also depends upon either temporary nursery/field nursery or permanent nursery. Temporary nursery is established temporarily to meet the requirements of planting stock for difficult and limited areas. It is cheaper and do not require any permanent staff, building, sheds and costly fencing etc. The tree species selected for the temporary nurseries are simple to raise and in general ready for out planting within a short period after sowing in beds. Permanent nursery is established to supply nursery stock on a long-term basis. It is usually established at a strategic point from where transportation of seedlings to all possible planting sites should be easy. By locating it at headquarters or near the offices, it receives constant and close supervision. A permanent nursery should contain most of the species in use. Cost of production of seedlings in a permanent nursery is considerably less than a temporary nursery. A permanent nursery should have a large fenced area, roads and inspection paths, well laid out irrigation system and shading facilities.

4.1 Size of a nursery

Size of the nursery is determined keeping in view the demand of planting stock in the plantation area and that of the local people. The first requirement of the forest nursery is the area where it is going to be constructed. Area should be sufficient meeting the requirement of seedlings/plant stock. The size of nursery should be determined by a thumb rule, i.e. one lakh seedlings can be raised in an area of about 0.4 ha. The area of nursery depends upon the total number of plants required and the spacing maintained in the nursery beds and the width of the polythene bags in case of polythene bags raised seedlings. The area of a nursery can be calculated by the following formulae (Kaushik et al., 2007):

$$A = \frac{B}{n} + C$$

Here, A is area in square metres, B is total number of plantable seedlings, n is number of plants per square meter in the bed and C is 25-30% additional area required for paths, drains, sheds, etc. In case of polythene bag raised seedlings, the area can be determined like:

$$A = \frac{N}{\text{No. of polythene bags per sq m}} + C$$

In this A is area in square metres, N is total number of plantable seedlings and C is 25-30% additional area required for paths, drains, sheds, etc. In normal, the diameter of filled polythene bags varies from 5.5 cm to 7.5 cm. In one square meter area, the number of polythene bags of top diameter 7.5 cm should be about 100 (10 × 10) square meter. The areas with swift and stormy winds should be avoided for the establishment of forest nurseries. Forest nurseries in dry areas should be established where there is forest/tree cover around the site so that a wind current gets deflected from the tree cover. Though limited shade is required in dry areas, however, it should be ensured that shade does not impede the growth of the seedlings.

4.2 Nursery design and construction

Important points that need consideration in preparing a plan for a nursery site are:

- Location of the building or sheds.
- An effective fencing or wall.
- Proper layout of external and internal paths.

- Erection of wind breaks or shelterbelt.
- Water tanks and distribution system.
- Seedbeds and stand-out beds.
- Soil storage shelter and compost making area.
- Working area.
- Seeds of the selected species.

Special attention is required about the drainage and water supply systems. Presence of roads in nursery facilitates to drive into the nursery, so that soil and sand can be unloaded directly into the storage area. A completely developed plan should be checked carefully at the nursery site also. One should consider the location of each component from the point of view of its own function and its relationship with the other components. The nursery beds should be laid preferably of the same size. Beds should not be wider than 1.25 m because of the difficulty of reaching into the centre, while beds narrower than 1 m indicates that the paths between them has taken up too much space. Paths should be about 50 to 60 cm wide, which provides adequate space to squat and work from. The length of the beds may vary from 10 to 15 m, but depends upon the space available in nursery. In the hill areas, nursery raised on the southern and northern aspects, the beds should be best laid out east to west direction as it provides protection from sun and frost both.

4.3 Planning and record keeping

The objectives of a nursery are to provide good quality seedlings of certain species for a specified site and in specified numbers. A nurseryman must find out what species are to be grown and what quantity of labour and materials are needed. For example, a large numbers of species are now planted on farmlands and farm boundaries, thus an agroforestry nursery can be created because of increased demand by different sectors. Before establishing a nursery an estimate must be made of the number and plant species needed, from one to three years ahead. The nurseryman should be well aware about the seed collection season and the sowing times. The quantity of seed required must be calculated, the sources identified, arrangements made for collection, and the cost involve should be estimated. The seeds of tree species which cannot be stored (like neem) should be sown immediately after collection. Quality seed sources must be either located in nursery area or collected from seed production area or identified candidate plus trees. Necessary arrangements should be made with the tree owners to make seed available. If the nurseryman does not collect the seed himself, one must advise farmers that when and how to collect seed, and be ready to process it immediately. One has to make frequent visits to the selected trees to maintain contact with the farmers/ tree owner and to ensure that the seeds are collected at the correct stage of ripeness.

For maintaining a record one has to use experiences to improve planning and therefore the efficiency of the nursery working. This is especially important for new species. For example, if plants of a particular species are not big enough for planting at the beginning of the monsoon, it may be quite easy to find out why, if the nursery register has a detailed record of how they were grown, indicating the sowing date, potting mixture, etc. All beds in a nursery must be numbered for use with the record, which could be modified to suit the needs of a particular programme. Additional information such as size of polypot, details of potting mixture and source, date of sowing, spacing and root pruning can also be included. Another register can also be kept to have a record by providing seedlings with unique identity number.

4.4 Bed preparation and potting mixture

Availability of soil, water, natural shed is must at the site. The ideal soil for a nursery should be sandy loam to loam in texture. It should be well drained and fertile. The soil of most of nurseries for raising hardwood species requires a mixture of loam and sand. The heavy soils with high clay content are generally avoided because of their poor aeration and drainage and are likely to crack in summer months. Soil pH should be close to normal and should contain organic matter not less than 2.5 percent. Thus most important bearing on the health of seedlings is the soil drainage. The nursery soils should have good drainage system. Water logging in vertisols can be reduced by addition of sand (one part sand to three parts of soil) and by in-bed drainage system.

4.4.1. *Potting mixture*

The most important growing medium is high water holding capacity, good aeration, high cation exchange capacity, appropriate pH, low natural fertility, low salinity, and devoid of weed seeds or pathogens. The soil for filling up the containers should be prepared by mixing one part local soil, one part sand and one part farm yard manure. In arid and semi-arid region a high proportion of FYM or compost is generally preferred (Gupta et al., 1992; Prasad et al., 2002; Kaushik et al., 2007). The texture of the potting mixture is most important that improves aeration, fertility and the ability to retain nutrients. However, potting mixture depends on the availability of sand and compost and on the texture of the soil (Table 8.5).

Table 8.5 Appropriate ratio of potting mixture for raising seedlings in nursery.

SNo	Mixture component			Specific remarks
	Soil	Sand	Compost	
1	3	1	1	Slightly infertile soils with too much clay
2	3	2	1	
3	1	2	1	
4	2	2	1	
5	3	0	1	Soils that are too sandy
6	4	0	1	
7	3	1	0	Soils with slightly medium in clay
8	4	1	0	

Source: Kaushik et al. (2007)

Addition of well decomposed compost shows an immediate and beneficial effect on the quality of seedlings raised. It increases the water holding capacity of light soils and improves the drainage of the heavy ones. Mixture of tank silt and FYM with sand also improves seedlings growth of *Dalbergia sissoo, Albizia lebbek* and *Prosopis cineraria* (Gupta, 1992). Here potting mixture producing best healthy seedlings are 10 percent tank silt and 2 percent FYM for *D. sissoo*, 10 percent tank silt and 4 percent FYM and 40 ppm nitrogen for *A. lebbek* and 10 percent tank silt for *P. cineraria*. Response of nitrogen application has been observed beneficial on *Albizia lebbek*. Soil: compost medium in ratio of 1:4 has also been reported superior for height, collar diameter, root nodulation and biomass of *Acacia nilotica* seedling. It was followed by compost: rice husk: pearl millet husk in 3: 1:1 ratio (Prasad et al., 2002). Various potting mixture viz.1:1:2 (soil : sand : compost), 1:1:3 (soil : sand : FYM), soil: sand: leaf compost (1: 2:1) and soil: sand : vermicopost (1:2:1) tested in different sized polybags and root trainers indicates that the composition of soil: sand: leaf compost (1:2:1 ratio) is the best for seedling growth of *T. undulata* (Anonymous, 2014). The combination of soil: sand: vermicopost (1:2:1) shows better average seedling height and collar girth. However, polybags seedlings have been observed better in height and collar girth as compared to the root trainer seedlings.

4.4.2 *Water Quality and Irrigation*

One of the most critical aspects of quality of nursery grown seedlings is the availability of adequate quantities of good quality water. Watering of a plant means soaking the soil-rooting medium to its field capacity. This means that watering, when done, should be adequate for the entire soil medium. Inadequate watering, even if repeated, is of no help. The requirement of water is about 200 litres per day for every one lakh seedlings. The cheapest method of irrigation is by flooding. Wherever water availability is less, irrigation can be done by sprinkling method or by percolation method. Because of requirement of electrical energy, the sprinkling method is expensive and may not be commonly available too. Irrigation in polythene bags can be done by rose-can manually but it is quite cumbersome. Nursery plants should be irrigated before sun rise and after sunset. Irrigation during day time, particularly in summer months should be avoided. The quality of water is not usually considered during establishment of the nursery but it becomes more important especially in saline-alkaline areas. The water should have pH between 6.5 to 8.0 and salts less than 400 ppm beyond which it may adversely affect the normal growth of the seedlings.

4.5 Seed sowing and pricking

4.5.1 *Seed Sowing*

Sandy loam soil mixed with compost in the ratio of 2:1 should be filled up in the polythene bags/beds/but it should be 1:1 ratio or pure sand in germination tray. Sowing can be done either by broadcasting or in lines across the length of the bed. Broadcasting excessive quantity of the seeds is wasteful and should be avoided as far as possible since it leads to spindly, thin seedlings unsuitable for successful pricking out. For small seeds, use of requisite quantity of seeds for broadcasting or sowing along the lines to raise around 3000 seedlings in 1 sq meter area is recommended. If the seeds are large, they should be planted along lines, each seed touching the next. The distance between the lines in either case should be 2-3 cm. Small seeds should be mixed with an equal quantity of very fine sand to facilitate uniform seed distribution. The depth of sowing should be 2-4 times the diameter of the seeds, ensuring that the seeds are just covered with the soil *in situ*. If the seeds are known to have a comparatively long germination time, the sowing should be deeper, but the soil cover should not be over compacted. Immediately after sowing in the seed flats, mulching by covering up the soil with paddy straw/similar materials is helpful. However, one has to see that the straw is not attacked by termites. Seedbeds or seed trays are recommended when the seed is very scarce or expensive, very small having low viability and prolonged germination. Seed trays are not commonly used, yet for many species they have several advantages. They are portable, and hence can be protected against both heavy rain and drying out.

When seeds are sown in polythene pots, a minimum of 2 to 3 seeds should be sown per bag. However, pot sowing is a more expensive practice and is not recommended particularly for small seeds. It is true that a certain percentage of mortality takes place during pricking out when seeds are sown in seed flats or seed beds. Germinated seedlings in seed flats are better attended and reduce the input cost of raising seedlings. On the other hand, if the seeds are sown directly in the polypots, raising cost of seedlings is relatively expensive. Because of greater chances of mortality during pricking out the seedlings from seed beds, sowing of larger seed directly in the polypots will be more beneficial.

Pure sand is ideal germination tray or germination bed for *Eucalypts*, *Azadirachta indica*, *Acacias* and *Prosopis* species which are pricked out within a few days after germination. Because of the need to prevent damping-off disease, compost should never be used for germinating seed in seed trays or seedbeds. After sowing, seeds should be covered evenly with pure washed sand, but care must be taken so that sand should be enough to cover the seed. Mulch can also be used to protect the seed from drying out. The tray or sand beds should be protected from heavy rain and putting them under the shades. If growth in the seed trays is slow, pricking out should be delayed accordingly. This happen in general when there is low moisture, heavy shade or lack of nutrients in soil medium (when pure sand is used). Spraying of nitrogenous fertilizer solution (1g/litre of ammonium sulphate or urea) to the seed tray is recommended to enhance growth of seedlings.

A soil of germination bed of depth 15 cm to 20 cm is suitable. The soil should be practically sandy to sandy-loam in texture. In case of heavy texture soil, quartz sand can be mixed with soil and the mixture should be exposed to the sun to kill pathogens. Then it should be sieved through mesh of 2 mm × 4 mm size. About 100 g of 5% aldrex should be mixed for every 10 sq. m of the germination bed. The pulverized, sand and aldrex mixed and finely sieved soil are spread evenly in the germination beds before sowing of the seeds for germination. The pH of the soil should range between 6.5 and 7.5. For *A. indica* seeds, between paper (BP) is the best in which maximum germination percentage, minimum MGT and maximum GV are obtained, whereas sand media appears inferior as compared to top of paper (Kumar et al., 2007c). Fresh seed of *Azadirachta indica* or other can be sown either downward or horizontal at up to 3 cm depth (Kumar and Mishra, 2007a). Horizontal orientation of the seeds can be preferred and done up to 3 cm depth even during slight delay in seed sowing to get maximum germination as well as better quality seedlings.

4.5.2 *Sowing Time*

Though sowing mainly depends on seed collection season, the viability of seed, required size of plantable seedlings, planting season and germination period, but correct time of seed sowing is major factor in nursery operations and it is often the reason for the poor quality seedlings produced when seeds are not sown in time. The general rule is to sow the seed well ahead of planting season and when weather is sufficiently pleasant. However, ideal germination temperature varies from species to species. Many species germinates when daily temperature rises above 20°C, whereas seeds of tropical species may require still warmer climate and geminate at temperature 25 to 30°C. Seeds of *Azadirachta indica* germinate over a wide range of temperature ranging between 25 and 40^{o}C. However, significantly higher germination percentage, germination value and minimum mean germination time are obtained at 30^{o}C. Lower (25±1^{o}C) and higher (40±1^{o}C) temperatures show adverse effect on germination of *A. indica* seeds (Kumar et al., 2007c).

4.5.3 *Pricking Out*

For most of the species, the best time of pricking out is shortly after germination, when the seedlings have only three or four primary leaves in addition to the cotyledons. If pricking out is delayed, the roots will extend too long and lateral roots will develop. The seedlings will then become much more difficult to prick out without damaging or distorting the roots. Pricking out should be avoided on a cloudy day or in the later afternoon or evening.

For better survival after pricking out, gentle watering of the seed trays or seedbeds/mother beds, one day before is recommended. After watering a hole in the soil of the pot can be made wide enough to contain the seedling's roots without bending them. The hole should be filled up with a 1:1 mixture of finely sieved soil and sand. This will prevent in developing any pockets of air remaining around the root. Light watering of the seedlings and ensuring that the soil around the roots remains fairly moist is recommended. However, light watering twice or three times a day for the next few days will be more appropriate. The shades should be kept on throughout this period, but when the seedlings start to produce new leaves, slow removal of the shade should be started. This can be done gradually by taking it off for an hour in the morning and in the late afternoon at first, and then increasing the daily full sunlight exposure so that after about a week no shade is provided. In general, shades should be removed sooner rather than later, and only very rarely they will be needed for more than two or three weeks after pricking out the seedlings.

5. PRODUCTION OF CONTAINERIZED SEEDLINGS

Seedlings raised in containers are a relatively modern practice (Fig 8.1). Productions of containerized seedlings are quicker and easy. Container grown seedlings, with intact root systems, show in general better survival and start height growth sooner than the bare roots stock. Moreover, container-grown seedlings tend to perform better on adverse sites than do bare-root seedlings, because the growing condition can be better-controlled and container planting offers seeding efficiency.

Five multipurpose tree species, i.e. *Eucalyptus camaldulensis*, *Prosopis cineraria*, *Acacia nilotica, Azadirachta indica* and *Pongamia pinnata,* commonly growing in dry areas, showed well developed fibrous root system in root trainers (Mishra and Emmanuel, 1997). After four-month of sowing seedlings of these species showed variable deformed root system either in the form of coiled tap root, bifurcated tap root, development of laterals like tap root and other deformities. Among these species, *P. cineraria* showed highest (64 percent) deformed root system followed by *E. camaldulensis* (47 percent), *A. indica* (41 percent) and *P. pinnata* (24.5 percent). However, *Acacia nilotica* showed a well pruned root system. Size of the poly-bag or root trainer also influences growth and biomass variables in general and *Commiphora* seedlings in particular (Anonymous, 2013). The poly-container can either be transparent or black. The transparent containers are liable to have algae and moss growing inside as the light gets into the root zone. Growing algae and mosses utilize the fertilizer of the root zone and deprive the desire of the seedlings. One of the methods to avoid this is to partly bury the bags in piled up soil. Further, the transparent polythene bags disintegrate faster than the black coloured ones. On the other hand, the white sheets reflect the heat, keeping the soil and the root zone cooler in the hot regions. The black one, on the contrary, absorbs sunlight, heating up the root zone, particularly if the bag is of small size. Thus in dry hot region, use of small diameter black polybags is generally unsuitable. Black bags or sleeves are recommended where larger sized containers are used for raising bigger seedlings. In case of smaller diameter polythene bags, transparent and half buried bag in damp soil should be given preference in dry hot regions.

Figure 8.1 Preparation of stand for raising containerized seedlings and raising seedling through cutting in containers.

Another common problem with polybags is that plant roots tend to develop-certain deformities once they hit the smooth surface. It will lead to plants with restricted growth, poor resistance to stress and wind throw and are susceptible even to early die-back because of enhanced root masses or pathogens. Smooth plastic bags causes the principal root to coil or become spiral along the walls or at the bottom of the bag or pot. This inevitably happens when plants are left in the nursery for too long period. These roots should be cut-off immediately before planting in the field.

6. DISEASE AND PEST MANAGEMENTS

Nursery diseases and pests play an important role in raising healthy planting stock material for afforestation purposes. A number of pathogens and insects attack on various stages of plant development

6.1 Nursery diseases

It is very essential to diagnose the disease in proper time and adopt suitable control measure (Table 8.6). Each pathogen develops peculiar symptoms on the host (Srivastava and Verma, 2004). The seed borne mycoflora are associated with the diseases damping-off, seedling rots and wilts. Pods and seeds of *A. lebbeck* are attacked by *Coniella* spp., whereas pods and seeds of *A. nilotica* are attacked by *Aspergillus flavus* and *Aspergillus niger.* Likewise, seeds of many species are also infected by *Botryodiplodia theobromae*, *Fusarium* spp., *Alternaria* spp., *Curvularia lunata* etc. For this following precautions are suggested:

- Seeds should be collected from marked CPT's.
- Collection of seeds from ground and damaged pods/seeds should be avoided.
- Seeds should be properly dried and stored in cool dry place.
- Using certified seeds from authorized agencies.
- Seeds should be treated with fungicides like, Captof (0.2%) or Foltaf (0.2%) or Bavistin (0,1%) or Fytolan (0.2%) or Blitox (0.2%) or hot water treatment at 50°C for half an hour before sowing.
- Soil of the seedbed should be fresh and must be treated with Captof (0.2%) or Dithane Z-78 (0.2%) + Chloropyriphos (0.05%).

As a prophylactic treatment schedule for pests and disease control drenching of one cubic meter soil-mixture with at least 25 lit of water suspension of 0.05% chloropyriphos 20EC (62.5 ml/25lit) and Dithane Z-78 (50gm/25 lit) and drying before filling the soil in polybags is effective. This checks the infestation of all soil insects/pathogens. Further, spraying of monocrotophos 20EC(0.02%) at the rate of one ml/lit of water) + Dithane M-45 (one g/lit) + humour plus (2 ml/lit) after 10 days of germination of seedlings also check attack of sap-sucking insects, cut worms, leaf minors and foliar diseases.

6.2 Insect pest in forest nurseries

There are numerous insect pests which cause damage to forest seedlings in nurseries (Kaushik et al., 2007). Major insects are termites, white-grubs, cutworms, crickets etc. Minor pests include several defoliators of Coleoptera, Lepidoptera, Orthoptera etc. Sometimes, nematode and rats take heavy toll of seedlings in nurseries.

Table 8.6 Common nursery diseases and their control measures.

Disease	Types of disease	Tree species	Symptom	Causal organism	Control measures
Root diseases	Damping –off	*T. undulata*, *Eucalyptus* spp.	Seedling does not emerge above the ground. In Post-emergence damping-off, the pathogen attacks after emergence of seedlings and seedlings fail to survive	Species of *Pythium*, *Rhizoctonia*, *Phytophthora* and *Fusarium*	Watering should be reduced to minimum and application of Bavistin (0.01%), Dithane M-45 (0.01%) and Emisan-6 (0.0025%) separately as soil drench at 20 days interval
	Fusarium wilt	*D. sissoo*, *Eucalyptus*, *Cassia siamea*, *Acacia tortilis*, *Prosopis juliflora*, *Azadirachta indica*, *A.lebbeck*	Wilting, yellowing and drying up of leaves. The vascular region of root and stem show browning of tissues	*Fusarium oxysporum*	Reduction in soil moisture and facilitation of drainage to avoid water logging. Soil drenching with Bavistin (0.1%) or Dithane Z-78 (0.2%) at monthly intervals
	Collar rot disease	*Acacia nilotica*, *Tecomella undulata*, *P. juliflora* and *A. lebbeck*	Cracked bark of collar and black pycnidia on collar region	*B. theobromae*	Soil drenching with Carbendazim (0.1%) or Dithane Z-78 (0.2%) control the disease successfully
	Charcoal root rot	*A. indica*, *Acacias*, *Prosopis* spp. and *T. undulata*	Yellowing of leaves, defoliation and finally seedlings death. Brown to black dots of pycnidia and sclerotia also appears on collar region giving charred appearance due to death of the cortical tissue	*Rhizoctonia bataticola*	Fumigation of potting mixture with formaline (1:20) and/ soil drenching with Bavistin (0.2%) or Dithane M-45 (0.2%). Pre-sowing seed treatment with Emisan-6 (0.05%) or other contact fungicides
Shoot Diseases	Shot hole disease	*A. indica*	Circular spots on leaf lamina. In later stage infected portion detached from the leaves and form shot hole appearance	*Pseudomonas azadirachtae*, *Xanthomonas azadirachtae*	Foliar spray of Blitox (0.2%) or Bavistin (0.1%) is very effective in reducing the incidence of this disease

Disease	Types of disease	Tree species	Symptom	Causal organism	Control measures
	Seedling blight	*A. indica, Emblica officinalis, C. siamea*	Dark brown discoloration of leaves on the tip of the seedlings and gradually covers the whole leaf lamina from top leaves to downwards and spreads on petiole, stem and finally the seedlings die.	*Phoma* spp., *Colletotrichum* spp., *Alternaria* spp.	Spraying of Bavistin (0.025%) and (0.01% ai) at weekly interval. Other fungicide like Foltaf (0.02%) is also effective by spraying at monthly intervals.
	Twig blight	*A. nilotica*, *P. cineraria*, *Mangifera indica* and *P. juliflora*.	Primary injury caused by tip borer or sap sucker attracts the fungal infection of weak parasites	*B. theobromae*, *Phoma* spp. and *Colletotrichum* spp.	Spraying the combination of Rogor or Monocrotophos (0.05%) + Cu-based fungicides at monthly intervals
	Powdery mildew	*A. indica*, *A. lebbeck*, *Cassia siamea* and *Tamarindus indica*	Irregular white patches, consisting of mycelium and asexual conidia on the surface of the leaves. The disease appears in the form of white grayish pustules on both the surface of leaf exhibiting chalky appearance.	*Oidium azadirachtae*, *Oidium spp.*, *Leveillula taurica*, and *Erysiphe polygoni*	Foliar spray of sulpher based fungicides like Karathane E.C. (0.05%) or Calixin (0.05%) at monthly intervals.
	Leaf spot and Blight diseasess	*A. indica*, *Eucalyptus* spp., *Cordia mixa*, *Cassia siamea*, *A. lebbeck*; *Pongamia pinnata & Polyalthia longifolia*	leaf spot & blight	*Alternaria* spp, *Colletotrichum* spp., *Phyllosticta albizziae C. pongamiae* and *Cercospora* spp.	Foliar spray of Cu-based fungicides at first appearance of the disease or prophylactic treatment of the same.
	Leaf Curl disease	*Azadirachta indica*	Leaf curling and crumbling	Mites	A combination of Ethion(0.05%) + blitox (0.15%) + Tracel @ 2gm per liter.
	Mosaic disease	*Peltophorum ferrgeneum* and *Azadirachta indica*	Yellowish and crumbled nature of leaves	Mosaic virus	Foliar spray of systemic insecticide

6.2.1 Termites

Termites are widely distributed and the most destructive pests of forest nurseries and plantations. Under favourable conditions, termites can cause total failure of nursery stock. They feed on the bark and roots of seedlings. The infested seedlings begin to turn pale in colour and gradually die. At the infestation site mud plaster covering made by termites on seedling or trees also indicate the presence of termites in the area. Important termite species which cause damage to nurseries are *Microcerotermes minor*, *Odontotermes indicus*, *O. microdentatus*, *O. distans*, *Microtermes obesi*.

6.2.2 White Grubs (Cockchafers)

The grubs of *Holotrichia consangunea*, *H. insularis*, *H. serrata* and *H. problematica* are subterranean in nature and are generally root feeders while adults are defoliators. They are recorded to take heavy toll of young seedlings to forest nurseries of many regions including Indian provinces like Haryana, Bihar, Gujarat, Rajasthan, Tamil Nadu and Uttar Pradesh as well as to the agricultural crops. Grubs are found below 6 to 50 cm of the soil surface. Their head is reddish brown and body is of white colour. Seedlings are killed by the destruction of the rootlets or removal of bark of the tap root by feeding. The life cycle is normally annual with a larval period of 8 to 10 months in tropical and sub tropical conditions. In temperate conditions, life cycle may last for 2 years.

6.2.3 Cutworms

Important insect of this group is greasy cutworms *Agrotis ipsilon* (Lepidoptera : Noctuidae). It is a polyphagous pest and causes heavy mortality to the nursery stocks of several species. The larvae cut the stem of young seedlings from the collar region. Sometimes larvae penetrate in soil and feed on the roots of the seedlings. These insects prefer dry climate in comparison to damp places but in summer they become activated because of high temperature. In plains, the insect completes many generations in a year but under temperate conditions, it usually completes only one generation. Pupation occurs inside the soil, whereas adults start emerging in the second half of May. Cricket, *Brachytrypes porientosus* (Orthopeta : Gryllidae) is also an important pest of nurseries when raised in sandy soil. Its nymphs and adults feed on the root system of seedlings and ultimately damage them completely.

6.2.4 Minor Pest and Non-insect Pests of Forest Nurseries

In addition to the major pests, forest nurseries are sometimes attacked by several other pests of minor importance. Some of these are defoliating beetles, and larvae of *Euproctis*, *Lymantria*, *Heliothis*, *Plecoptera* etc. Some sap feeder like *Oxyrachis tarandus*, mealy bug and thrips also damage the seedlings at varying extent. Besides, nurseries seedlings are also vulnerable to attack of nematodes which sometimes cause immense damage. Some vertebrates like rats, hares, squirrels, porcupine, deer, etc. cause damage to seedlings in forestry nurseries as well as plantations. Among these, rats are most destructive. They have been reported to feed on the roots of *Acacia nilotica*, *D. sissoo*, *Melia azedarach*, *Tectona grandis* and *Cassia siamea* etc. Likewise, porcupine use to uproot *A. tortilis* plant to feed on the roots of this species (personal observations).

6.3 Management of the insect pests

To reduce pest population in nurseries following practices can be adopted:

- Deep ploughing of the nursery soil is necessary to expose the white grub and cutworm population to birds and sunlight. However, ploughing should be avoided when beetles are on wings for which loose soil may provide suitable sites for oviposition.
- At the time of the emergence of beetles weeding should be done to avoid the eggs deposition in loose soil. It should be done at least 6-7 weeks before spring sowing. For autumn sowing, weeding should be done in August.
- Light traps can be used to trap the winged termites and beetles during their emergence.
- To control white-grubs 200 g phorate (Thimet) 10 G per bed of 10 m × 1 m is most effective. For control of subterranean pests, 50 ml chlorophyriphos (20 EC) in 50 litres of water can be sprayed in the nursery bed of 10 m × 1 m before sowing. Polybag soil treated with chloropyriphos 20 EC (0.3%) is effective to protect seedlings from termites during transport and even after the transplantation in fields.
- Reliable prevention to control Rodents is to cover the seedbeds under fine wire mesh and digging the edges of the mesh into the soil. This also prevents birds from eating the seed.
- Cattle, goats, pigs, dogs and chickens must be completely excluded from the nursery by constant maintenance of the fence or wall.

7. GENERAL CULTURAL TECHNIQUES

Seedlings require water, nutrients and sufficient light and heat for healthy growth till they attain appropriate plantable size for planting out in the field. The primary aim is to produce nursery stock of suitable size, healthy and disease free so that when planted out the seedlings should be tough enough to bear the transportation shock, isolation shock, and difficult field conditions. To make the seedlings really tough and hardy it is necessary to train the seedling in the nursery itself by regular shifting and grading practices.

7.1 Shading

Shade is essential at various stages of seedling growth in dry areas and particularly important in hot arid region. It should however, be used thoughtfully and with care as pine seedlings grown in deep shade showed higher mortality and lower growth after planting than those grown in full sun and intermediate light treatments, while intermediate light only reduced the growth (Puértolas et al., 2009). Further, it was advised to use low light levels for *Q. ilex* seedlings during summer to save water without impairing field performance and culturing of *Pinus halepensis* seedlings under full sunlight conditions to maximize post-planting growth (Puértolas et al., 2009). Thus shading is beneficial for germination and for protecting recently pricked out seedlings, and protection from excessively hot sun, heavy rain and hail or frost.

In most of the forest nursery, young trees are used as a shade. Different shading capacity agroshed net are also available in the market namely 90%, 75% and 50% for their use depending upon the light requirement of the newly emerged seedlings.

7.2 Watering

Water is prime resource which affects seed germination and seedlings growth and biomass**.** Watering in most nurseries is done with watering cans or a hosepipe with a watering rose. A hose needs more care than a watering can to ensure a uniform application. In High-Tech nurseries, sprinkler system with micro fogger is economically useful for irrigation system in agro-shed house/mist chamber. Watering should be done twice a day except during rainy days. If adequate moisture is available, there is no need of watering for the day. The optimum watering is the field capacity of the soil, i.e. the watering should soak the entire soil medium without any stagnation of water. Excessive watering cause luxuriant growth of seedlings, hence reduction in the frequency of watering is recommended under such conditions. This steady reduction in nursery growing period is part of a process called hardening off. This makes the seedlings hard so that when planted, seedling could be able to meet the moisture requirement from the soil. This hardening period may be about two months before planting in the field. Water used for watering the seedlings should not be saline water and it should be free from silt discharge. Muddy water and water with silt discharge must be avoided as it forms crust on the surface which harden the soil and reduce the aeration of soil mass. This retards the growth of the seedlings also.

7.3 Fertilization

Countless research studies and published texts about plant nutrition necessitate changes in management practices, such as those necessary to provide optimum nutrition to seedlings and juvenile trees under varying site conditions with refined fertilizer rates, formulations, application timing and management objectives (Smethurst, 2010; Haase and Jacobs, 2013). The requirement of mineral nutrient depends on age of the plants. In nursery stage, 3 to 6 month old seedlings of tree species takes nutrient from added farm yard manure (FYM) in polybag or root container. For nourishing the plant for longer period, fertilization can be done through organic or chemical manure. Slow release nutrient namely organic manure includes decomposed FYM, oil cakes and green manure. The inorganic fertilizers include urea (as aerial spray), ammonium sulphate or ammonium nitrate, potassium nitrate (dissolved in water) and NPK. Fertilizers can also be mixed in the soil used for filling the polybags or containers. A better system is to apply top dressing in liquid form every fortnight after the seedlings are around 2 months old or one can use it as a foliar spray at a regular interval. However, precaution should be taken as wrong dosages burn the leaf tips and sometimes the entire shoot stock. Fertilization should be stopped during the last two months of the nursery life of seedlings to make them hardy and to allow lignification of the stem, i.e. proper hardening.

Two months old seedlings either in container or in transplant beds should be top dressed with NPK (15:15:15) mixed with water once in 30 days. For this 2 kg NPK should be dissolved in 500 litres water for irrigating 1000 seedlings so that each seedling receive 2 g of NPK and 500 ml of water (Kaushik et al., 2007). Foliar spray of urea at intervals of 30 day is necessary if seedlings need to be given a quick boost in height growth.

7.4 Weeding

Weeds compete with plants for moisture, nutrients and light and must be carefully controlled in the whole of the nursery area. During weeding it is ensured that the weeds are completely uprooted without disturbing the roots of the seedlings either in beds or in container. Though manual operations should be given preference, application of herbicides like 2, 4-D, MGP B2, 4, 5-T etc. can also be used to kill the weeds. One should keep in mind that no single herbicide controls all weed species. Oxyfluorfen, simazine, and isoxaben are pre-emergence herbicides effective against broadleaf weeds, whereas Oryzalin, pendimethalin, and prodiamine are effective in preemergence control of grasses and some small-seeded broadleafweeds (Altland et al., 2003). Metolachlor is the only herbicide currently labeled for nursery crops that is effective against pre-emergence *Cyperus* spp. Glyphosate, paraquat, and glufosinate are nonselective postemergence herbicides used under spray for broad-spectrum weed control.

7.5 Shoot trimming

Sometimes seedlings height is larger than the required ones. For many species like *Melia azedarach*, *D. sissoo*, *A. indica* etc., the shoots (extra height) are cut back to a prescribed height, i.e. to a height of 20 cm. It should be done at least two weeks before planting. The roots of overgrown plants may also be pruned only in exceptional circumstances, but it should not be the part of the routine nursery practices. Wherever seedlings are produced in open beds, as in the case of stumps production, it is routinely necessary to cut back the tallest seedlings in the bed to prevent suppression of some plants by their taller neighbours. These plants should also be cut back to the height of the plants around them, before competition from the neighbouring taller plants suppresses the smaller ones. If necessary, this process can be repeated as and when required.

7.6 Culling

To improve the survival under field conditions, seedlings are also sorted according to their suitability for planting. Only those seedlings are considered for field planting that have a good chance of survival. Poor seedlings that are in stage of dying when planted in the field conditions should be destroyed in the nursery itself. This saves the cost of planting, and also of the replanting which is generally done later. It should be considered perfectly normal to reject as many as 20% of the plants in a nursery because they are not suitable for planting. Therefore, there need to raise 20% extra seedling than the required numbers of the seedling for the field plantation.

8. COST OF RAISINGS NURSERY SEEDLINGS

The estimated rates for the tree seedlings is about Rs 5.20 in one season raised in 150 cc root trainer, Rs. 7.50 for two season raised in 300 cc container and Rs. 9.70 for three season raised in 500 cc containers. This includes the cost of maintenance also (Table 8.7).

Table 8.7 Different activities and cost estimates for raising 2000 quality seedlings in root trainers (cost based on rates July 2015).

SNo.	Item	Unit Cost		150 cc		300 cc		500cc	
	Rate for 2000 nos. seedlings	**Unit**	**Rs**	**MD**	**Cost(Rs)**	**MD**	**Cost(Rs)**	**MD**	**Cost(Rs)**
1.	Preparation of potting mixture	MD	206	2	412	4	824	6	1236
2.	Supply of coarse sand	cu.m.	2000	0.1	100	0.2	200	0.33	330
3.	Supply of compost	cu.m.	4000	0.1	200	0.2	400	0.33	660
4.	Supply of burnt rice husk	cu.m.	1200	0.1	60	0.2	120	0.33	198
5.	Filling of root trainers	MD	206	8	1648	12	2472	14	2884
6.	Collection of seeds	LS		1000		1000		1000	
7.	Treatment of seeds	LS		150		150		150	
8.	Sowing of seeds in mother bed	MD	206	1	206	1	206	1	206
9.	Pricking out and transplanting of seedlings	MD	206	3	618	3	618	3	618
10.	Supply of insecticides			500		750		750	
11.	Spraying of insecticides	MD	206	1	206	2	412	2	412
12.	Watering	MD		14	2884	21	4326	30	6180
13.	Weeding and Cleaning	MD		4	824	6	1236	10	2060
14.	Grading and Shifting	MD		3	618	6	1236	8	1664
15.	Contingencies for spraying machine & other tools etc.	MD		1000		1000		1000	
	Total (2000 seedlings)				10426		14950		19348

Likewise the estimated cost for the tree seedlings raised in poly bags is about Rs 6.30 per seedlings raised for one season in 300 cc polybag, Rs. 9.05 per seedling raised for two seasons in 375 cc polybag and Rs. 11.70 per seedling raised for three season in 800 cc polybag (Table 8.8).

Table 8.8 Different activities and cost estimates for raising 2000 quality seedlings in polybags of different sizes.

SNo	Activity	Unit Cost (Rs)		10 x 20 cm or 200 cc		12.5 x 30 /15 x 25 cm or 375 cc		20 x 40 cm or 800 cc	
	Rate for 2000 nos. seedlings	**MD***	**Cost**	**MD**	**Cost**	**MD**	**Cost**	**MD**	**Cost**
1.	Preparation of potting mixture	MD	206	5	1030	8	1648	13	2678
2.	Supply of coarse sand	cu.m.	2000	0.15	300	0.3	600	0.5	1000
3.	Supply of compost	cu.m.	4000	0.15	600	0.3	1200	0.5	2000
4.	Filling of poly bag	MD	206	8	1648	12	2472	15	3090
5.	Collection of seeds	LS		1000		1000		1000	
6.	Treatment of seeds	LS		150		150		150	
7.	Sowing of seeds in mother bed	MD	206	1	206	1	206	1	206
8.	Pricking out and transplanting of seedlings	MD	206	4	824	4	824	4	824
9.	Supply of insecticides			500		750		750	
10.	Spraying of insecticides	MD	206	1	206	2	412	2	412

SNo	Activity	Unit Cost (Rs)		10 x 20 cm or 200 cc		12.5 x 30 /15 x 25 cm or 375 cc		20 x 40 cm or 800 cc	
	Rate for 2000 nos. seedlings	**MD***	**Cost**	**MD**	**Cost**	**MD**	**Cost**	**MD**	**Cost**
11.	Watering			16	3296	22	4532	30	5768
12.	Weeding and Cleaning			5	1030	8	1648	14	2472
13.	Grading and Shifting			4	824	8	1648	12	2060
14.	Contingencies for spraying machine & other tools etc.			1000		1000		1000	
	Total cost (2000 seedlings)				12614		18090		23410

MD-Mandays

9. CONCLUSION AND RECOMMENDATIONS

Importance of good quality seedlings has increased significantly because of increased demand from both public and private plantations. It is high time to develop seedlings that should not only of good quality but strong enough also to adapt and resist to the varying site conditions particularly in drylands. While plant population per unit area and crop homogeneity are the factors in field productivity, but plant health, seeds quality, type and dose of fertilizer, weed and pest control etc. are important for quality plant materials. In this availability of quality seeds and its reliable sources have considerable impact.

- Majority of the species shows wide variations in flowering and fruiting throughout the year. A high number of species observed flowering and fruiting during the rainfall period, whereas some species produce fruit in a very short period of time. Such phenological records should be kept in mind or prepared during planning of nursery development.
- Physiological behaviour of seeds (species) should also be taken care of while there is need to store the seeds either for a short period or for a longer period. Fruit or seed properly washed and dried to reach equilibrium moisture content (7%) are better for storing the seeds of orthodox in nature. The storage should be in cool and dry conditions.
- Seed viability is one major factor that one should determine as germination percentage so that the sowing density can be known and time and input cost of nursery could be saved. Seed supplied by an organization are clearly mentioned about its viability.
- Small seeds should be mixed with an equal quantity of very fine sand (fine than the seed size) to facilitate uniform seed distribution. The depth of sowing should be 2-4 times the diameter of the seeds, ensuring that the seeds are just covered with the soil *in situ*.
- Many species germinate when daily temperature is above 20°C, but seeds of many tropical species require still warmer climate and geminate in a temperature range of 25 to 30°C. Hence suitable temperature should be maintained for effective germination of the seeds.
- Because of better-controlled growing condition container-grown seedlings tend to perform better on adverse sites than do bare-root

seedlings. But retention for a longer period, i.e., 3-4 month many species like *Eucalyptus camaldulensis*, *Prosopis cineraria*, *Azadirachta indica* and *Pongamia pinnata* shows deformed/ coiled root system that requires frequent shifting and root pruning.

- Black bags or sleeves are recommended where larger sized containers are used for raising bigger seedlings, but in case of smaller diameter polythene bags, transparent and half buried bag in damp soil should be given preference in dry hot regions.
- More basic research is needed to elucidate the mechanism to appraise the better seed source variations and seed storage behaviour and techniques in important multipurpose species.
- To better understand the underlying mechanisms of desiccation tolerance and intolerance, the physiological responses in the tree seeds require in depth research at the metabolomic and trans-criptomic levels.

Annexure 8.1. Proper time of collection and storage techniques of seeds of different tree and shrub species of dry areas.

S N.	Tree/shrub species	Seed collection time	Number of seed per kg mass	Germi-nation (%)	Seed pretreatment	Time and method of seed storage
1	*Acacia auriculiformis*	February to March	30,800-42,800	50-90	Hot water/ acid/ mechanical scarification	Storage in cool place in pack tin container for 2-3 years
2	*Acacia nilotica*	April to June	7,000-11,000	75-98	Hot water/ acid/ mechanical scarification	After proper cleaning and drying the seeds are stored in gunny bag or tin container etc. for 3-4 years
3	*Acacia senegal*	December to February	8,200-10,900	60-90	Hot water/ acid/ mechanical scarification	After proper cleaning and drying the seeds are stored for some period in gunny bag, tin container etc.
4	*Acacia tortilis*	November to February	12,000-13,800	45-80	Hot water/ acid/ mechanical scarification	After proper cleaning and drying the seeds are stored for some period in gunny bag, tin container etc.
5	*Acacia catechu*	January to March	20,000	60-90	Hot water/ acid/ mechanical scarification	After proper cleaning and drying seeds may be stored for 2-3 years in gunny bags, tin container etc.
6	*Acacia leucophloea*	March to April	11,000-16,000	50-85	Hot water/ acid/ Mechanical scarification	Clean and shade dried seeds are stored for 1-2 years in pack tin container etc
7	*Aegle marmelos*	April to June	5,300-6,100	50-70	No need of pretreatment	Depulped, washed infresh water, clean and shade dried seeds are stored for 1-2 years in pack tin container etc
8	*Albizia procera*	April to May	19,380-24,000	60-90	Hot water/ acid/ Mechanical scarification	Clean and properly dried seeds are stored for one year in tin container, polythine or gunny bag in fresh air
9	*Ailanthus excelsa*	April to May	9,500-10,000	70-90	No need of pretreatment	Seed can not be stored for long time. It can be stored for 6-7 month in polybag
10	*Albizia lebback*	December to February	8,000-10,000	60-90	Acid and mechanical scarification	Cleaned and dried seeds are stored for 2-3 years in gunny bag, tin container etc
11	*Anogeissus latifolia*	March to May	1,46,000-2,41,000	0.1-2	Water soaking	Cleaned and dried seeds are stored for 2-3 years in gunny bag, tin container etc
12	*Anogeissus pendula*	March toMay	1,54,000-2,49,000	0.1-2	Water soaking	Cleaned and dried seeds are stored for 2-3 years in gunny bag, tin container etc

S N.	Tree/shrub species	Seed collection time	Number of seed per kg mass	Germi-nation (%)	Seed pretreatment	Time and method of seed storage
13	*Azadirachta indica*	June to August	4,00-4,500	60-98	No need of pretreatment	After proper cleaning and drying seeds can be grown immediately. Seed can be stored only for one month that is in humid condition.
14	Bamboo species	April to May	25,000-35,000	40-60	Water soaking	After proper cleaning and drying seeds are stored for 1-2 years in gunny bag, tin container etc
15	*Boswellia serrata*	May to June	19,000-21,000	15-20	Warm water	Clean and dried seeds are stored for 2-3 years in gunny bag, tin container etc
16	*Cassia fistula*	March to April	6,000-7,090	40-70	Acid scarification	Dried seeds collected from pod are stored in cool and dry place in gunny bag
17	*Cassia siamea*	April to June	37,000-41,000	40-70	Hot water/ acid/ mechanical scarification	Clean and dried seeds collected from pod are stored in cool and dry place in gunny bag or tin container
18	*Dalbergia sissoo*	November to January	50,000-53,000	70-90	No need of pretreatment	After proper cleaning and drying of seed, store for 1-2 years in gunny bag, tin container etc
19	*Delonix regia*	March to April	2190-3245	50-85	Hot water/ acid/ mechanical scarification	Seeds are stored in pack tin container or gunny bag for 4-5 years
20	Eucalyptus spp.	May to June October to November	36,5000-37,0000	75-80	Water dipping	Clean and dried seeds are store for 2-3 years in shield tin or polypot container
21	*Hardwickia binata*	April to June	4,830-5,200	60-80	Warm water	Properly dried pods are stored for 1 year in gunny bag or tin container.
22	*Leucaena leucocephala*	July to November & February to May	20,000	80-90	No need of pretreatment	Clean and properly dried seeds mixed with fungicide/ insecticide are stored for 8-10 years in pack tin or polypot container
23	*Madhuca indica*	June -July	423-670	40-70	No need of pretreatment	Seed collected from depulping of fruit and washing out in water are grown immediately as seed viability loss quickly

S N.	Tree/shrub species	Seed collection time	Number of seed per kg mass	Germi-nation (%)	Seed pretreatment	Time and method of seed storage
24	*Moringa oleifera*	April to June	8,000-9,000	60-85	No need of pretreatment	Clean and shade dried seed are store for 2-3 years in pack tin container etc
25	*Prosopis cineraria*	May to June	20,000-28,000	75-95	Hot water/ acid/ mechanical scarification	After proper cleaning and drying seeds are stored for number of years in dry condition in pack tin container
26	*Prosopis juliflora*	December to January	32,000-35,000	70-90	Hot water/ acid/ mechanical scarification	Dried seeds collected from pods are stored for 2-3 years in cool and dry place in gunny bag
27	*Pongamia pinnata* or *Derris indica*	April to June	460-530	65-85	No need of pretreatment	Clean and properly dried seeds are stored for 6-8 months in tin container or gunny bag
26	*Tectona grandis*	January to February	1,850-3,100	30-40	Decaying of dried pulp in cow dug mix soil pit for 1-2 months	Seed/fruit store in tin container or gunny bag for 2-3 years
29	*Terminalia arjuna*	March to May	175-450	60-70	No need of pretreatment	Seeds/fruits are stored in tin container or gunny bag for 1 year.
30	*Terminalia belerica*	November to February	420-500	40-50	No need of pretreatment	Seeds collected from fruit and properly dried are stored in gunny bag for 2 years.
31	*Tamarindus indica*	May to June March to April	1,450-2,000	65-80	Hot water treatment	Dry seed collected from pods are stored for 2-3 years in cool and dry place in gunny bag
32	*Zizyphus mauritiana*	January to February	700-1,800	60-75	Hot water/ acid/ Mechanical scarification	Properly dried seeds are stored in gunny bag for 2 years
33	*Salvadora oleoides*	May to June	50,000-61,000	70-80	Warm water	Short lived seed
34	*Salvadora persica*	May to June	76,000-81,000	80-90	Warm water	Short lived seed
35	*Tecomella undulata*	May to June	90,000-1,05,000	50-70	No need of seed pretreatment	Proper dried seeds are stored in gunny bag or container in dark place for 2-3 years

Source: Mishra et al. (2012)

9

PLANTING STOCK IMPROVEMENT

Despite of having high biodiversity, productivity of Indian forests is very low against the global average due to lack of long-term programme on tree improvement. Though India has initiated tree improvement programme of many species but the results obtained so far are not so encouraging. Lack of commitment, continuity of long-term the improvement programmes and not learning from failures are key reasons of poor success is such endeavours. Provenance trails of Pines and Teak was started in 1930 involving different geographical seed sources. Guidelines were developed in 1960s for further improvement work for priority species like *Tectona grandis, Bombax ceiba, Pinus* spp*., Dalbergia sissoo, Santalum album, Morus alba* and *Pterocarpus santalinus*. Since then many more tree species have been added on national or regional priority basis that includes *Abies pindrow, Acacia auriculiformis, Acacia mangium, Acacia nilotica*, *Ailanthus excelsa*, *Albizzia lebbeck*, *Azadiracta indica*, *Bamboo* spp*.*, *Bauhinia variegata*, *Bombax ceiba, Casuarina equisetifolia*, *Cedrus deodara*, *Commiphora wightii*, *Dysoxylum malabaricum*, *Eucalyptus* spp*.*, *Gmelina arborea*, *Grewia optiva*, *Leucaena leucocephala*, *Neolamarkia cadamba*, *Picea smithiana*, *Pinus roxburghii*, *Populus deltoids,, Prosopis cineraria*, *Tecomella undulata* and *Toona ciliata*. This chapter provides the essence of genetic improvement, methodologies used for genetic trials viz., provenance, progeny and clonal trials as well as establishment of Seed Production Areas (SPAs), Seedling Seed Orchards (SSOs) and Clonal Seed Orchards (CSOs) including evaluation of such trials. Chapter also deals with establishment of Vegetative Multiplication Garden (VMG) and development of various clonal techniques for different tree species and achievements therein.

1. INTRODUCTION

Selection and domestication of plants and animals has been one of the important steps of human civilization. People were having the idea of heritability in all life forms to reproduce themselves and offspring have high similarity to their parents long before Gregor Johann Mendel's experiments conducted on pea plant from 1856 to 1865 and published *Principles of Heredity or Mendelian inheritance* in 1866. In 1900 his work was re-emphasized by three European scientists, Hugo de Vries, Carl Correns, and Erich von Tschermak. Their ideas attracted scientific community and gave a new thrust to agriculture genetics and created a new discipline of biology. Genetic improvements of crops and animals have been initiated in many countries to improve the productivity as well as quality of foods to meet the ever increasing population's demands. The great "Green Revolution" was the result of series of genetic research and technology transfer initiatives, occurred between 1940s and the late 1960s on pioneer breeding work of the agrarian genetist Nazareno Strampelli in the 1920s and 1930s (Salvi et al., 2013). The initiatives led by Norman Borlaug, the "Father of the Green Revolution," who won the Nobel Peace Prize in 1970, credited with saving over a billion people from starvation by increasing agricultural production worldwide.

Tree breeding is far difficult and time consuming in comparison to annual agriculture crops. Moreover, tree breeding programs were initiated late being second priority over the agriculture crops. In mid of 19th century forest and environment also gained importance and research and development activities initiated. First activity toward forest trees was initiated in Tanzania during the German colonial period in 1891 (Schabel, 1990) with introduction of exotic tree species and establishment of species trials in the arboreta at Kigogo, Sao Hill (1935) and Lushoto (1952). Eucalyptus and Pinus were the most widely planted tree genera, followed by *Cypress*, *Cedrela*, *Gmelina*, *Azadirachta*, *Senna*, *Acacia* and *Tectona grandis* (TAFORI, 1999). However, the emphasis on provenance testing, progeny testing, seed orchard and seed stand establishments, selection of plus trees and establishment of clonal banks for commercially important species were initiated after World War II in 1945. Large-scale tree improvement programs were initiated in the 1950s in more than 14 countries (Zobel and Talbert, 1984). A major thrust of these public programs was on the development of field methods that became important for successful tree improvement programs such as selection, designing and evaluation of trials, progeny testing, vegetative propagation, pollen extraction, controlled pollination, breeding tools etc.

Consumption of forest products is expected to continue its rapid increase during the 21st century. In contrast, the land base use for wood production is expected to decline because of population pressures, environmental stresses, lack of adequate management by landowners, and the divesture of lands deemed nonstrategic. Even today, biomass removals equal or even exceed growth rates in some areas (Wear and Greis, 2002). However, models indicate that the potential productivity of forests in many regions can be much higher than the currently realized ones (Allen, 2000; Bergh et al., 1998; Sampson and Allen, 1999). With investments in appropriate management systems, growth rates >25 m^3/ha/year for pines are biologically possible and can be financially attractive for a broad range of sites in temperate, subtropical, and tropical regions. Indian forests are known for its biodiversity, but their productivity is low per unit area per annum as compared to the global average. Indian forests are unable to meet the gap in wood supply (excluding fuel wood) of some 26 million cubic meters. This gap is expected to increase in future. There are few success stories also, where productivity of certain tree species has been enhanced many times through selection and clonal plantations (Lal et al., 1998; Lal, 1999). Therefore, planting stock improvement program of priority species is essential and must be continued for long-time.

Tree improvement programs are much more time consuming than annual agriculture crops. The problems associated with trees are:

- Most tree species are out-crossing, inbred lines do not exist and pedigree tracking is critical. Thus they must be bred to survive over decades in highly heterogeneous environments.
- Most tree species possess a lot of genetic variability for most of the traits of interest, whereas the traits of interest are typically controlled by many genes and have low heritability. For this improved varieties must be widely adapted and retain a lot of diversity.
- All trees may not be good candidates for marker-assisted selection and breeding applications.
- While trees require a lot of land and time to breed and test, the desirable traits are not always easily measured.

2. FUNDAMENTALS OF GENETIC TREE IMPROVEEMNT

Genetic tree improvement (GTI) refers to the application of forest genetics principles within a given silvicultural system for the purpose of improving the genetic quality of the forest. Its goal is to improve the genetic value of commercial plantations while maintaining the genetic diversity of the forests and base population. Genetic improvement is aimed at the population level, rather than improvement of breeds or inbred lines to increase the productivity and meet the goal (Williams, 1989). These programs provide a known source of quality seed, seedlings or propagules for forest establishment. In tree improvement, the desired traits phenotypes are selected from the naturally existing variations in the population. Genetic gains (i.e., higher productivity) are achieved through tree improvement process or tree breeding cycle like: (i) assessing genetic variation range for the selected commercial trait(s) in a species; (ii) selection of the most desirable phenotypes/genotypes from natural stands and plantations; and (iii) breeding and multiplication of these selected trees for plantations and utilization (Fig 9.1).

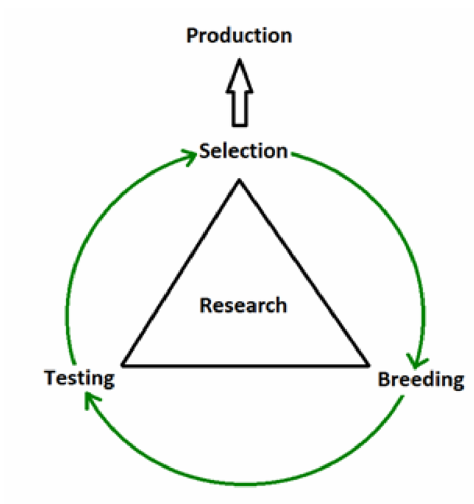


Figure 9.1 Basic tree improvement cycle

Selections can be of individuals (genotypes) from plantations, natural forest or groups (genepool) like Provenances and Seed Production Areas. Natural breeding cycle includes selection and inter-mating of superior genotypes viz., Seed Production Areas and Seed Orchards, whereas manual breedings are carried out to combine new characters in superior genotypes like disease resistant, abiotic stresses tolerant etc. Testing or evaluation includes testing of Candidate Plus Trees (CPTs), Provenances, Seed Production Areas (SPAs), Seed Orchards and Hybrids. Finally selected individuals and groups are multiplied for productivity enhancement through seeds collected from provenances, SPAs and Seed orchards and higher gains are achieved through clonal multiplication of elite material using conventional and advance methods (Tissue Culture). These three steps are repeated again and again to improve further the average commercial value of the breeding population. Each cycle of this improvement is referred to as a generation and accordingly product is labeled (Fig 9.2).

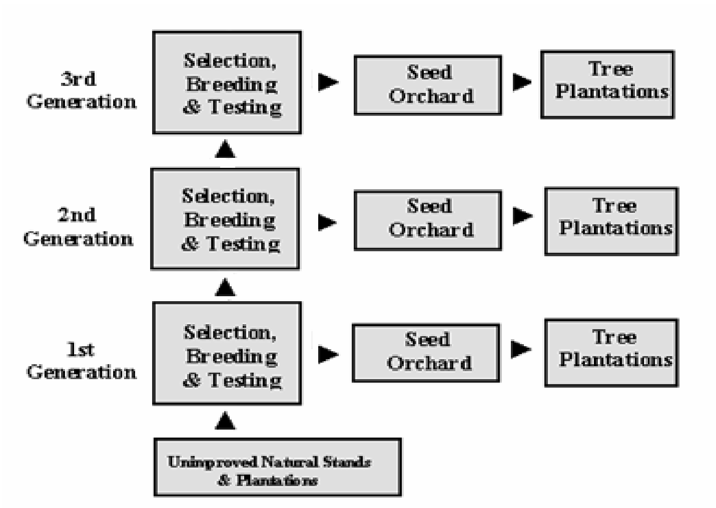


Figure 9.2 Recurrent breeding cycle

The variation of most important tree traits can be described with a bell-shaped or normal distribution. This distribution is symmetric around the average value with fewer trees occurring as the value increases and decreases from the average. In a tree improvement program, the best trees in the upper tail of the distribution (black shaded areas) are selected. These selected trees are then taken under breeding and their progeny are established in test plantations. Successive generations of selection, breeding and testing are carried out to further increase the average value of the breeding population (Fig 9.3). A base population (BP) is unimproved natural forest or plantations with high genetic diversity, from which individuals or groups are selected in the form of CPTs, Provenances or SPAs and always has high genetic diversity. It reduces in selected population (SP) raised after selection from SPAs or CPTs. The production population (PP) is another group of trees established to meet commercial planting demands with lowest genetic diversity. Thus after every generation cycle some genetic gains are achieved but it narrow down genetic base after every cycle (Figure 9.4). Hence a continuous supply of a superior germplasm is necessary to maintain desirable genetic base of production population. Usually the production population is a tested and evaluated seed orchard or group of trees at a single location managed specifically for seed production. For species which can be readily propagated using rooted cuttings, a hedge orchard are managed to produce cutting material and it may also serve as the production population. Seed and hedge orchards generated from a tree improvement program are established from grafts, rooted cuttings or seed of the plus trees in the breeding population.

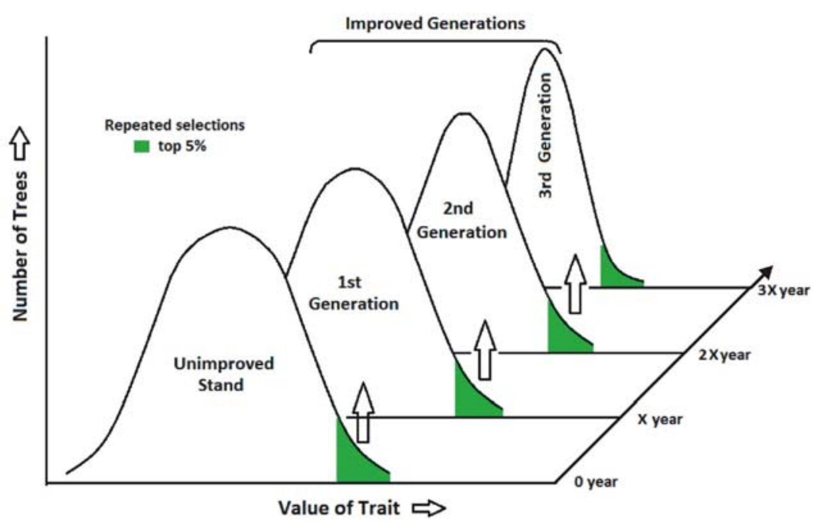


Figure 9.3 Distribution curves of unimproved stand and consecutive selection generation by generation indicating an increase in average value of trait after each selection.

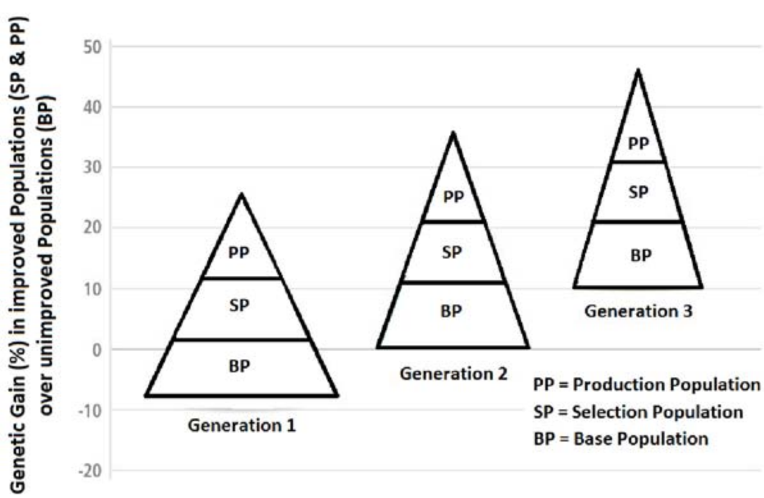


Figure 9.4 Genetic gains at Y axis and genetic diversity on x axis showing improvement but decrease in genetic diversity after each generation.

2.1 Selection

Genetic variation is the key of success for any tree improvement program. Expected improvement in a species is directly proportional to the variation range. It means if variation is small the likelihood of improvement in such species will also be low. Therefore, assessment of available genetic variation in a species is a prerequisite before initiating any tree improvement program. Provenance trial or seed source studies provide an idea about adaptability and overall variability range and scope of selection in the tree species for different useful traits. A logical first step in tree improvement is the provenance trial.

A wide variation exists in trees of natural stands in terms of growth rate, colour, branching habit and disease resistance. These characteristics are referred to as the phenotype of a tree. A tree's phenotype is determined by both its genetic constitution, or genotype and the effect of the environment as described by the following equation:

$$P = G + E$$

Where P is phenotype, G is genotype, and E is environment.

Phenotypically selected tree, what one see is not necessarily genetically superior, whereas genetically inferior trees may sometimes appear phenotypically desirable because they grew in an unusually favourable microenvironment. Conversely, genetically superior trees may appear phenotypically undesirable due to poor environmental conditions. Characteristics vary in the degree of genetic versus environmental influence. For example, genetic control of branching habit is stronger than for height growth so the selection process is generally more effective for branching traits. Initial selections of trees from the natural stands or unimproved plantations are necessarily based solely on phenotype. Since the variation due to environmental effects is less in plantations than in natural stands, the selection is more effective in plantations. In order to ensure that the selection process is as effective as possible in unimproved stands, candidate trees are graded according to predetermined criteria. Both the candidate tree and the neighboring check trees are measured and compared in order to account for local environmental effects. Once a tree improvement program is underway, genetic information (performance of relatives) is used to increase the effectiveness of the selection process. Selection is classified into two distinct groups based on gene pool and genotypes selection and they are termed as mass selection and individual selection, respectively.

2.1.1 Mass Selection

It is a short-term method of selection where individual plants are selected based on their phenotypic performance and their seed is bulked. Such selections proved to be quite effective in improvement at the initial stages but its efficacy especially for improvement of yield, soon came under severe criticism that culminated in the refinement of the method of mass selection. The selection after pollination does not provide any control over the pollen of parent as a result of which effective selection is limited only to female parents. When only parents are used to harvest seed and the pollen source is not known after the cross pollination has taken place, the heritability estimates are reduced by half. Collection of superior seeds from SPAs, Seed Orchards and best provenances is the result of mass selection where one gets superior gene pool, planting stock and germplasm.

2.1.2 Individual Selections

Identification of superior clones and their mass multiplication after a series of genetic tests are based on individual selections and by this way one can achieve maximum genetic gain out of a population. Further improvement is possible only through breeding and genetic engineering programmes.

2.2 Breeding

The next step in the tree improvement process is mating or breeding among the select trees or population. Seed Production Areas (SPAs) and Seed Orchards (SOs) are developed for this purpose. SPAs are the selected plantations (plus stands) developed after removing inferior trees and adopting silvicultural practices for higher seed yield and cross pollination. Seedling Seed Orchards (SSOs) are raised from seeds of Plus Trees, whereas Clonal Seed Orchards (CSOs) are developed through vegetative means of propagation (stem cutting, grafting etc.). If species is cross-pollinated (out breeder) no extra efforts are required for breeding amongst the selected CPTs. Field design plays an important role in providing opportunity to get a good combinations of all selected CPTs. However, if species prefers self-pollination, control pollinations can be performed. Here knowledge and expertise of reproductive biology is desirable to execute the plan successfully. It starts with emasculation of immature anther from hermaphrodite flowers and covering such flowers with bags to avoid natural pollination. Pollen collected from other select trees or mixed of a group of select trees is then injected into the pollination bag. After pollination has occurred, the bags are removed and flowers are allowed to produce fruits. Each fruit producing branch is labeled to ensure correct identification at fruits harvest. Control pollination is performed according to certain mating designs among the select trees in order to maximize the overall genetic information derived from the resulting progeny.

2.3 Testing

Seeds produced from SPAs and SOs after breeding efforts are used to establish progeny tests. The purpose of these tests are to (i) provide genetic information about the selected parent trees; and (ii) provide an improved population of trees from which the next generation of the select trees is made. Tree families established in progeny tests are randomized and replicated in a designed manner to meet statistical and genetic criteria. Families are planted at several sites in the same year so that samples can be obtained from an adequate number of environmental conditions. Tree progeny tests are intensively managed plantations, where growth and quality measurements are made periodically until harvest. These data are entered into a software data base for genetic and statistical analysis. The results are used to assess the genetic worth of the original selections for making further selections of elite trees to be used for next generation and recommendations for establishing and upgrading seed and hedge orchards for mass multiplication for their commercial use. Procedures of tree improvements are also modified and new tools like DNA markers, genetic engineering, tissue culture and statistical tools are incorporated. These programs are also tailored according to the traits and choice of the species.

3. METHODOLOGY

A successful program always has a strong scientific methodology. Programme is initiated with selections of superior germplasm.

3.1 Selection

Selection can be divided into two categories viz. mass selection (i.e., SPAs selection) and individual selections (CPTs or elite trees selection). Provenance trial and SPAs are beginning of tree improvement programmes and are short-term programmes to get the results as early as possible. The long term programmes of screening individuals are of continuous in nature and passes through a series of test like progeny and clonal trials.

3.1.1 Provenance Trials

Origin and provenance are synonymous in the case of a native species that has naturally regenerated on a site. It differs slightly in case of exotic species in which origin denote the geographic locality within the natural range of a species where the parent seed source or its wild ancestors grew, whereas provenance represent to the geographic locality of a stand of trees from where the seed was collected. The main objective of provenance trials is to find out the provenances yielding well-adapted and productive forests in an economical and timely manner. These studies also produce following informations:

- Patterns of genetic variation associated with patterns of geographic variation.
- Study of contrasts progeny of trees from many geographic origins in a uniform environment(s).
- Often such tests are designed to simultaneously test families within provenances.
- Selecting the right provenances within which selections for a tree improvement program may begin.

Provenance trials can be divided into three stages necessary to locate the best provenance or provenances of a species for a given site, country, or region. These provenance trails are called range-wide sampling phase, restricted sampling phase and proving phase.

3.1.1.1 Range-wide sampling phase: This is first stage planned to indicate broad regions in which provenances have reasonable adaptation and productivity. Depending on the range of the species and/or seed availability, the number of provenances tested may be large enough (>20) because the main purpose of this phase is to eliminate obviously unpromising provenances as early as possible thus reducing the provenances to a manageable number for more critical testing. If sufficient seed and resources are available large blocks of each provenance may be planted elsewhere for yield estimates at full rotation age and for individual tree selection, provenance hybridization, seed production, and maintenance of the gene pool.

3.1.1.2 Restricted sampling phase: This provenance trial is laid out on the basis of results obtained from Range-wide trials. The number of provenances tested may be between 5 and 10 and it may be valuable to represent each by seed from superior and randomly selected parent trees. This depends upon the resources of the seed collecting agency. Apart from financial, availabilities of space and plant resources are two conflicting considerations affecting plot size. If there is less variation between the plots of selected provenances, the plot interactions will be smaller and therefore plot size could be reduced. On the other hand, these plots should be maintained to full rotation age that could provide yield information (height and diameter) prior to that obtained in the proving phase. Larger plot sizes are therefore desirable and plots of between 49 and 169 trees are commonly used. A one- or two-row edge plantation may be desirable to minimize the edge effects.

***3.1.1.3 Proving phase*:** A small number of useful provenances obtained from the restricted provenance trial are tested at this stage under normal plantation conditions. Replication of sample plots within and between proving plots is essential. Proving plots are large enough to support standard mensurational assessments (0.5 to 1.0 hectare) or to facilitate costing and silvicultural studies (2 to 5 hectares). As with the earlier stages, these should be repeated on the major site types. If yield can be correlated with some simpler traits such as height, plot size and duration of the proving phase could be reduced. Attention should be drawn here to the desirability of developing early test methods for all stages of species, i.e. provenance and progeny testing.

***3.1.1.4 Experimental design and layout*:** The purpose of experimental design is to minimize environmental heterogeneity and to increase the precision of treatments (provenance) comparisons. Therefore, the advice of a qualified experienced statistician is desirable in designing and laying out of provenance trial experiment, particularly if local conditions indicate that some deviation from common designs is necessary. It is possible to minimize experimental error by choosing a uniform site although a typical uniformity should be avoided in siting provenance trials. Use of valid experimental design facilitates the separation of experimental error from other sources of variations.

A randomized block design (RBD) is useful for the range-wide sampling phase but for all stages the most favoured design is the randomized complete block (RCB) in which each replication contains one plot of each provenance. It is simple, so that the layout can be done and seedling planted and assessed by relatively untrained staff. Preliminary analysis of variance of plot means can be undertaken easily with desk calculators. It is statistically robust, so that loss of some plots or even entire replications will not invalidate the use of remaining data. The number of replications depends upon the variability of the site, the variability of the provenances, the precision of measurement, and the size of plot, in addition to resource considerations. Repetition in separate years may be necessary if annual climatic fluctuations are great at the site.

When large numbers of provenances are tested or when large plots are used, increased environmental heterogeneity may reduce precision. In such a condition some form of incomplete block design is desirable. Treatments are arranged in small blocks and blocks are laid out so that intra-block environments are homogeneous. The balanced types are preferable because each treatment occurs once in a replication with all other treatments so that the entire experiment can be analysed using RCB design if necessary. This allows early analysis by local staff and it may become the only possible analytical method if several plots fail or become damaged, or if only the better provenances are assessed for economy. Further, it permits estimation of the increased precision obtained by using the incomplete block design. Balanced incomplete block designs that are currently being analysed by the Commonwealth Forestry Institute, Oxford, for tropical species or provenance trials include rectangular lattices for 12, 20 and 30 treatments, and triple lattices for 9, 16, 25 and 36 treatments. These are proving more efficient than RCB designs but they are more difficult to supervise, layout, assess and record and should not be used unless absolutely essential.

Whatever design is chosen for the plantation stage, it is desirable to use the same design in the nursery. Plants for a given field replication is taken from the same nursery replication. In this way nursery and field replication effects are confounded and within-plot variance is minimized. When a provenance trial involves a series of plantation at several sites there must be a choice between the use of one central nursery and several separate nurseries. The decision must be based on local considerations of labour and transport costs, chances of plant damage by transport, chance of losing entire experiment if based on one nursery, and likely future practice. As with all aspects of nursery and field management, the techniques applied should be typical of what is currently practiced or anticipated for the future for each site.

***3.1.1.5 Management and assessment*:** It is not possible to generalize on the management and assessment of provenance trials but details should be included in each trial plan. It is difficult to determine in advance whether silvicultural operations such as thinning and pruning will be undertaken at prescribed times for the trial as a whole or for provenances differentially. Thinning may be systematic, random or selective, depending on the objects of the trial.

The types and frequency of assessment will vary with the stage of provenance testing but they should be specified in the plan. At the end of the nursery stage the relative performance of the provenances can be examined as a self-contained study. This may yield biosystematic information or predictive information for the plantation stage. Nursery characters, particularly plant dimensions, can be used as co-variants in plantation analyses. Other nursery traits of value are seed germination rate and amount, plant survival, uniformity, cotyledon and leaf characteristics. Because of limited resources priorities must be assigned to productive, descriptive, and taxonomic traits. Productive and descriptive characters that can be assessed usefully in both the range-wide and restricted sampling phases include height, diameter, bark thickness, crown depth and width, branch number, angle and length, survival, and uniformity. Straightness of stem is assessed either by some quantified continuous measurement or by categorical classification. These traits are evaluated at three-to five-year intervals throughout the test period with more frequent (half-yearly or annual) sampling in the first two or three years. The most useful measurements of yield are made at the crop performance phase by assessing height, diameter, form, taper, and bark thickness. Wood quality comparisons can best be made at the end of this stage although preliminary information can also be made in the earlier testing phases. Other important traits that are assessed in all phases are phenology of growth and flowering, and seed productivity which may require intensive observation over several years. Reaction to adverse environmental and biotic factors must be recorded throughout all stages. Whenever biotic damage is observed the causal organism must be identified. Attention is concentrated on early measurements for four reasons:

- To estimate juvenile-mature correlations, particularly for countries establishing large areas of plantation with incompletely tested species.
- To make decisions on choice of provenance before information is available on mature crop performance or on juvenile-mature correlation. An increased safety should be obtained by multivariate analysis of several juvenile performance indicators by measuring height and diameter at 6, 12, 18, 24,…… months age.
- To explain variation in mature characteristics of juvenile traits by covariance analysis. In this attention must be given to possible subsistence immediately after planting that could cause an apparent decrease in tree height. An assessment six months after planting may be preferable although an initial establishment survey is essential immediately after planting.
- To compare the total growth of provenances over the entire test rotation. Where sigmoid growth curves are involved, great changes in slope and precision occur early in the rotation and hence greater sampling intensity is required to obtain uniform precision of provenance comparison over the entire growth curve.

3.1.2 Seed Production Area (SPA) Selection

SPA selection is one of the interim options for meeting immediate seed requirements of a plantation agency like State Forest Departments. Likewise establishment of SPA is an important investment to provide a reliable least cost source or well adapted seed until improved variety of higher genetic quality becomes available. SPAs are very popular in the earlier phases of plantation programme of exotic species like eucalyptus, acacias etc. and adopted by many countries of the world. Plantations of the local land race of the species provide a reliable source of seed which may be less expensive than importing seed from the external sources. When natural stands of plantation are chosen for its conversion to SPA, the following points needs consideration:

1. The species should originate from an appropriate seed source adapted to climatic conditions of the targeted plantation zone.
2. Species should be of sufficient size and contain sufficient number of good phenotypes to ensure adequate pollination and sufficient seed production even after poorer phenotypes are thinned out.

3. A minimum area of at least 2 ha with 50 to 150 good phenotypes per ha is more appropriate.
4. The plantation or natural stand should show clear evidence of past seed production and sufficient crown surface area to continue producing adequate amount of seeds.
5. Easy accessibility during seed collection time.
6. Located at an adequate isolation distance from other seed sources to prevent chances of cross pollination.

The plantation of selected stand should have desirable characters like height (top height), clear bole height, girth at breast height (GBH), straightness of stem, roundness of stem, crown and tree health. All these characters enhance gain from SPA selection. Operations that can be carried out for management of an area includes: removal of understory vegetation to improve access, flower induction through fertilization and chemical or mechanical means, and application of pesticides to control insects destroying or harming the flower and seeds.

The selected stand is thinned by removing the poorer phenotypes while the good trees are left to inter-mate and produce seeds which are collected for operation in forestry programs. However, genetic gains from SPAs are minimal for traits with low heritability like bole volume. Genetic gains are highest for traits like total height, clear bole height and GBH. SPAs also provide an inexpensive supplement to more elaborate and highly technical tree breeding activities. The amount of genetic gain (higher productivity) by plantations raised from seed of SPA is expected to be small, but it is an improvement compared to plantations raised from seeds of a non-selected stand. SPAs are important because of the following reasons:

i. Immediate assistance of seed supply from phenotypically superior stands for forest plantation establishment.
ii. High-quality trees with broad-base foundation for a tree improvement programme.

While converting the selected seed stand or a plantation into a seed production area, the trees retained for seed production should be the best trees in the population. This can be achieved by ranking of trees for selected traits and culling out the inferior trees. As the number of trees to be scored for various traits in a seed stand is quite high, it is not easy to score for all the traits as is done in the case of plus tree selection. Comparison and ranking of trees based on the growth, form and health within the selected plot may be possible by following guidelines:

- Identification of potential sample plot to be laid out as SPA.
- Size of sample plots 0.25 ha with minimum 3% sampling intensity.
- Scoring of quantitative and qualitative traits like total height, Clear Bole height, GBH, Straightness of stem, Roundness of stem, Crown and Health.

3.1.3 Selection of Candidate plus Trees

Preferably 40-50 plus trees of each species from established plantations are selected. Selection can also be done in a virgin forest but never in logged-over areas or second growth forest.

***3.1.3.1 Selection procedure*:** Following points required to be considered in selecting CPTs:

(i) A map of plantation(s) or natural stand(s) must be available. The plantation(s) or stand(s) on which selection will be done should be delineated on the map as well as on the ground.

(ii) Familiarization is necessary about the plantation(s) or stand(s) site by going to the area and taking note of the species composition, topography and growth of the trees.

(iii) A preliminary selection can be conducted by going through the plantation(s) or stand(s). In plantation where trees are equally spaced going through a couple of rows would enhance and facilitate selection. In natural stand grids of 25 m × 25 m can be delineated and selection therein can be conducted. Good looking tall, big in diameter with straight cylindrical stem and healthy (without any sign of insect or disease damage) trees can be marked initially.

(iv) Going back to the area and evaluating the trees marked in step (iii) is necessary. It is possible that one may find other trees better than those previously marked. In this case, these trees should also be evaluated or rated.

A tree which receives 80-90 points (before wood property evaluation) or 110-120 points (after wood property evaluation) is 'Acceptable seed tree' and should be marked and painted with one band and a code number to the tree should be assigned. If tree receives greater than 90 points (before wood property evaluation) or 120 (after wood property evaluation), it is called 'Plus tree' and should be marked with two bands with a clear code number. Selected tree that has been progeny tested and proven to have a high general combining ability is 'Elite tree' and should be marked with three bands.

***3.1.3.2 Plus trees evaluation*:** Trees inferior in an important character should not be selected in the first step. Results of evaluation should be recorded on the 'Plus Tree Recording Form'. The following traits are evaluated:

Vigour (25 + points possible): Candidate tree is compared with other trees within a radius of 15 meters. This requires measurements of DBH over bark and height of 10 representative trees and calculation of the mean or average.

Diameter: 10 comparison trees are measured for DBH over bark and mean or average is calculated. DBH over bark of the candidate tree should be measured and then using the computed average as a reference, points are given like: 0 – 2 for smaller than average, 3 - 5 for between average and tallest tree, 6– 8 for equal to largest tree, and 9 –10 for larger than other trees in the plot.

Height: Total height of the candidate tree must be measured. Ocular comparison is made with the 10 comparison trees. Points assigned are 0 –4 for shorter than average, 5 –10 for intermediate or average, 11 –12 for equal to tallest other tree, 13 – 15 for taller than trees in plot.

Bole form (maximum 20 points): Candidate tree is subjectively scored by visually comparing with comparison trees. 20 points are provided for a tree with trunk perfectly straight and less taper, 1 –3 points are deducted for basal sweep, 1 -5 points are deducted for trunk bends, spiral bole, 1 – 5 points are deducted for trunk curves, 1 point is deducted per degree lean, 1 – 3 point are deducted for cross section not circular, and 1 – 3 points are deducted for detectable bole swelling.

Branching habits (Maximum 25 points): Branch angle score 15 points. For this point at the main stem, if one wants to utilize the stem for timber or pulpwood, is determined and marked/cut. Then angle in degrees between the main stem and the third branch located above the point of cut, or the third branch of the dominant fork located above the point of cut is measured and points are allotted in following manner:

Third Branch	Points
80° - 90°	15
70° - 80°	12
60° - 70°	8
50° - 60°	3
40° - 50°	0
< 40°	-3

Branch diameter (maximum 10 points): Because of its relation to tree vigour, trees with smaller branches are favoured. Third live branch located above the point of cut or the third live branch of the dominant fork located above the point of cut are measured. Points are like: 0 – 4 for bigger than average, 5 –7 for intermediate, 7 –10 for remarkably small for vigour of tree. For epicormic branch 1 point for every epicormic branch is deducted, whereas a tree with more than 10 epicormic branches on the trunk is rejected. Likewise, 1 -3 points are deducted for excessive length of the branch, whereas 1 –2 points are deducted when evidences of ramicorn is there.

Apical dominance (maximum 10 points): Stem length to the first live branch or at the point of cut are measured and recorded as percentage of total height. Trees are graded like 10 for over 70%, 7 -9 for 55 - 65%, 4 - 6 for 40 - 54%, 1 – 3 for 25 - 39%, 0 for below 25%.

Forking (maximum 5 points): For this points are allotted like: 5 points for forking above 10 metres from the ground, 3 -4 points for forking from 5 -10 metres from the ground, and 1 –2 points for forking below 5 metres from the ground.

Health (maximum 10 points): Candidates are expected to be healthy and resistant to disease or insect attack. Points are deducted for evidence of past dead-top, insect borings, rotten knots, etc.

Wood properties (maximum 30 points): Candidate trees are expected to have higher specific gravity and longer fiber length than the average for a certain geographic location. For this core samples are taken from the trunk and examined in the laboratory for these two properties. Wood properties of selected plus trees with that of ordinary routine trees are also compared. The assessment of wood properties is optional as it relates to the end-use objectives of the organization. These are important traits for pulpwood and timber production.

Specific gravity (maximum 20 points): Points allowed are: 15 –20 for above average, 10 –14 for average, 5 – 9 for light, and 0 – 4 for very light wood.

Fiber length (10 points): Points generally permitted for this trait are: 5 –10 for above average, 3 – 4 for average, and 0 – 2 for short fiber length.

3.2 Seed Orchards

Feilberg and Soegaard (1975) states that "A seed orchard is a plantation of selected clones or progenies which is isolated or managed to avoid or reduce pollination from outside source and managed to produce frequent, abundant and easily harvested crops of seed". Although the concept of seed orchard was applied before 1940 to species like *Hevea brasiliensis* and *Cinchona officinalis*, it was only in 1949 that the first pine seed orchards were planted in Sweden (Barrett, 1985). There are numerous kinds of seed orchards, but they generally fit into one of the two broad categories, i.e. vegetative orchards or clonal orchards. These are established by using vegetative propagules such as grafts, cuttings, tissue culture plantlets etc. Seedling seed orchards are maintained by planting seedlings followed by removing the inferior trees, generally leaving the best trees of the families for seed production purposes. Seed orchards are the most common type of planted population and nearly all tree improvement programs establish seed orchards to produce genetically improved seeds for practical purposes. In most of the cases, mating among trees in the orchard is uncontrolled (open pollination) which may be mediated by wind, insects or animals. Two types of seed orchards are:

i. Seedling Seed Orchards (SSO) established with open pollinated or full-sib offspring from selected trees.

ii. Clonal Seed orchard (CSO) for which the vegetative propagation tools like grafting, rooting or tissue culture are used to establish clones of the selected tree species in the orchard.

3.2.1 Seedling Seed Orchard cum Progeny Trials

Seedling seed orchards (SSOs) are the most common method of producing genetically improved seeds for forestry programs and are popular for both gymnosperms and angiosperms. Typically an SSO is established with 20 to 30 families from the best selections available and the number of offspring per family is determined by the number of trees required to meet the total seed demand for afforestation. Usually around 20 to 50 offspring per family are planted in a typical SSO. SSOs are preferred over CSOs when:

- The vegetative materials from the selected trees are difficult to obtain and propagate by rooting, grafting or tissue culture.
- In case a species requires progeny trial than seedling seed orchard can also be evaluated as progeny trial and after removing inferior families and genotypes the same trial can be used as SSO.
- The orchard is used for producing genetically improved seeds.

3.2.2 Clonal seed orchards (CSO)

Clonal seed orchards are the most common method of producing genetically improved seeds for forestry programs. Typically a clonal seed orchard is established with 20 to 60 clones from the best selections available and the number of ramets per clone is determined by the number of trees required to meet the total seed demand for an afforestation programme. Usually, around 50 to 100 ramets per clone are planted in a typical CSO. CSOs are favoured over SSOs when:

1. The vegetative materials from the selected trees are easy to obtain and propagate by rooting or grafting or tissue culture.
2. The species flower only at older ages after originating as seedlings and the material from older selections is vegetatively propagated.
3. The orchard is used for producing genetically improved seeds.

3.3 Vegetative multiplication garden

The objective of Vegetative Multiplication Garden (VMG) is to provide juvenile stem cuttings from selected germplasm in hedge form near the mist chamber for production of superior clonal planting stock. There are two possible approaches employed are: (i) short-term through seeds with modest gain in productivity; and (ii) long – term through clones with greater genetic gain. The latter is highly desirable although much time is required to produce the desired plants to meet the immediate need of planting material for impact forestation projects. Depending upon the financial and technical capabilities of the implementing agency both approaches can be employed but giving a little more priority to the former ones.

3.3.1 Short term approach

In this, multiplication garden is established through seeds from the selected CPTs as half sib progenies. Establishment and Management of a Clonal multiplication Garden through this procedure are given below:

- At least 200 seedlings of each plus tree are raised. If seeds are not available, collection of vegetative propagules from the plus trees can be made and clonal plants can be raised.
- VMG is generally established at 2m × 3m spacing in case of Eucalyptus species. However, it can be modified according to species coppicing potential and site conditions. Assuming a planting distance of 3m × 3m, the number of plants required in the multiplication will be at least 1100. Each selected genotype (good coppice) can produce at least 200 plants in a year and one hectare VMG with 1000 plants must produce 2 lakh plants in a year. Therefore, VMG is established according to plantation targets. Generally it is in a ratio of 1:100 ha. It means 1 ha VMG is sufficient to meet the 100 ha plantation targets.
- Seedlings (progenies) from each plus tree are being planted within a row or line. To prepare the lines, an identification tag on a meter tall stake indicating the plus tree code numbers is placed followed by putting

stakes at each planting spot in a line between rows of established trees in the plantations and digging of planting holes. It will be more appropriate to prepare a sketch of the lay out plan of multiplication garden on a map itself. The distance between seedlings (within line) is 2.0 meters. Seedlings or wildlings should be fully hardened in the nursery before planting out. This layout will also serve purpose of a pure line progeny test. Because of the inherent sensitivity of young reproductions of dipterocarps to direct full sunlight, partial shading is required in case of an open area. Before out planting during the onset of rainy season, a shade made of two layers of black fish net, raised at about two meters from the ground by strong posts and beams are constructed over the multiplication area. The upper layer of the net could be rolled in during rainy and shady months and unrolled during the sunny (summer) months of the year.

- The hardened seedlings/wildlings are planted during the rainy season; however, mixing of the seedlings/wildlings should be avoided. All seedling belonging to a particular plus tree must be planted in one line. Location of each seedling should be properly recorded / indicated on a map of the clonal multiplication area.
- Percentage of rooting of stem cuttings decreased abruptly after age 4 –5 years of the families in the plants of some woody species. Therefore, it is very important to monitor the rooting strikes of the families in the multiplication area. Once an abrupt decline in rooting is observed in a family, the progenies of that family are replaced by seedlings of the same plus tree (if it is a good performer) or by a new family. Commercial fertilizer rich in nitrogen or organic fertilizers can be applied to induce the production of more shoots in addition to maintain general health of the plants.

3.3.2 Long – term approach through clones

In place of seed vegetative material is used from selected CPTs in this procedure to harvest higher gains. A clonal bank is a living collection of selected clones (asexually propagated plants) which are managed for breeding work. After a clonal test, the best performing clones are retained, then pollared to induce the production of juvenile shoots which are then vegetatively mass multiplied by rooting of the cuttings. These rooted cuttings are used as propagules for clonal plantation development.

Establishment of a clonal bank: Vegetative materials (twigs, branches) from the selected plus trees are collected and grown by either grafting, budding or rooting, whichever is most effective to obtain high success of establishment. Ramets are hardened in the nursery for sufficient duration to allow them to fully develop as seedling before planting in the field and clonal bank is establish under an existing plantation, preferably of leguminous species. In this, ramets of a clone are planted in one line, that is 20 or more ramets per line spaced at 2 meters between the rows of established trees in the plantations. Each line or clone is properly marked with the clone’s identification number.

Roguing the clone bank: Based on the result of the clonal test, the poor performing clone (including ramets) with respect to the aforesaid traits are removed from the clonal bank. The inferior clones, however, could be replaced by new selected ones. The best clones are sources of vegetative materials (cutting) under mass multiplication.

Maintenance of the clonal bank: Regular pruning of the ramets is required to remove old branches and also to induce continuous production of juvenile shoots. Commercial fertilizer rich in nitrogen or organic fertilizer are added to the clones at the rate of 100 kg per hectare at every six months. This practice induces the production of more vegetative parts in addition to maintaining the general health of the clones.

Multiplication of juvenile shoots: The ramets are pollarded after the clonal test to induce the production of more juvenile shoots. Under mass multiplication, cuttings from the juvenile shoots are rooted in mist propagation units using standardized propagation procedures (Leakey, 2004). Properly graded and rooted cuttings are then utilized for the development of clonal plantation.

Clonal Multiplication Area: In this coppice above 60 –65 days old from the clonal bank are harvested, transformed into stem cuttings for rooting and are then transplanted in a clonal multiplication area, usually situated near the major mist propagation facilities and nursery. It is important to ensure that the ramets of a clone should not mix with other clones and ramets of a clone are planted in a line or in a block with proper ID tags. At every 50-65 days, coppices from this multiplication area are harvested, converted into stem cuttings for rooting in a mist propagation unit. Rooted cuttings are kept for 5-10 weeks in the shade house, on an adjacent open area for further hardening before out planting.

3.3.3 Mass clonal multiplication

Mass multiplication of rooted cuttings requires an environment where the temperature, light intensity and humidity are at optimum level and conducive for rapid vigorous root growth of the clonal materials. The kind of rooting medium, type and concentration of rooting hormones, age of the ortet, size of stem cuttings and collection and handling of the clonal materials are critical factors that should be given utmost attention in rooting stem cutting. The major structural facilities are greenhouse, propagation beds, and hardening area. The propagation beds are set up inside the mist polyhouse. The hardening area is constructed close to the mist chambers and polyhouse.

3.3.4 Plantation establishment and management

Site preparation: Planting lines are prepared by clearing 1.5 meter wide strip at given intervals. The distance between the lines depends on the planting distance. All vegetation along the lines should be removed or slash and the debris should be spread on the ground to serve as mulch. Burning of the planting area should generally be avoided.

Spacing: An initial spacing of 2 m × 2 m or 2 m × 4 m is preferred to allow rouging of poor performer ramets, though spacing also depends on site conditions and the type of species under plantation. However, 1200 clones per hectare in VMG can be established (Anon., 1999).

Planting layout: After the site preparation, the planting spots are marked properly by tagging in the identified lines. A particular clone is planted at the beginning and end of the line after digging of pits of suitable size. Mixing of the clones in a line should be avoided. The planting lay– out can be drawn on a map, indicating the location or position of every clone.

Weeding and Watering: Periodic weeding of the plantations is a necessary operation. Strip weeding should be done thrice during the 1st to 3rd year and twice during the 4th and 5th year and once a year thereafter or whenever necessary. Watering is highly essential in dry regions for high growth and it is required at least twice in a month.

Application of fertilizers: Five grams of complete fertilizer at the base of each ramet should be applied three months after out planting. Subsequent application of the same amount can be done every six month until the 5th year. Future application of certain amount can be followed only after conducting soil fertility test.

Pests and diseases control: The plantation should be protected against serious pest/insect infestation and disease infection. Remedial measures should be immediately taken once imminent signs of such occurrence are happen.

Regular pruning: Planted material in VMG must be pruned twice in a year to maintain it in a juvenile form. Material (cuttings) must be collected each year to check the rooting potential.

Keeping and maintaining good records: A presentable record sheet or format, which should be encoded in a computer, should be prepared. If the plantation is composed of several blocks, then each block should have a separate record.

3.3.5 Methods of vegetative propagation

Clones are vegetatively propagated through stem nodal cutting raised in mist chamber or through tissue culture using species specific protocols developed by researches using following steps:

Preparation of Cuttings: About 10-15 cm long cuttings (for example *Dalbergia sissoo*) are prepared from CPTs branches, but from VMG smaller sizes (3-4 cm) juvenile cuttings are appropriate. Leafy cuttings are prepared in case of Eucalyptus. Two half leaves along with 2-3 cm long stem node can be cut from the coppices.

Treatment of Cuttings: All the cuttings are treated with 1.5 % IBA talc preparation in case of juvenile cuttings, whereas stem cuttings collected from *D. sissoo* CPTs are treated with liquid IBA for 30 seconds. Cuttings are raised in root trainers under intermittent misting in mist chambers or mist poly house.

Rooting period: Almost 15-30 days are required to achieve rooting in arid zone tree species during summer season, whereas in winters a longer period is required. However, there is tremendous reduction in rooting percentage when process conducted during winters (Meena et al., 2013).

Potting of the rooted cuttings: After rooting, these plants are transferred to polythene bags with soil mixture (Sand: compost in 1:1 ratio) and kept in polymist house for 2-3 weeks, before shifting them to shade house for hardening.

Hardening: Ramets from polyhouse are shifted to shade house for hardening. At this stage watering is highly essential and each plant is watered every day. This clonal material must be kept in shade house for 2-3 months before planting them out in the field.

3.4 Clonal trials

Clonal trials are established to test the clones for a site (Clonal Test) or multiple sites (Multilocational clonal Trials). Following procedure are followed in establishing a clonal trial:

Field lay-out: The clonal test plots are established in an open area near the nursery. Clones are planted in pure lines, which means that, ramets (which are rooted cuttings) from a clone are planted within a row or line after proper tagging and stacking. The distance between lines/clones is 3 m and between ramets (rooted cuttings) is 2 m with proper sketch of the lay–out map.

Planting out: Sufficiently hardened ramets are planted in the field at the onset of rainy season. But mixing of the clones or ramets should be avoided. All ramets belonging to a clone must be planted in one line, where location of the clone are properly recorded / indicated on a map.

Clonal Test: Since the clones are planted in lines, it is possible to compare them with ease in regard to their growth behaviour, stem form and resistance or susceptibility to insects and disease. The clonal test should be maintained and monitored for a period of 8 to 12 years.

4. IMPROVEMENT IN SOME INDIAN SPECIES

4.1 Teak (*Tectona grandis*)

Tree improvement program on teak has been started to utilize the inherent variation in the species characteristics (Kedarnath and Matthews, 1962) like superior stem form, high rate of growth in height and diameter, freedom from fluting, buttressing and epicormic branches, resistance to leaf skeletoniser (*Eutectona machaeralis* syn. *Pyrausta machaeralis*) and leaf defoliator (*Hyblaea purea*). Studies carried out on early growth performance of 20 clones at New Forest, Dehra Dun have shown considerable variation between clones (Kedarnath et al., 1970). These differences have persisted in later years also. Similar observations have also been recorded over the years on the relative resistance/susceptibility of the different clones to two leaf infecting fungi- *Olivaea tectonae* and *Caldariomyces tectonae*.

Different studies on clonal performance of teak indicate differences in fruiting phenology and number of fruits per inflorescence (Gunaga and Vasudeva, 2002), resistance to insects (Lyngdoh et al., 2012; Javaregowda et al., 2010) and diameter growth (Lyngdoh et al., 2012). Time of fruit initiation alone has been found genetically controlled (h^2 = 0.756 individual tree basis), while other traits (i.e., fruiting duration and number of fruits per inflorescence) have been influenced by the environment, where heritability estimated based on the clonal means have higher suggesting a strong genetic control (Gunaga and Vasudeva, 2002). All reproductive traits viz. number of flowers per inflorescence, number of fruits per inflorescence, fruit set per cent, Pre-Emergent Reproductive Success (PERS), fruit diameter, fruit volume, fruit weight and fruit density show significant inter-clonal variation, except seed to ovule ratio per fruit (Hanumantha et al., 2001). Variations among-clone for diameter at breast height (dbh) and volume has also been observed significant, though variation within-clones are negligible, suggesting a strong genetic basis for these traits, where clones MyHuN1 and MyHuT1 are 'tolerant' to trunk borer (Lyngdoh et al., 2012). A general trend of higher volume with higher level of tolerance to trunk borer has also been observed in the study although the strength of the association has not been observed significant. In another study, six teak clones viz. MyMK-3 from southern provenance, MyKN-1, MyKN-46 from central provenance, STG-3, STG-06 of state graft series as well as Teli teak of Dandeli of Karnataka have been found resistant, whereas other clones are moderately resistant to teak defoliator *H. puera* (Javaregowda et al., 2010).

4.2 Acacia spp.

There is significant phenotypic variation in pod and seed size in natural stand of *Acacia senegal* and other species in western Rajasthan (Solanki et al., 1985). Provenance trials of *A. senegal*, *A. albida* and *A. tortilis* sub sp. *radiana* have been established at CAZRI, Jodhpur (CAZRI, 1984, 1986, 1988). Growth performance of progeny trial developed after collecting seeds from ten provenances of *Acacia catechu* in Himachal Pradesh indicates that Jachh seed source perform the best with respect to phenotypic characters followed by Kangra seed source. Mother trees of *Acacia catechu* (khair) are also being evaluated for katha content.

***Acacia nilotica* (L.):** This is a multipurpose tree species and a good source of food, fodder, tannin and small timber. Its fast growth, good coppicing ability, atmospheric nitrogen fixation capacity and wide range of adaptation have gained attraction of the people of South-east Asia and Africa. It is found throughout semi-arid regions of the country from Punjab in north to Tamil Nadu in south and is available in almost all farmlands across India. Provenances/progeny trials of this species have been conducted by CCS Haryana Agriculture University, Hisar; Forest Research Institute, Dehra Dun; Tropical Forest Research Institute, Jabalpur, JNKVV, Jabalpur, PAU, Ludhiana, AFRI, Jodhpur, IFGT, Coimbatore, State Forest Research Laboratory, Kanpur and NRCAF, Jhansi as described in Table 9.1.

4.3 Marwar Teak (*Tecomella undulata*)

Tecomella undulata is one of the most important desert timber species. It shows a wide phenotypic variability in morphological traits and flower colour (Chakravaty and Chand, 1975). A wide variation in tree height, basal diameter and DBH also occurs (Jindal et al., 1985a, 1985b) leading to establishment of progeny trial comprising 11 progenies and 20 progenies at CAZRI in 1984 and 1986, respectively. Provenance trials (Rai and Chowdhry, 1995) and the progeny trials have also been established at AFRI using seedling of 40 CPT's. The progeny trials established at Bikaner and Jodhpur show survival of 66% and 91%, respectively. Procedure of clonal multiplication discussed (Arya and Shekhawat, 1986) and *in vitro* propagation have also been achieved through cotyledonary nodes (Nandwani et al., 1995), nodal shoot segments (Rathore et al., 1991) and through axillary and terminal shoot buds from 10-15 years old trees (Bhansali, 1993). Recently, factors affecting shoot proliferation and *in vitro* rooting have also been studied to make tissue culture protocol more reliable (Tyagi and Tomar, 2013).

Table 9.1 Seeds of provenances and plus trees of *A. nilotica* collected by different institutions.

Name of Intitution	No. of collections	Best plus tree/provenances
CCSHAU, Hisar	21 plus trees	North west and central Indian are better than southern Indian provenances
JNKVV, Jabalpur	10 provenances	Not known
PAU, Ludhiana	39 provenances	Not known
FRI, Dehra Dun	20 provenances	Not known
AFRI, Jodhpur	28 provenances	Shivpuri and Hastinapur provenances
IFGT, Coimbatore	18 provenances	Hisar provenance
State Forest Research Laboratory, Kanpur	9 provenances	Banaskantha, Akola, Adilabad
NRCAF, Jhansi	19 provenances and 20 plus trees	Results awaited

4.4 *Gmelina arborea*

Genetic improvement of *Gmelina arborea* was started in 2003 at RFRI, Jorhat by assembling different divergent populations. Subsequently three CSOs have been established at three sites Naharoni (Assam), Teliamura (Tripura) and Imphal (Manipur). These orchards have now started bearing flower and fruits (Anon, 2009). Initial observations on inter-clonal variations offer possibilities for selecting superior clones for planting at different locations to assess their performance to the specific site. Success of vegetative propagation through branch cuttings of adult trees of *G. arborea* is however, poor (Pal, 1993), but budding and grafting has been recommended to establish clonal seed orchards (Beniwal and Singh, 1990). Chip budding technique of propagation has been suggested for propagating plus trees using two established CSOs to cater immediate demand of improved seeds (Kumar and Matharoo, 2003a). Though there has been significant variation in seed weight between different progenies (100-seed weight 43.75 to 86.99 g) with a mean weight of 58.16 gram. Out of 38 clones only 11, 38 and 50 per cent clones have produced bold, medium and light seeds, respectively (Kumar and Matharoo, 2003b).

In a study on superiority of plus trees (60 CPS from the states of Assam, Arunachal Pradesh and Mizoram) of *G. arborea* over the comparison trees indicates 18.72, 20.68 and 46.48 per cent superiority for height, GBH and clear bole height (CBH), respectively (Kumar et al., 2003). Plus trees of Mizoram have shown maximum improvement for CBH (67.28%) and GBH (31.52%), whereas plus trees from Arunachal Pradesh have attained maximum improvement for height (22.74%). Likewise, testing of 24 months old clonal trial consisting of 70 clones selected from northeast India have indicated heritability of 0.3122, 0.4416 and 0.3734 with a genetic gain of 18.15, 24.60 and 30.15 per cent for height, diameter at ground level (DGL) and DBH, respectively (Kumar and Matharoo, 2003a). DBH has been observed the most important trait with genotypic and phenotypic coefficient of variations of 18.55 and 30.37 per cent, respectively. Clones selected from Lanka (Assam) are best performers. Clone RFRI/GA/106 has attained maximum height (517 cm) and DGL (119 mm), whereas RFRI/GA/108 has performed poorly for all the traits studied. Further, Clone RFRI/GA/106 maintains its superiority from an early age of 18 months itself. Clones RFRI/GA/009, 017 and 079 shows an upward trend for height, and markedly change rankings from 13th, 15th and 20th positions at the age of 12 months to 2nd, 4th and 15th positions at 24 months of age.

4.5 Siris (*Albizzia lebbeck*)

Exploration team of NRCAF, Jhansi, made a survey of 36 districts of Uttar Pradesh, Madhya Pradesh and Rajasthan, in which high variability for leaves, pods, tree canopy, DBH, tree height, number of seeds per pod, 1000-seed weight and retention of leaves during dry period in *A. lebbeck* have been recorded. Limited trees are straight and attain a height of more than 18 m against the normal tree height of 10-12 m. Seeds of these trees have been collected and progeny laid. Performance of progeny is however yet to be tested. In another study at CCSHAU, Hissar, provenance trial of 12 provenances have been conducted, where provenance of Jammu is better than others for early growth parameters (Toky, 1995). The outcomes of these trials are summarized in Table 9.2.

Significant variations in fruit, seed and seedling traits have also been observed and recorded for 20 geographic sources of Karnataka. Pods of Mysore provenance are longest, widest and have higher mass but show lowest germination, while maximum germination and shoot length has been in Bidar collection (Nayak et al., 2004). In another study of 28 half sib families, the traits like total height and clear bole length have much variation than girth. Half sib family CAL 21 exhibited better crown traits, while CAL 21 have higher leaf N content (3.97 per cent), carbohydrates (0.395 per cent), starch (24.82 per cent) and crude protein (24.81 per cent). A high heritability is associated with high genetic gain for carbohydrate and crude protein. Based on the growth and nutrient traits the half sib family CAL 21(Mysore region) and CAL 18 (Bagalkot) are the best (Mohan Kumar, 2003).

Table 9.2 Seeds of provenances and plus trees of *A. lebbek* collected by different institutions.

Name of Institution	No. of collections	Best plus tree/provenances
CCSHAU, Hisar	12 plus trees	Jammu provenances
IFGTD, Coimbatore	13 provenances	Shimoga provenance from Karnataka and Salem provenance from Tamil Nadu
NRCAF, Jhansi	147 provenances	Results awaited

4.6 Shisham (*Dalbergia sissoo* Roxb)

Dalbergia sissoo is an important timber species belonging to family Leguminosae, subfamily Papillionaceae. It enriches soil fertility, provides fuel-wood along with fodder. It also provides raw material for a variety of wood based industries especially for furniture and building construction. The wood is hard, heavy and strong, double elastic, seasoned well and decay resistance. Exploration of seed collection work in *Dalbergia sissoo* has been done by several organizations, where wide variability has been reported for tree height, clear bole height, straightness, crown shape, pod character and DBH. Among the seeds of 32 plus trees by NRCAF, Jhansi collected, PT-6 and PT-2 of Mahurani are fast growing and straight with mean annual increment of 15.53 cubic m/ha/yr and 12.73 cubic m/ha/yr, respectively (Gupta et al., 2003). The progeny tests by CCSHAU, Hisar indicates that plus trees PT28 and PT12 from Haldwani, PT-283 from Gonda, PT-84 from Nepal and PT-9 from Tanakpur are more promising in straightness, basal diameter, total height and unforked height. Heritability in broad and narrow sense is high for straightness and unforked height (Bangarwa and Kulvir, 2002). Progeny trials conducted by different institutions are summarized Table 9.3.

4.7 Poplars

The history of poplar is quite old but it has been largely confined to Kashmir and temperate arid zone. However, in and around 1950 with the import of large number of exotic clones and subsequent trial in north India, usage patterns have been changed. Now these exotics (few clonal selections of *Populus deltoides*) are becoming an important part of agroforestry systems in some districts of Punjab, Haryana and Uttar Pradesh. Forest Research Institute, Dehra Dun introduced 24 clones from England (Mathur and Sharma, 1983), where 'IC' clones have been considered the best performers however, by 1978 these clones lost their vigour and resistance to pests and diseases by 10th cycle. Since then several species, clones and cultivars of exotics poplar have been introduced, multiplied and tested (Gupta et al., 2007). Most widely planted species is *P. deltoides* growing on a large scale in many states of India.

Table 9.3 Seeds of provenances and plus trees of *D. sissoo* collected by different institutions.

Name of Institution	No. of collections	Best plus tree/provenances
CCSHAU, Hisar	106 plus trees	PT- 9 (Tanakpur), PT- 280, PT- 12 (Haldwani), PT- 283 (Gonda), PT- 84 (Dangarhi, Nepal), PT- 6, PT- 2 (Mauranipur)
NRCAF, Jhansi	32 plus trees collected from Bundelkhand region	MAI of best tree 3.08 m for height and 5.14 cm for collar diameter
GBPUA&T, Pantnagar	170 from northern states	-
TFRI, Jabalpur	10 Provenances	Raipur provenance
FRI, Dehra Dun	70 Plus trees	-
SFRI, Kanpur	20 Provenances	Mauranipur provenance

A large number of exotic clones of *Populus* spp. are grown in field plantation like G3 and G48 from Australia; D66, D121, D75 and D81 of *P. deltoides* from America; Lux 69/55 of *P. deltoides* and 72/58 of *P. deltoides* × *P. euramericana* from Italy etc. Some new clones introduced recently show promise in agroforestry practices like S7C4, S7C8, S7C15, S7C20 etc. Clones of 'L' series developed by Forest Department at Haldwani Research Centre (Uttrakhand) from open pollinated seeds of G48 and D121 mother plants is also encouraging and are soon expected to become more popular among the farmers. WIMCO Seedlings Ltd. Rudrapur (Uttrakhand) has also come out with some clones namely Udai, Kranti and Bahar which are also being planted by the farmers. However, clones developed by Uttrakhand Forest Department and WIMCO Seedling Ltd. have very narrow genetic base and as a result, none of the L-series clones could perform better than G48 (Sidhu, 1996). In order to explore the possibility of augmenting the genetic base of new clones, breeding orchard has been established at Dehra Dun in 1998 with planting of 40 clones (Table 9.4; Singh et al., 2002).

Superior clones of *Populus deltoides* with intensive management practices yield mean annual increment (MAI) of 49.35 cubic m/ha/yr observed in Punjab (Singh et al., 2001). Concept of plus tree selection, establishment of seed orchards and producing of quality seeds are still at experimental stage in India except few sporadic efforts made at ICFRE, Dehra Dun, ICAR, New Delhi and agricultural universities. However, these efforts are not in a coordinated one, location trials are not being conducted and site specific varieties are not being identified. However, productivity of economic products can be raised by 20-30% even by small efforts in tree improvement (Chuntana Parb and Mac-Dicken, 1991).

Table 9.4 Clones of Populus developed and planted in the breeding orchard in India

Clone	Source	Percentage	Sex
L-200/84	State Forest Department, Haldwani	G48 × G3	Female
L-34/82	State Forest Department, Haldwani	G48 × G3	Female
Udai	WIMCO Seedling Ltd., Rudrapur	G48 × G3	?
No. 36	Univ. of Horticulture and Forestry, Solan	Open pollinated selection USA	?
U.D -88	Univ. of Horticulture and Forestry, Solan	Open pollinated selection USA	?
P.D -1	Univ. of Horticulture and Forestry, Solan	Open pollinated selection USA	?
100-7	Univ. of Horticulture and Forestry, Solan	Open pollinated selection USA	?
103	Univ. of Horticulture and Forestry, Solan	Open pollinated selection USA	?
U.D -55	Univ. of Horticulture and Forestry, Solan	Open pollinated selection USA	?
98	Univ. of Horticulture and Forestry, Solan	Open pollinated selection USA	?

Note: "?" indicates that sex is not known at this stage. These clones are included on the basis of outstanding performance in the field.

Poplars tree improvement carried out at University of Horticulture and Forestry, Nauni through open pollinated seeds collection from 103 trees of *P. deltoides* from Texas and Davenport, USA. Rooting behaviour (Bhrot and Khurana, 2001), *in vitro* propagation (Thakur et al., 1995; Gangoo and Khurana, 2002), morphological variations (Khurana and Mohanty, 2000; Sharma and Khurana, 2011) etc., have been studied. Significant differences have also been observed among clones and sites with respect to survival, height, diameter and leaf area (Khurana et al., 1992). The genotype × site interactions has also been studied at nursery stage by planting cuttings of 35 clones of *P. deltoides* under four different climatic conditions of HP and studied for natural variation (Ramesh and Khurana, 2003) and rooting behaviour (Ramesh and Khurana, 2006). Provenances trials of *Populus alba* L. and standardization of its vegetative propagation techniques have also been conducted (Ramesh and Khurana, 2007). Isozymes (Handa et al., 2001), AFLP (Chauhan et al., 2004) and RAPD markers (Rajgopal et al., 1999; 2000) techniques have been used to screening the poplar clones. Clones of *Populus ciliata*, *P. deltoides* and hybrids of *P. ciliata* × *P. maximowiczii* have been released for various agroforestry regions.

4.8 Ardu (*Ailanthus excelsa*)

Ailanthus excelsa is an ideal species for matchbox industry which meets the various requirements of the industry like colour of the wood, wax stability, consistent burning and splinting ability. Wood is yellowish white that changes into grayish white with age. It is very light in weight, soft and not durable and used for packing cases, match box and sticks, fishing floats, catamarans, sword handles and toys (Pearson and Brown, 1932). Apart from being an excellent match wood resource, the species also has several medicinal properties. Because of fast growth, adaptability to high density planting, ready market and substantial revenue makes this species an attractive species to farmers (Jat et al., 2011). Isolation of genomic DNA, PCR analysis and its diversity has been conducted and results indicate a total number of amplified products of thirteen primers. 74 PCR products have also been obtained and all are polymorphic. Genetic distance values range from 0.27 to 0.65 (Rajasugunasekar et al., 2012). The primer gives the maximum and the minimum levels of polymorphism from 88% to 40% and is used for the long term breeding programme.

4.9 *Eucalyptus* species

This species was introduced around 1790 in India and a large scale plantation of *Eucalyptus tereticornis*, *E. grandis* and *E. globulus* has been established all over the country particularly under agroforestry systems in many states. *E. globulus* is mostly used in the Nilgiris in South India, but no work on the genetic improvement of this species has been initiated so far. *Eucalyptus tereticornis* usually referred as ‘Mysore Gum’ or ‘Mysore hybrid’ is used in most of the states, whereas *E. grandis* is usually raised in higher ranges of Western Ghats particularly in Kerala and to a small extent in Tamil Nadu. Latter two species are worked on a short rotation of eight years.

Tree Improvement work was first initiated at FRI, Dehra Dun and two hybrids, i.e. FRI 4 (*E. tereticornis* × *E. camaldulensis*) and FRI 5 (*E. camaldulensis* × *E. tereticornis*) have been developed that give 109% more wood volume than Mysore Gum (Mysore hybrid) (Venkatesh and Sharma, 1977). However, these two hybrids could not become popular for plantation due to lack of information on trials conducted all over India. Later on several plus trees of *E. tereticornis* have been multiplied through tissue culture at TERI, New Delhi; NCL, Pune; ITC Bhadrachalam etc., which are giving 40-60% higher wood volume than the seedlings grown materials. A total of 17 provenances received from CSIRO, Australia have also been tested at IFGTB, Coimbatore, where provenances of Paluma, Ravenshoe, Gadgara and Herberton have been found superior in volume growth. M/s Bhadrachalam Paper Board Ltd in Khammam District, Andhra Pradesh did pioneering work in identification of phenotypically superior Eucalyptus trees in the plantation and conducted extensive tests of several clones in different agro-climatic zones and the clones numbers 1, 3, 4, 6, 7, 8, 10, 27, 32, 52, 71, 93, 99, 100 and 128 are extensively grown in all eucalyptus growing areas (Lal, 2001). Valuable information on various genetic parameters of *E. tereticornis* and *E. grandis* and their hybrids like *E. grandis* × *E. tereticornis* and hybrids of *E. citriodora* × *E. torreliana* and F1 has also been reported (Kedarnath and Vakshasya, 1977; Venkatesh and Sharma, 1977; Kedarnath, 1980; 1982; Krishnaswamy et al., 1984). These hybrids manifest good hybrid vigour for growth and volume production and hence it is very beneficial to multiply them clonally and establishing plantations using the tissue culture approach. Significant gains in productivity of genuses Eucalyptus, Casuarina and Leucaena have also been achieved through clonal selection, vegetative propagation combined with Root Trainer Technology and field testing of clones. These clones, for the first time developed in India are known as `ITC-Bhadrachalam' clones. Site-specific, high yielding, fast growing, disease resistant clones of Eucalyptus, Casuarina and Leucaena have been developed and it is followed by rapid adoption and raising of large-scale clonal plantations under Social and Farm Forestry (Kulkarni, 2013).

4.10 Casuarina (*Casuarina equisetifolia* Linn)

An ideal tree crop of coastal region Casuarina is tall, fast growing, salt tolerant, wind resistant tree adaptable to moderately poor soils because of its capacity to form root nodules and fix atmospheric nitrogen, and thus ameliorate soils (Patel and Singh, 2000). It was introduced in India during the late 19th century (Pinyopusarerk and Heuse, 1993) and is now planted in more than 50,000 ha (Gurumurti and Rawat, 1992) with short rotation of 3 to 4 years. The wood yield variation per tree ranges from 4 to 35 kg in five year plantation, suggesting that there is a tremendous scope for identifying superior performers (Gurumurti and Rawat, 1992). Regional Forest Research Centre, Rajahmundry established provenances trial of 40 clones, progeny trial of 16 wind pollinated families and family-in-provenance trial of 100 wind pollinated families as a part of international provenance trial, where provenances of Malaysia and Thailand have shown superior growth. However, landrace population often demonstrates superior stem straightness (Prasad, 1998). Progeny trial of three sources has also been established by TNU, Mettupalayam reporting high heritability for tree height, root collar diameter and number of branches (Jambulingam, 1990). Clonal seed orchards of elite trees and international provenance trial with seeds of 40 provenances obtained from CSIRO, Australia have also been established at IFGTB, Coimbatore. Many provenances of international collections perform better than the local source. The Gede Forest Resat provenance from Kenya shows promising growth.

4.11 Phyllodinous acacias

Phyllodinous acacias are native to northern Australia and Papua New Guinea islands, in which *A. auriculiformis* and *A. mangium* have become major short rotation industrial plantation species in the humid tropical lowlands of Asia including India (Kushalappa and Turnbull, 1991). The success is due to extremely vigorous growth of these species under varied soils and climatic conditions. Annual wood volume increment of over 30 cubic meters per hectare on favourable sites has been reported for acacias and their hybrids. Tolerance to moderate dry seasons makes *A. auriculiformis* a useful species for rehabilitation of degraded lands. The wood properties of these species and their hybrids potentially make them acceptable for a wide range of end uses like pulp wood and paper, fuelwood, building, furniture timber and also for manufacturing of particle boards. Large scale pulp wood plantations are being raised in Indonesia, Malaysia and many South East Asian countries. In India also it is being raised as pulp wood plantation (6-7 years rotation) by industries and state forest departments (Hegde, 2010).

Progeny of *A. auriculiformis* land race has been initiated to reduce multiple and crooked stems, which restricts its utilization. Large scale plantations possessing characteristics like single stem and good clear bole lead to selection of better trees. Some provenances from Papua New Guinea and Queensland have been reported to be performing well. The wood properties of *A. auriculiformis* have been studied; and its strength and safe working stresses are comparable with those for teak in green and air-dry conditions (Kumar et al., 1987). Pedigree seedling seed orchards have been established after receiving bulked seeds from CSIRO Australia during 1996 that were collected from more than 1000 trees of selected families from seedling seed orchards of *A. auriculiformis* as well as *A. mangium* in Australia, Papua New Guinea, Fiji and Thailand. After two successive thinning inferior trees were removed and seeds are being collected and supplied to user agencies (Varghese et al., 1999). Superior trees have also selected based on stem form and wood volume in various first generation seed orchards in Karnataka, Kerala and Tamil Nadu and half-sib families of selected trees have been raised and four progeny trials (1.5 ha each) established at Panampally, Pondicherry and one hectare each at Palode and Wadakkancherry. After assessing tree form these progeny trials have been then converted into second generation orchards after thinning (Hegde, 2010).

After provenance evaluation some of trials have been converted into seed orchards and suitability of timber and wood properties have also been studied at IWST Bangalore and KAU. Differences in wood properties are there among seed sources/provenances as well as different age group of trees. Vegetative propagation technology has also been standardized for *A. auriculiformis* as well as putative acacia hybrids (Hegde, 2010). Seed orchards of *A. mangium* established in Australia, India (Varghese et al., 1999) Indonesia, Malaysia, Philippines, Taiwan and Thailand are first generation seed orchards and do not provide high quality seeds because of asynchronous flowering among trees and families (Awang and Bhumibhamon, 1993). Seed orchards of *A. mangium* × *A. auriculiformis* hybrid have also been established in Indonesia to build up base for a clonal forestry programme (Arisman and Havmoller, 1994), whereas hybrid clones selected for better growth and form are multiplied by tissue culture of meristems (Le Dinh Kha, 1996) and cuttings from coppice shoots (Banik, 1995). Expected gain in volume production in progeny from seedling seed orchards of *A. mangium* in Indonesia is 50-70% higher as compared to local selections. The selection criteria in addition to fast growth are its propensity for producing single straight stems, low branching and high wood density.

4.12 Subabul (*Leucaena leucocephala* (Lam.) de Wit)

Subabul is a self-pollinated fast growing multipurpose leguminous tree species originated from Mexico and Central America (Brewbaker, 1987). The important characteristics are presence of large quantity of protein and vitamin A in leaves, deep taproot system, erect growing habit and ability to improve soil fertility through fixation of aerial nitrogen and decomposition of protein rich leaves in the soil in a short duration. Average protein content varies from 22-30 per cent in their leaves and protein yield is around 3.63 tons/ha/yr under cutting management system (Brewbaker and Hutton, 1979). After evaluation of selected germplasm, six outstanding varieties (K8, K132, K28, K29 and K62) have been released, where K8 has maximum success. Forage yield from K8 is 19.5 tons/ha/yr against 10.5 tons/ha/yr obtained from Hawaiian types (Brewbaker, 1987). However, these hybrids could not become popular due to lack of simple and economic technology to multiply it vegetatively and retain good hybrid vigour or hybrid seed production. Two provenances viz. K636 and K584 have been found tolerant and advocated to planting in psyllids infested areas. Other species of Leucaena resistant to psyllids are *L. diversifolia*, *L. collinsii* and *L. pallida* (Brewbaker, 1987).

Interspecific hybrids KX1 (*L. diversifolia* × *L. pallida*), KX2 (*L. leucocephala* × *L. pallida*) and KX3 (*L. diversifolia* × *L. leucocephala*) have been released by University of Hawaii (Stewart and Dunsdon, 1998). These trees are quite resistant to pysllids and are also vigorous in growth.

4.13 Sandal (*Santalum album*)

Santalum album L. is one of the important tree species of India which is famous throughout the world for its fragrant wood and oil. In India, it has been known to exist for more than 2500 years. Its high value in the cosmetics, perfumery and handicrafts industries, and religious ceremonies has resulted in the heavy exploitation of this species. Forests, which were once protected due to inaccessibility, have now been exposed to severe biotic factors including over exploitation and massive clearance. Tree improvement in sandal aims at evolving trees with more heartwood and oil in a short period (Shankaranarayana et al., 2006) and have characters like clear bole, height, good crown and heartwood depth. Two- to five- fold increase in chromosomes owing to endoploidy has been reported in this species, whereas length and width of the leaf is largely influenced by environment causing inter-clonal variability. Germination and survival of seedlings are under genetic control and governed by separate genetic mechanisms. In progeny trials, the existence of segregation, pleiotropy, variation, twin-triplet seedlings and albinism has also been reported. Tetraploid sandal is reported to exhibit greater spectral variation over diploids (Anon., 2002).

Percentage of sandalwood oil varies from 0.45% and 0.55% (Shankaranarayana and Venkatesan, 1982; Shankaranarayana et al., 2006), and is major criterion of improvement. However, composition of oil varies from central and transition zones of sandalwood disc (Shankaranarayana et al. 1998). The sapwood does not contain any oil and heartwood formation or any occurrence of oil in the heartwood can be estimated using UV-Vis spectroscopy (Shankaranarayana et al. 1997). A correlation has also been established between oil content and activity of a specific peroxidase isoenzyme (SPI) in the living bark tissue which can be utilized for forecasting oil bearing potential of sandal plant on maturity. Sandal plants having SPI activity < 0.2 are superior and those > 0.28 are considered inferior. Isoenzyme studies help in identification of provenances, characterization of phenotypes, developing biochemical marker for oil bearing capacity in sandal, diagnosis of spike disease and deficiency symptoms of trace elements in sandal at an early stage (Parthasarathy et al., 1986; Angadi et al., 1998; Angadi et al., 2002). Isozymic study data shows a gap in genetic distance between different provenances of Sandal indicating that they are of separate varieties or races, requiring further confirmation (Angadi et al., 2003). Sandal tree grows under different edaphic and eco climatic conditions indicated by large genetic distance between provenances and diverse locality factors sandal adapts in terms of tree growth, heartwood formation and oil content (Jain et al., 2003).

4.14 Semul (*Bombax ceiba* L.)

Bombax ceiba grows well in eastern part of India including Uttar Pradesh and is valued more by the match industry because of the quality of wood. The objective of tree improvement in this species is to evolve varieties of fast growing with good stem form and narrow crown without buttresses. In nature, some tree areas are subject to heavy attacks by shoot borer (*Tonica niviverana* Walk.), thus incorporating resistance against this pest is one of the breeding objectives (Kedharnath, 1974). Plus trees of this species have been selected from those growing in Assam and in Uttar Pradesh and search for plus tree from other areas is in progress. A small clonal seed orchard has also been established at Gorakhpur, Uttar Pradesh using simple grafting technique by FRI, Dehra Dun (Kedharnath, 1974).

4.15 Beul (*Grewia optiva*)

Twenty three superior genotypes have been identified by HFRI, Shimla, from established open pollinated seed orchard of *Grewia optiva* based on morphometric and fodder quality parameters (Anon, 2013). Molecular profiling of 30 superior genotypes and grafting and chip budding of 23 superior genotypes have also been carried out and clonal seed orchard developed. Reproductive biology studies show that it is a cross pollinated species with some success in selfing in the initial stages but fruits drop later on.

4.16 Kachnar (*Bauhinia variegata*)

Different provenances have been evaluated for seed germination, seedling growth and biomass and nutrition quality of leaf fodder. The genetic divergence analysis is being carried out in HFRI, Shimla using 18 clones of clonal seed orchard (Anon, 2013).

417 Neem (*Azadiracta indica*)

Neem belongs to Meliaceae family and native to Indian subcontinent. It is distributed throughout south and south-east Asia, Australia, Africa and many other countries in Central and South America including Caribbean, Puerto Rico and Virgin Islands. It has estimated population of 15 million trees that produces 500,000 tons of neem seed annually in India (Venkateswarlu, 1996).

Multilocational national Neem provenance trials have been established at three locations (Jodhpur, Jabalpur and Coimbatore) in 1992 by ICFRE Institutes. Similarly International Neem trials have also been established by Arid Forest Research Institute Jodhpur at three locations viz. Jodhpur, Jaipur and Coimbatore in 1996. All trees of the introduced provenances and national provenances have started flowering since 1st week of March 2001 except in the Thai provenances which flowered at the end of November 2001. One Tanzanian Provenance and 4 Indian provenances have produced the fruits in 2007. The quantity of the fruit yield was very poor in all 4 introduced provenances (10 to 40 g) and the highest amount of seed (467 g) has only been obtained from the Indian provenance (Anon, 2008). Forty one Neem genotypes from provenances of India (37) and Thailand (4) have been characterized using AFLP markers. These genetic studies clearly reveal a broad genetic base of Indian Neem with the values of genetic similarity coefficient ranging from 0.74 to 0.93 and a narrow genetic base with similarity coeffcients ranging from 0.88 to 0.92 in four Thailand genotypes (Singh et al., 1999).

At National Research Centre for Agroforestry, Jhansi, a trial of 26 provenances collected from central India shows a wide range of variability for tree height (472 – 662 cm), collar diameter (12 – 18 cm), DBH (10 – 14 cm), seed length (1.2 – 1.6 cm), 100 seed weight (19.1 – 25.0 g), fruit bearing and oil content (35 – 51%) at the age of 6.5 year. On the basis of overall performance, Bhopal provenance ranked first for growth, seed yield and oil content (45.71%) (Gupta and Kumar, 2001).

A National Neem Network involving 11 different institutions located in different zones of India was launched by the National Oilseeds and Vegetable Oil Development Board, Gurgaon, Ministry of Agriculture, Government of India in 1999. One of the objectives of this network was the systematic collection and characterization of neem germplasm from almost every part of India. Azadirachtin has been evaluated from 1501 accessions collected from all over India. Azadirachtin content varies from 200 to 16,000 ppm (mg/kg of the seed kernel). Azadirachtin content has been found affected by climate and habitat. Annual variation in azadirachtin content is significant. The highest azadirachtin content is in the neem tree populations growing in the southern part of India (Kaushik et al., 2007).

AFRI has studied Gujarat neem seed samples collected from four different agro-ecological regions (AERs) viz., AER-2, AER-4, AER-5A and AER-5B during 2000 to 2002 Azadirachtin, oil and fatty acids have shown significant variations between years and AERs zones. The azadirachtin ranges from 142 to 9527 ppm of seed kernel with an average of 2426 ppm for Gujarat state. AER-5B zone (hot semi-arid ecoregion with medium, deep black soils, deep black coastal alluvium, sub-humid) has shown highest azadirachtin and oil content. Fatty acid composition has been found affected by environmental factors particularly by varying degree of annual rainfall and temperature during fruit ripening period. They also reveal that tree girth at breast height has no significant relation with these biochemicals (Tomar et al., 2011).

In a progeny trial, twenty plus tree progenies of Neem including check have been evaluated for growth, straightness and seed yield. Results of 6.5 year old trial reveal that PT-24, PT- 22, PT-15 and PT-14 are quite promising for growth parameters, straightness and seed yield, whereas PT-24 is higher fruit producer and more straight than others. CRIDA, Hyderabad has also identified four superior clones one each from Ananthpur and Hyderbad in Andhra Pradesh, Sabarkantha in Gujrat and Philibani in Orissa. National and international Neem provenance trials initiated at AFRI Jodhpur during 2001 and progeny trial established in Govindpura, Jaipur in 2002 are to study the heritability pattern of selected CPTs for their oil and azadirachtin content. Likewise, model plantations of Neem have also been established at Hathrol, Gujarat and subsequently at Rohat and AFRI, Jodhpur under NOVOD Board Programme and SSOs with high oil and azadirachtin content progenies at Govindpura, Jaipur and 4 ha at AFRI, Jodhpur (Anon, 2013).

4.18 Guggul (*Commiphora wightii*)

Commiphora wightii is an endangered species possibly because of its slow growing nature, poor seed viability and germination, lack of cultivation, excessive harvesting for religious and domestic purposes (as fuel by rural people) and unscientific tapping for its gum resin by the pharmaceutical industries. Because of these reasons, the population of this plant has reduced drastically and at present this plant has been put in Data Deficient category of IUCN’s Red Data list. In a survey conducted in Rajasthan, guggul density varies from 74 plants ha^{-1} in Sawai Madhopur to 69 plants ha^{-1} in Jhunjhunu district, whereas Bikaner, Banswara, Churu, Shri Ganganagar, Hanumangrah and Pratapgrah districts are lacking in its natural population (Tomar, 2014). Mature seeds collected from six sources and 26 CPPs (candidate plus plants) indicates that some genotypes have potential to produce high percentage of viable black seeds depending upon site conditions, which play an important role in defining black and white seed ratio.

Germplasm collected for *ex situ* conservation from identified 117 CPPs. About 1428 vegetative cuttings with source details (GPS locations) have been collected and raised in our vegetative propagation area for rooting. Differential response in sprouting and rooting has been studied. It appears that genotype, physiological conditions and age of the source greatly influence the rooting process. January to April is ideal period of the year for rooting though rooting is possible in this species throughout the year (Tomar, 2014). *Commiphora wightii* germplasm have collected from 24 locations of Rajasthan and *in vitro* regeneration protocols developed using micropropagation and somatic embryogenesis methods from immature embryos pathways. AFRI is also working to improvise a non destructive guggul gum tapping method.

4.19 Khejri (*Prosopis cineraria*)

Prosopis cineraria is a far better species than is perceived, in terms of survival, adaptation, growth, production of fodder and fuel in arid conditions. This species has an important role in increasing soil fertility and checking desertification in Thar Desert. Increasing demand of fodder and fuel wood in Thar desert may not be achieved unless fast growing provenances/genotypes of this species are identified. In this direction little efforts have been made before 1981 to study genetic variability available in nature particularly in Rajasthan. Intensive genetic improvement work was initiated in 1983 in CAZRI, Jodhpur to evolve fast growing genotypes by selection as well as to understand extent and pattern of genotypic variability present. Seeds from the best trees in eleven districts of Rajasthan were collected, single tree progeny raised in 1984, where progeny 264 from Jodhpur ranked first throughout the study period. Subsequently seventy plus tree of *P. cineraria* from Jodhpur, Bikaner, Barmer, Jaisalmer, Churu, Sikar and Nagaur selected in 1985 and seed collected for testing of progeny, which show significant variations in plant height at four and five month age. Variations in growth has been highest in collar diameter and DBH sowing coefficient of variation of 65.7% for collar diameter, 64.9% for DBH, 52.7% for height and 48.14% for crown diameter (Kackar et al., 1986; Singh et al., 1993). Coefficient of variation is also high for number of seeds per pod and seed weight (Kackar et al., 1986; Arya et al. (1992). In other study, acute and horizontal branching has been observed in *P. cineraria* (Jatasara and Paroda, 1983), with predominance of horizontal branches (69%). Two types of *P. cineraria*, i.e. one spineless with drupping twigs and a compact crown, and the other with spine, non-drupping branches and a comparatively wide open crown have also been observed in Thar Desert (Jatasara, 1982).

First progeny trial using 10 plus trees (JU-1 to JU-5 from Jodhpur and BK-1 to BK-5 from Bikaner) was established during 1977 at CAZRI Jodhpur and observations on fodder and other component characters recorded at the age of 7.5, 8.5 and 9.5 years. There have been significant differences among progenies at two locations during different years, though JU-5 consistently showed good performance and both heritability and genetic advances are moderately significant. A provenances trial of about 8 sources has also established at CCCSHAU, Hisar (Toky, 1995) together with a hybrids, which is superior in relation to DBH, tree height and clear bole height. Some elite selections of *P. cineraria* attain height up to 7.3 m in seed orchards as compared to 6.5 m by *Acacia tortilis* in 6 years. Such identified elite trees have been used to establish seedling seed orchards (SSO). SSO containing 156 elite trees (attained mean height 3.54 m in 6 years) and CSO obtained through air layering have also been established showing significant variation among progenies (Jindal, 1998). AFRI has also initiated the genetic improvement programme on *P. cineraria* after the selection of plus trees and development of refined protocol for rapid and mass clonal production of plus trees/superior genotypes (AFRI, 2015).

4.20 Bamboos

Approximately 50% of the total bamboo species reported from India is from north east region. There are country report on bamboos (Varnah and Bahadur, 1980) and status of research carried out in India by Banik (1991, 1993, 1994 and 1995). Improvement work was initially taken up in respect of eight important bamboo species, viz. *Bambusa balcooa*, *B. nutans*, *B. pallida*, *B. tulda*, *Dendrocalamus giganteus*, *D. hamiltonii* and two local species viz., mangal and nal (*Bambusa* spp) in 1980 in Arunachal Pradesh. A systematic approach for bamboo improvement starting from exploration, collection and conservation of the germplasm for six species of bamboos of northeastern India has been carried out by Pathak et al. (2000, 2005). In general, the selected plus clumps of bamboos show marked superiority over base population (Singhal and Gangopadhyay, 1999).

There are many studies on genetic conservation (Subramanian, 1994), improvement of bamboos productivity (Kumari et al., 2001), utilization of diversity (Pathak, 2003; Pathak et al., 2000; 2005; Lawrance, 1995); nursery technology (Pattanaik et al., 2002), improved planting materials (Rao and Zamora, 1995; Williams et al., 1995) and vegetative propagation (Azzini et al., 1978; Cabanday, 1957; Khan, 1972; Zhang, 2001) of different species of bamboo. Candidate clumps of *Dendrocalamus stocksii* from different forest ranges have been observed varying in all characters including clump, except height (Ravi Shankar, 2004). Altitude and temperature has shown a positive effect on growth and yield of bamboo. Culm diameter ranges from 3.58 cm (Siddapur) to 5.90 cm (Hulekal), while nodal length ranges between 22.7 cm (sirsi) and 27.7 cm (Siddapur). In another trial of 86 candidate clumps of *Dendroclamus strictus* from ten different locations in Karnataka, culm diameter, crown diameter and number of culms per clump have varied among the locations (Iqbal, 2000) with highest culm and DBH for Banavasi Range (7.56 cm) and lowest for Sirsi range (3.57 cm).

Genetic diversity of bamboos studied in the Western Ghats region of peninsular India targeting 2 species of bamboo, like *Bambusa bambos* and *Dendrocalamus strictus* (Uma Shaanker et al., 2004) indicate restriction of *B. bambos* to moist regions and that of *D. strictus* to mostly in drier regions. *D. strictus* is an allopolyploid with a chromosome number of 72 poses inherent problems in genetic analysis through isozymes and DNA based approaches. Genetic variability of 16 sources of *D. strictus* in Western Ghats using isozyme analysis has also been done (Cheluvaraju et al., 2001), where highest genetic diversity has been recorded for northern Karnataka populations and least for those from southern Karnataka. Sambrani population in northern Karnataka is the most diverse (0.26 ± 0.11) while the Banawara population in Southern Karnataka has least genetic diversity (0.14 ± 0.13). Nei's genetic diversity index ($r=0.48$, $p<0.05$) and the Shannon index ($r=0.49$, $p<0.05$) of *D. strictus* population has shown significant positive correlation with latitude at which they occur, indicating that populations from northern latitudes are more diverse than those from southern latitudes. Conversely, the hotter and drier climate of northern latitude seems to favour higher genetic diversity in *D. strictus* populations compared to cooler and humid climates of southern latitudes. In contrast spatial pattern of genetic diversity has been obtained for *D. strictus* (Cheluvaraju et al., 2001) indicating that the genetic diversity of *B. bambos* decreased from southern to northern latitudes.

5. CONCLUSION AND FUTURE PROSPECTS

Possibilities and limitations in tree breeding in general and with specific trees are described by many scientists in past (Pauley, 1953; Namkoong et al, 1988; Strauss et al. 1997; Gurmurthy and Rawat, 1992; Emmanuel, 2007). The term “Tree Breeding” itself was considered misleading and ambiguous and suggested to be substituted by “Tree Improvement” in 1953 by Professor Scott S. Pauley. Tree breeding is always compared with annual crops like corn or wheat (Pauley, 1953). Wherein well defined pedigree germplasm is established and available for conducting genetic experiments to develop desired hybrid or “Super Hybrids” in relatively much shorter period than tree crops. In case of trees, reaching to this level require at least few decades time, huge amount of money and administrative support. Tree breeding in general is restricted to selection, evaluation and multiplication of superior (plus or elite) trees for enhancing productivity clubbed with best silvicultural practices.

In India, Tree improvement has completed almost half century for some of the species, i.e. half the rotation age of species like teak and conifers. Improvement work has been carried out for *Eucalyptus* spp., *Tecotona grandis* and *Dalbergia sissoo* and initiated for *Azadirachta indica, Acacia nilotica, Ailanthus excelsa, Melia dubia* etc on provenance trials, CPTs selection, Seed Orchards and progeny trails. The achievements in these species are satisfactory but not admirable due to limitations of trees improvements programmes as they have long life span, difficult accessibility of flowers, uncontrolled locality factor, interpretation of yield, and additive effect of the annual growth increment which differentiates it even from horticulture crops. Certain other limitations pointed out in literature and restrict the tree improvement progress in different stages includes low level research training, lack of funding from year to year, poor library and information services, inadequate interaction with improvement organizations within and outside the country, inadequate political support for quality seed production and associated research activities, and lack of coordination of research efforts within the country (Pauley, 1953; Namkoong et al, 1988; Gurumurti, 1992; Strauss et al. 1997; Gurmurthy and Rawat, 1992; Emmanuel, 2007). Some points need to be considered are:

1. Provenance trials have been initiated approximately for 125 species, but the results for most of the trials are inconclusive and this has resulted in colossal loss of important information. Provenance trial or the proven seed source is considered as base population for tree improvement work. Moreover, seed orchards developed also exhibited low productivity lead to frustration among field foresters and scientists. Achievements of previous tree improvement programmes are not enough to satisfy the aspirations of the stakeholders also. There is a need to understand the contributory factors specially management practices, site and environment etc. related to low productivity in such cases.
2. Proper records of seed movements are still not maintained by SFDs, which is very important and help provide some information on adaptability and geographic variations in research programmes.
3. Seed certification scheme (Anon., 1979a) was launched by Indo Danish Project but could not be implemented in all the states. The same was the

case for the delineation of provenances (Anon., 1979b) which was a supplementary document to the Seed certification scheme. If the productivity of the forests is to be increased Seed certification scheme has to be implemented and monitored. The preliminary requirement for the scheme is available with all the state forest departments.

4. Clonal trial is another area where one has to look that how best these bio resources can be utilized. The countries where high productivity has been recorded for their forests is only due to the clonal plantations and not with the plantations raised with seed collected irregularly. One has to take care and not blindly plant clones suited best in temperate conditions to the tracts like hot arid region and then come to a conclusion that it is not a high yielding clone. One has to test the clones depending upon the agroclimatic conditions and later on plant them only on the sites where high management practices could be adopted in better ways.
5. One has to divide the planting sites into three categories like (i) area for commercial purposes; (ii) area for maintaining variability in the population; and (iii) area for conservation of germplasm.
6. The changing environmental condition is a challenge for the forest geneticists and tree improvement scientists also. There are two points which may be considered under improvement programme. First one is preserving the genetic variations and their adaptability towards changing climatic conditions and the second is inducing variability through genetically modified trees, i.e. GM trees. This is a pressurizing need as the fertile lands is converting into degraded area such as reduction in soil fertility and increase in salinity, alkalinity and sodicity. The only alternative is to have trees which can grow in these degraded areas and put them on track to increase livelihood.
7. The documentation of Plus Trees, Elite Trees, CPTs, Seed Production Areas, Seedling Seed Orchard, Clonal Seed Orchards and vegetative Multiplication Gardens is very much essential as different authors have quoted different statistics in their studies.
8. Such programmes can be made successful with a long term commitment of scientists and supporting staff. Political and administrative supports are also necessary in making available sufficient funds and infrastructure to the executing teams. One should learn from the past failures in such research programs and should not repeat those mistakes again and again.
9. There is a need of collaborative projects between forest departments and ICFRE institutes with clear cut understanding in their respective roles. Regular interactions between Institute Scientists and Field Officers are necessary to implements such programmes.

10

PLANT PRODUCTION AND PLANTING TECHNIQUES

Field survival and productivity of plantation are very much related to the quality of planting stock, which varies from seedlings to mature trees used under transplantation. Considering the extent of vegetation removal, deforestation and forest degradation across the world the demand of quality planting material is increasingly highly. To fulfill the demand and objective of afforestation or reforestation, there are several methods and procedures of plant production developed over several decades of experiences and researches. Apart from seeds, other methods are also available to propagate plants through vegetative means like cuttings, layering, grafting and budding or by using plant modified organs. In addition, tissue culture or micropropagation method provides an excellent system to produce plants at faster rate and through out the year. This method is also prerequisits of genetic modification of a species for its futher improvement. Although quality planting stock give initial boost to establishment and growth of plantation but it cannot provide the desired results unless plants are supported by appropriate soil depth and improved soil conditions including soil water and nutrients. This chapter describes plant production of suitable tree and shrub species using vegetative means, assessing quality of planting materials, plantation techniques including site preparation, plant spacing and post planting cares to get the desired results of a plantation programme.

1. INTRODUCTION

Billions of forest tree seedlings (young trees or plants raised from seeds or vegetative means) are produced each year throughout the world to regenerate public and private forestlands. Some of these are also used for landscaping and decorative purposes in the public gardens. Plant production is brought out to deal with various issues relating to environmental protection, forest production, tree improvement, ecosystem balance, forest regeneration and many other programs. Multipurpose and more useful, indigenous species are relatively slow in growth and take longer time in providing immediate environmental benefits in many of the cases. Because of this attention was more on the introduction and selection of fast growing exotic trees and shrubs from isoclimatic regions of the world. For example almost about 115 *Eucalyptus* species, 73 *Acacia* species and 170 miscellaneous species from different countries like Mexico, USA, Latin America, former USSR, Africa, Israel, Peru, Kenya, Australia, Chile, Sudan and Zimbabwe and the Middle East have been introduced in arid and semi-arid regions of India. *Acacia tortilis, Acacia nubica* and *Prosopis juliflora* for sand dune stabilization, *Colophospermum mopane* and *Dichrostachys nutanse* for fodder purpose and *Eucalyptus camaldulensis* for block plantation are some exotics suited for low rainfall area. The exotics like *Eucalyptus camaldulensis*, *E. melanophloea*, *Acacia tortilis*, *A. cillata*, *A. radiana*, *A. senegal, A. siberiana*, *A. aneura*, *A. salicina*, *Colophospermum mopane*, *Dichrostachys nutans*, *Brasiletta mollis*, *Schinus molis* and *Prosopis juliflora* have emerged very promising for the Indian desert region. Many of these species are propagated either through seeds or through vegetative multiplication to fulfill the demand and objective of afforestation or reforestation.

Plants of various sizes ranging from seedlings to mature trees are considered planting stock. There are several methods of plant production developed through and research experiences of scientists and foresters. Further, successful seedling establishment and growth depends on the soil condition of the site of afforestation and the stored soil moisture to ensure survival in the following growing seasons (Warren et al., 2005). The seedlings of some trees or shrub species are very much sensitive to drought, and may be killed by even short dry spells in the region (Engelbrecht et al., 2007). Furthermore, seedling quality, competitive existing weeds and site access to animals also affects the growth and survival of out planted seedlings. Besides, prevailing environmental conditions and the site quality including soils play important role in the success of plantation programme.

2. PLANT PROPAGATION

Propagation is a natural phenomenon, where all plants multiply by sexual or asexual means to ensure the continuation of its progeny. Propagation is achieved artificially on the field by adopting techniques suitable to the specific plant and its growth characteristic. It ensures the continuation of the progeny of a species and in nature propagation allows plant species to enter into different growth stages and adapt to the prevailing climatic conditions. Propagation allows a species to flourish and develop into a population by making use of the available resources in a particular region. Plants have evolved different methods of propagating themselves in nature by seeds or through vegetative parts or special and modified organs. There are basically two types of propagation among the plants, i.e. sexual and asexual propagation. Sexual propagation involves seed as the starting point for plants production, whereas asexual propagation is the multiplication of plants from vegetative parts like shoots, roots, and leaves, or from specialized organs like bulbs and corms.

Asexual propagation is the method where unique plant characteristics are maintained. The superiority of vegetative propagation over sexual regeneration lies in the possibility of transferring the whole genetic potential of a selected tree in its asexually reproduced progeny. Asexual propagation is the only practical means of propagation when (i) no seeds are produced from the plants; (ii) seeds are difficult to germinate; (iii) seed of plants often produce variations that are not desirable (like roses or most fruit trees); and (iv) if one wants to combine two or more plants to get the specific benefit of a particular rootstock (only grafting method). This includes cuttings, layering, grafting, and divisions. It is gaining importance as a tool for tree improvement and establishment of clonal plantation. Clones offer the advantages of genetic uniformity and the immediate availability of superior individuals for tree improvement programmes and for field plantations. It also helps to make investment in trees more attractive by increasing yield and quality, shortening rotation, and allowing some of the biological problems hindering plantations programmes. However, asexual propagation has some limitations too like damage of mother plants during intensive collection of the planting material, because the parts used are of a specific in nature, hence a single mother plant may not provide the required planting material in a large quantity leading to variability. Asexual propagation also requires proper skills and time to carry out the exercise because of involvement of a definite procedure and seasonal in nature. Further, the propagation material cannot be stored for longer periods of time under room conditions due to fleshy nature of the parts used for propagation. New plants raised from this method generally lack development of a strong tap root system leading to more proneness of the seedlings to wind damage.

2.1 Plant production through macropropagation

Plant production through cuttings, layering, grafting, budding and plant modified organs are different asexual methods of propagation and are also called macropropagation. Mist and non-mist propagation methods are applied for this. Mist propagation based on traditional horticultural experiences in temperate region involves usually intermittent spraying of fine water droplets onto the cuttings (Furuka, 1998). The controlling mechanisms to determine the frequency and duration of the misting are numerous and are based programable and non programable timer clock. The system requires high technology and is most recommended for temperate countries or areas where water and electricity are well supplied with. The non-mist propagation is generally carried out in a wooden frame enclosed in a single sheet of polyethylene so that the propagation unit is completely watertight and is called non-mist propagator. The polyethylene base of the propagator is covered with a thin layer of sand and onto this large stones are placed to a depth of 10-15 cm. This is then covered by successive layers of small stones and gravel to a total depth of 20 cm. The space between the stones and gravel are then filled with water, resulting in a permanently humid environment throughout the propagation period. The saturated layers of stones and gravel are then covered by the rooting medium (fine sand, coarse gravel, or a mixture of sand and gravel), which remains moist by capillarity action and can be dampened from the above as and when necessary. An inter-node section of bamboo or an open cylinder is inserted in the medium and stones. This is used as a water filling point and allows a regular check of the water table. The rest of the frame is covered tightly with preferably a single piece of clear polyethylene and a closely fining lid. Following should be maintained while using this propagator:

- About 60% shade cloth should be used to protect the propagators.
- In non-mist propagators temperature should range between 28 and 30ºC. In dry zones, frequent watering of the propagator could reduce the high temperature.
- Humidity should range between 90 and 100% after watering.

A number of methods are available to propagate plants vegetatively like cuttings, layering, grafting, budding or by using modified organs.

2.1.1 Propagation through cuttings

Propagation through cuttings is an easy and less expensive method of vegetative propagation. A cutting is usually a division of the stem, branch, root or leaf of a plant. However, stem cuttings are most widely used. The cuttings are generally extracted from a plant part and planted in the soil or soil medium. Depending upon the requirement, the cuttings are extracted from a mother plant of a definite age. The extracted cuttings are trimmed first and then planted in the soil medium either horizontally or vertically depending on the need. Different types of cuttings used are softwood, semi-hardwood, hardwood and root cuttings. Softwood and hardwood cuttings are further divided into stem and branch cuttings. The softwood cuttings include: (a) herbaceous cuttings, i.e. a portion of soft succulent seed plants which does not typically develop wood tissues, and (b) green wood cuttings, i.e. cuttings taken prior to lignifications. *Azadirachta indica, Ailanthus excelsa, Acacia nilotica, Dalbergia sissoo* and *Eucalyptus camaldulensis* are the species, which can be propagated through this method (Tomar et al., 2002). The cuttings collected from the mother plants are first treated with 1.5% IBA (Indol, 3-buteric acid) or talc preparation in case of juvenile cuttings for 30 seconds.

Cuttings are raised in root trainers under intermittent misting in mist chambers or mist polyhouse. The lower portions of the vegetative cuttings are treated with auxins too. The upper portions of cutting are covered with Chaubattia paste (petroleum jelly, red lead and copper sulphate) to prevent the fungal attack. About 15-30 days are required to achieve rooting during summer season, whereas during winter a longer period is required and because of reduction in rooting percentage. However, *Acacia nilotica* takes 1-2 months time to root in. After rooting these plantlets are transferred to polythene bags with soil mixture (Sand: compost or Sphaganum moss) and are being kept in polymist house for 2-3 weeks before shifting them to shade house for hardening. The plantlets from polyhouse are shifted to shade house for hardening. At this stage watering is highly essential and each plant should be watered daily. This clonal material must be kept in shade house for 2-3 months before planting them into field.

Table 10.1 Effects of cutting types and treatments on the vegetative multiplication of different species.

Species	Sample type	Treatment	Results	Reference
Azadirachta indica	25 cm long, 0.5-1.0 cm diameter	100 to 500 ppm lAA or IBA for 5 minutes	Highest rooting percent at 500 ppm of IBA.	Pal (1995)
	Mini-cuttings about 7 to 8 cm long with two to three leaf pairs	Sand, vermiculite and soil as rooting medium and concentrations (100, 250, 500, 750, 1,000 and 1,500 mg L^{-1}) of IBA, IAA and NAA	250 mg L^{-1} IBA 80% rooting.	Gehlot et al. (2014)

Species	Sample type	Treatment	Results	Reference
	15-20 cm long and 2-3 cm thick with at least 3-4 buds having one year growth	Dipping of 2-3 cm of basal portion of cutting for 16 hrs in solution of 1000, 2000, 4000 and 5000 ppm concentration of IAA, IBA, NAA and Thiamine (Vitamin B_2)	85-100% rooting, 4000 ppm thiamine closely followed by 1000 ppm IAA.	Anonymous (2011a)
Ailanthus excelsa	Cuttings from two –year old saplings	500, 1000, 1500 and 2000 ppm of IBA	About 40% rooting recorded with 1000 ppm IBA.	Sharma and Tomar (2003)
Acacia nilotica	Stem cutting of 3-5 cm thickness with six nodes	Cuttings dipped in various auxins of different concentration for 10 sec.	5000 ppm IBA concentration gave best results	
Dalbergia sissoo	Stem cuttings, root cuttings coppice shoots and root suckers	Seasonal study with varying concentrations of IBA together with intermittent misting in polyhouse	March-April is the best period for raising cuttings. 1000 ppm IBA for 30 seconds is suffic-ient for 60-90% rooting	
Eucalyptus camaldulensis	Coppice shoots and branch cutting	Treatments of propagules with rootex powder (1.5% IBA) and placed in mist chambers	Almost 40% rooting achieved in the month of August and September.	
Tecomela undulata	Branch cuttings collected from different crown portions	Seasonal effects together with cutting from different crown portions	Maximum 15% in January-March. Stem cuttings of middle crown showed 17.8% rooting but cuttings from upper portion of the middle crown rooted up to 33.3%.	Tyagi et al. (2011)
P. cineraria	15 cm long and 3-6 mm diameter, from 6 months old seedlings,	NAA +IBA + thiamine (4 + 4+ 4 g/l) in February and NAA+IBA+THI (2 + 2+ 2 g/l)	No rooting with hormone treatments less < 1g/l. Maximum 60% rooting	Arya et al. (1993)
	15 cm long and 3-6 mm diameter lopped from 8 years old trees and 6 months old seedlings	IAA, IBA and NAA applied singly or in combinations with 2,4-D and thiamine (THI) at concentrations of 1000, 2000, 4000 and 8000 mg/l	Rooting up to 35% only in IAA+IBA+2, 4-D (1000mg/l) and NAA+IBA+thiamine (4000 mg/l). Cuttings from 6 months old seedlings gave 50% rooting 2000mg/l of IAA+IBA+2,4-D and 60% with 4000mg/l of NAA+IBA+ thiamine.	Arya et al. (1994)

Species	Sample type	Treatment	Results	Reference
Pongamia pinnata	15-20 cm long and 2-3 cm thick with at least 3-4 buds having one year growth	1000, 2000, 4000 and 5000 ppm concentration of IAA, IBA, NAA and Thiamine	85-100% rooting with 4000 ppm thiamine closely followed by 1000 ppm IAA	Anonymous (2011)
Jatropha curcas	Uniform cuttings of 20-25 cm long and 2-3 cm thick from middle portion of 3 year old plants	50, 100, 200, 400, 800, 1000, 2000 mg l^{-1} of IAA, IBA, NAA and Thiamine		Anonymous (2011)
Commi-phora wightii	Cutting of different diameter	Effects of cutting diameter, light condition, season and growth hormone	About 85% rooting in 1.5 cm diameter cutting, 78% rooting in cutting grown in open area and 80% rooting in July. Application of IBA increase rooting up to 80% (at 5000 ppm)	Kumar et al. (2012)
	Field performance of stem cutting of 15 cm diameter class	A 18 months old field trial of clonal material collected from 21 Districts of Rajasthan	56.3% survival for Jalore to 100% for Ajmer, Jaipur and Tonk source. Cutting from Bhilwara, Alwar, Dausa, Jhunjhunu, Pali, Sikar, Tonk, Rajsamand and Udaipur were fast growing	Mishra et al. (2009)
	Cutting of diameter 0.50 cm to > 1.50 cm	100, 200, 500 and 1,000 ppm IAA and IBA	0.75 -1.00 cm dia cutting sprouted upto 90% and rooted 73%. About 93% rooting with 200 followed by 500 ppm IBA (87%)	Kulhari et al. (2014)
	Stem cutting	Treated with IBA of concentration 500 ppm	Six hours treatment gave 97% rooting whereas 30 minutes to 1 hour treatment gave 90% rooting	RFD (2008)
	Air layering	Effect of time and different methods of propagation	95% rooting during first showers against 75% rooting during rain period. Plant survival was greater than the plants growth with seeds or cuttings	Kasera et al. (2012)

Species	Sample type	Treatment	Results	Reference
Boswellia serrata	3-4 inches dia and <2 m long. Thick end a slanting cut and coating of thin end with white oil paint	Burying cuttings up to 50 cm in 60 × 60 × 60 cm^3 pits followed by affirming soil around the cuttings. Latter half of April to first week of May is the right season of planting	Sprouting in 76% cuttings and establishment of about 70-80% of the sprouted ones in the field	Soma-shekhar and Sharma (2002)
	Root suckers extracted from trees of about 2 feet girth	Root suckers are planted in June and July	The sprouts are seen in about 15 to 30 days	
Butea monosp-erma	Stumps of 2' shoot and 12' long root from 1-year old seedlings from root suckers	Stumps have to be prepared at the onset of rains	About 80% survival and satisfactory growth. July– August is the favourable time for transplanting *B. monosperma.*	Soma-shekhar and Sharma (2002)

***2.1.1.1 Hardwood cuttings**:* The cuttings collected from the branches of the current year's growth of a plant are usually considered to be "Hardwood cuttings". These cuttings usually measure to about 20-25 cm long with 4-5 nodes. The cuttings of pencil thickness with uniform inter-nodal growth are preferred sample types for propagation purpose. *Acacia catechu* (Kher), *Dalbergia sissoo* (Sissoo), *Ficus carica* (fig), *Bougainvillea glabra*, *Hibiscus rosa-sinensis* (China rose, gurhal), *Punica granatum* (Pomegranate), *Lawsonia inermis* (Mehdi), *Hippophae rhamnoides* (Seabuckthorn), *Prospis cineraria* (Khezri) etc are some plants propagated through hardwood cuttings (Puri and Verma, 1995; Reddy et al., 2008; Sharma et al., 2009; Singh et al., 2011; Janifer et al., 2013).

2.1.1.2 Semi hardwood cuttings**:** The cuttings prepared from tender shoots and branches of the current year's growth that are not too hard but show brown blotches on the green stem are termed semi-hardwood cuttings. They also measure about 20 cm with a pair of leaves retained at the tip of the cuttings. Some plants that are usually propagated by semi hardwood stem cuttings are: *Tectona grandis* (Teak), *Dalbergia sissoo*; *Syzygium cumini* (Jamun), *Jatropha curcas* (Jatropha) *Adhatoda vasica* (Adusa), *Tinospora cordifolia* (Guruch), *Gymnema sylvestre* (Gudmar) etc. (Puri and Verma, 1996; Husen, 2013; Kumari et al., 2013).

2.1.1.3 Softwood stem cuttings: The cuttings prepared from the soft tender shoots which are still green are considered softwood cuttings. These cuttings are of 8-10 cm long with a growing tip and the leaves are usually retained at the tip of the cuttings. The species are: *A. catechu*, *Commiphora wightii* (Gugul), *D. sissoo*, *P. cineraria*, *Psidium guajava* (Guava), *Thuja compecta* etc (Puri and Verma, 1995, Kumar et al., 2006; Singh et al., 2013a; Kareem et al., 2013; Tripathi et al., 2014).

2.1.2 Propagation through layering

This is a technique in which a vegetative branch is intimidated to root while the branch is still attached to the mother plant (Kasera et al., 2011). The rooted branch is later excised and planted as a new individual. Different layering methods are air layering, mound layering and serpentine layering. Different steps followed in air layering are:

- A pencil size shoot of the current year's growth is selected from the mother plant and a ring of bark is removed at the basal portion of the selected shoot.
- The exposed wood is scraped first and then wrapped with moist inert rooting medium like Sphagnum moss, moist coir etc and is made air tight after covering with a polythene sheet.
- The branch is left undisturbed on the mother plant for about 2 to 8 weeks depending on the type of species. During this period several adventitious roots are emerged from the base of the exposed bark covered as above.
- The rooted branch is later cut below the covered portion and planted as a separate seedling. Air layering is frequently used in *Emblica officinalis* (Aonla), *Tamarindus indica* (Imli), *Mangifera indica* (Mango), *Ficus* spp. etc.

Mound layering is another technique of air layering in which following steps are followed:

- A long and simple branch is selected from the mother plant and a ring of bark is removed at the base of the selected branch.
- The ringed branch is then buried in the soil and left undisturbed. In due course of time, fine roots emerge from the buried portion of the branch.
- After sufficient emergence of the roots the branch is separated from the mother plant and planted as an independent plant. *Mangifera indica* (Mango), *Citrus* spp etc are some examples, on which mound layering is generally applied.

A series of mound layering can be done on a single long branch that is buried and exposed alternately making a serpentine layer is known as serpentine layering. This technique is applied for the species, which have drooping long and supple branches. *Tinospora cordifolia* (Guruch) and *Celastrus paniculatus* (Malkangani) are some examples where serpentine layering can be followed.

2.1.3 Propagation through grafting

This is a propagation technique employed usually to improve the quality of the planting stock or to produce seedlings that carry the plus qualities of a mother plant. In this, two vegetative parts from two different plants of a same species are brought together and joined so that they can grow as a single plant. Usually the stem branches are used for the purpose of grafting. The part of the plant that receives another plant part is called the stock, whereas the plant part that serves as the graft is called the 'scion'. When these two parts (i.e., stock and scion) are united together, graft union takes place. The scion always carries the qualities of the mother plant while the stock serves as the root system. After the graft union is taken place, scion becomes the upper part while the stock becomes the basal (root) part of the new plant. The different methods of grafting are available for plant propagaton. The commonly used methods are approach grafting, wedge grafting, epicotyl grafting and softwood grafting. Some of the species where this type of grafting is applied are *Artocarpus* spp. (Katahal), *Syzygium cumini* (Jamun), *Garcinia* spp etc.

2.1.3.1 Approach grafting: This method involves causing the graft union between the two selected branches of 'stock' and 'scion' while the branches are still growing on the mother plants.

2.1.3.2 Wedge grafting: In this method the union takes place by inserting the scion, which is in the form of a wedge, onto an incision on the stock plant. The scion is usually a branch excised from the mother plant.

2.1.3.3 Epicotyl grafting: In this method, the grafting is done on the tender shoot of about 5-7 days old of a germinated seed with its epicotyl seeds still intact.

2.1.3.4 Softwood grafting: This is the method in which grafting is done on the soft shoot of the stock plant which is a seedling of about 6 months old.

Table 10.2 Performance of different forest species towards budding, grafting and air layering methods of propagations.

Species	Sample type	Method	Results	References
P. cineraria (budding)	One year old seedling rootstocks with diameter of 0.4 – 0.8 cm	2-3 cm vertical incision in the bark of stock at 15 cm height from the ground level. After slight loosening of the bark with the help of budding knife a piece of scion plumpy bud is inserted and then tied with a polythene wrap.	The I-method of budding during July to September gives about 60% success	Meghwal and Harsh (2008)
Ailanthus excelsa (grafting)	One year-old seedlings as stock and sixty days old scions from sprouts of 7-year-old trees	A simple slant cut of the same length and angle in both the rootstock and scion with a grafting knife. After joining the scion with rootstock both tied with polythene wrap.	About 90% survivals at one-month. About l0% survival of grafted scion in shade house after three months.	Tomar et al. (2004)
P. cineraria (air layering)	Branches upto 15 mm thick	Removal of bark from a 15 mm girdle and applying 100 ppm IAA alone or with Seradix B3 hormones to the upper end of the girdle. The girdle is then covered with a layer of moss or clay and wrapped in polythene.	Rooting in 10-15 mm dia. branches but not in 7 mm branches. Seradix and clay gave best result. 100% success in July and August, and a little rooting in January and February too.	Solanki et al. (1986)
		Air laying using seradix B3 (IBA) and moss as a rooting medium	70- 80% rooting after 1.5 months.	Rawat et al. (1982/83)

Species	Sample type	Method	Results	References
	With 5 to 10 years old plants	Lanolin paste containing 20, 200, 2000 mg IAA, IBA, NAA or 2, 4-D applied in various combinations to girdled twigs and wrapping of girdle after covering with polythene	No rooting was obtained after 3 months. The experiment was unsuccessful	Arya and Tomar (1989)
Pongamia pinnata, Jatropha curcas and *Azadirachta indica*	Branches of 1.5 to 2.0 cm girth	Girdling of 3-4 cm length at 30 cm from branch base during March to first week of April and treated with IAA, IBA and NAA (500, 1000, 1500 and 2000 ppm) for *P. pinnata* and *A. indica*. During spring and monsoon seasons and treatment with IAA, IBA, NAA and Thiamine (75, 150, 300, 600, 900, 1200, 1500 ppm) for *Jatropha curcas*	*Pongamia pinnata* rooted 100% with 500 and 2000 ppm IBA. 100% rooting in *A. indica* with 1000 and 1500 ppm IBA, 500, 1000 and 2000 ppm IAA and 500, 1500 and 2000 ppm NAA. Spring season is best for multiplication of *J. curcas*. 75, 150, 300 ppm Thiamine is effective for *J. curcas* in both seasons	Anonymous (2011a)

2.1.4 Propagation through budding

This is one of the most common methods of plant propagation in many plant species. In this a single bud is grafted on the stem of the rootstock. The stem or branch should be of 2 cm in diameter. Therefore, this method is applicable only for the young rootstock plants or smaller branches of trees. To obtain best results, bud wood or bud sticks which are of a vigorous current season growth should only be used under this method. Removal of the top and bottom part of the branch is necessary as the tip buds are too immature, whereas the bottom buds may be a cluster of buds or they are too weak to use for budding. The length of the stick should be about 30 cm. Leaves should be removed leaving a 1-1.5 cm long of leaf petiole on the stem.

Different methods of budding are patch budding, T or shield, I and Chip budding and are generally applied during April to September, but spring budding in April may also be tried.

2.1.4.1 Patch budding: This is the simplest to perform among the various methods of budding due to ease in removing or preparing rectangular patches of bark. It is widely used in plants with thick bark that can be easily separated from the wood.

2.1.4.2 T or Shield budding*:* It is method in which incisions are made in the bark of the rootstock to form the shape of a letter "**T**" with one horizontal cut and another downward cut that originates from the center of the first cut.

2.1.4.3 I-Budding: In this incisions is made in the shape of an "**I**" (capital of letter "i") in the bark of the rootstock by a single vertical cut and a horizontal crosscut at both ends. A rectangular bud patch, similar to that in patch budding, is then inserted in the stock.

2.1.4.4 Chip budding: Chip budding method is used on the plants or stems with barks that do not readily separate from the wood as in *Citrus* spp. Procedures and precautions are similar to those for T-budding (Meghwal and Harsh, 2008).

Following steps are followed in this method:

- Selected vegetative bud is removed along with a patch of bark from the scion plant and inserted on to the stock plant.
- The grafted vegetative bud is further tied to keep the bud in place and maintained as such till the union of both stock and scion takes place.
- After ensuring the effective union of stock and scion, the portion of the stock above the bud union is removed and the sprout from the scion bud is encouraged to grow further.

2.1.5 Propagation through modified organs

Several plant species make sure their propagation with the help of modified organs that serve as the propagules. Root sucker, tuber and rhizomes are some such special organs, the plants use to propagate.

***2.1.5.1 Root sucker**:* A root sucker is a small plantlet that appears around a mother plant particularly from its base or detached/cut root. These plantlets remain attached to either the mother plant or the detached root system and continue to grow. They assume to grow as independent plants even when they are separated from the mother plant or root system and are planted elsewhere. Root suckers are the propagating material of most of the species of dry regions like *Prosopis cineraria* (Khezri) *Tecomella undulata* (Rohida), *Aerva pseudotomentosa* (Bui), *Leptadenia pyrotechnica* (khimp) etc and other species like *Boswellia serrata* (Salar), *Aloe vera* (Gwarpatha), *Aegle mormelos* (Bel), *Holorrahena antidysenterica* (Dudhi), etc.

2.1.5.2 Propagation though tuber: Tubers are the swollen and fleshy underground stem or roots. These are found attached at the base of the stem of a plant. On separation, the tubers or the pieces of a tuber grow as independent plants. Tuber is the propagating material of many plants species like *Asparagus racemosus* (Satawari), *Dioscoria* spp. *Gloriosa superba* (Glory), *Ipomoea* spp. (Sweet potato), etc.

***2.1.5.3 Propagation through rhizome**:* Rhizome is the swollen and compressed underground stem with short scaly leaves and vegetative buds. A piece of rhizome with a bud, if planted, grows in general into an independent plant. Rhizome is the propagating material of many plant species like *Zinziber officinale* (Ginger), *Curcuma domestica* (Turmeric), *Solanum tuberosum* (pottato) etc.

2.2 Plant production through micro-propagation

Tissue culture provides an excellent system to study the factors involved in vegetative multiplication and the possibilities of obtaining improved plants by genetic engineering. Some works related to regeneration of different tree species including *P. cineraria* through tissue culture are available (Table 10.3) with varying success rates (Goyal and Arya, 1984; Nandwani and Ramawat, 1989). The existing literature indicates involvement of genotype, age of tree, nature of explants and size, season of explants collection, explants position on medium, plant growth regulators and addition of certain regulators or harmones (ascorbic and citric acid, adenine, sulphate, L-arginine, glutamine and ammonium citrate) as the factors. However, incubation conditions and subculturing period greatly influence the *in vitro* multiplication of many species and *P. cineraria* in particular (Shekhawat et al., 1993). Murashige and Skoog's (MS) medium has been most commonly use medium, whereas most commonly added harmones to the medium are varying concentrations of Indole-3-acetic acid (IAA), Naphthalene acetic acid (NAA), kinetin (kn), benzylaminopurine (BAP) etc. *Prosopis cineraria*, *Zizyphus mauritiana*, *Tecomella undulata*, *Aegle marmelos*, *Eucalyptus viridis, Eucalyptus sideroxylon*. *Tecomella undulata, Ailanthus excelsa, Balanites aegyptiaca, Commiphora wighttii, Dalbergia sissoo* etc are commonly used species under micropropagation (Arya and Sekhawat, 1986; Arya et al., 2013; Gour and Kant, 2006; Goyal and Arya, 1984; Praveen and Tomar, 2009; Srivastava and Kant, 2010; Tyagi et al., 2011).

Table 10.3 Micro-propagation of different tree species with varying explants and additives.

Species	Sample type	Treatment	Results	Reference
P. cineraria	Nodal shoot segment from pruned thorny adult trees	Influence of genotype, tree age, nature of explants and size, season of explants collection, explants position on medium, plan growth regulators, and addtitives like ascorbic, citric acid, adenine, sulphate, L-arginine, glutamine and ammonium citrate	Maximum 10-12 shoots on MS medium containing 0.1 mg 1^{-1} IAA + 2.5 mg 1^{-1} BAP + additives. Nodal shoot segments obtained from root and stump sprouts produced multiple shoots	Shekhawat et al. (1993)
	The explants (axilliary and terminal buds), 8-10 mm size	MS medium supplemented with organic and inorganic salts. After 4 to 6 weeks fully developed planted were removed from medium and transplanted to pots with soil + vermiculite (1:30) and nurtured under semi-controlled temperature	The plant is successfully propagated	Arya and Sekhawat (1986)
	Single bud explants	NAA, IAA, IBA and 2,4-D and cytokinins (Kinetin and BAP)	3.0 mg l^{-1} IAA:with 0.05 mg l^{-1} Kinetin is found best for shoot multiplant	Goyal and Arya (1984)
Z. mauri-tiana, A. marmelos, Eucalyptus viridis and *E.*	Axilliary and terminal buds, 8-10 mm size	MS medium, supplemented with organic and inorganic salts	The plant was successfully propagated	Arya and Sekhawat (1986)

Species	Sample type	Treatment	Results	Reference
sideroxylon, T. undulata				
Tecomella undulata	Axillary shoots	MS medium supplemented with (2 mg/l) BA + (0.1 mg l^{-1}) NAA	MS medium with l mg L^{-1} BA is best for shoot multiplication, whereas B5 medium for rooting (43%)	Tyagi et al. (2011)
Ailanthus excelsa	Coppice shoot	MS medium multiplied for more than two years on MS with 2 mg l^{-1} BA	Four fold multiplica-tion after every subcul-ture. 50% rooting on half strength MS medium containing 1.5 mg l^{-1} NAA.	Sharma et al. (2008)
	Hypocotyl explants	MS medium with 1.61 µM NAA + 4.44 µM BAP supplemented with ascorbic acid 100 mg l^{-1} and citric acid 50 mg l^{-1}	About 10-15 shoots were regenerated from a single explant. Maximum 50% rooting when excised shoots transferred to 1/2 strength MS medium containing 5.37 µM NAA and 2.32 µM Kn	Praveen and Tomar (2009)
Balanites aegtptiaca	Apical buds & root segments	NAA and 2,4-D supplemented MS medium	100% callusing but poor growth on NAA supplemented medium. Best callusing response from root segments and apical buds on both NAA and 2,4-D supplemented media.	Gour and Kant (2006)
Commiphora wightii	Cotyledonary node	MS medium supplemented with 2.68 µM NAA and 4.44 µM BAP and on 2.68 µM NAA; 4.44 µM BAP with additives (glutamine 684.2 µM; thiamine 29.65 µM; activated charcoal 0.3%) and various other hormonal combinations	Elongation of microshoot on IBA and BAP supplemented MS medium. Efficient rooting on pretreated microshoot with IBA for 24 hours	Kant et al. (2010)
Pongamia pinnata	Cotyledonary nodes	MS medium supplemented with 8.8 µM BAP and 0.53 µM NAA	About l6-24 shoots per cotyledonary node. Shoots formed in vitro rooted on full strength MS medium supplem-ented with different concentration of IBA	Srivastava and Kant (2010)

Species	Sample type	Treatment	Results	Reference
Dalbergia sissoo	Nodal explants	Various concentrations of BAP	*In-vitro* shoot multiplication is highest at 2.5 µM BAP. *In-vitro* roots are induced on IBA supplemented medium. Effective IBA concentration is 5-7.5 µM IBA for rooting (60-65%) in different clones	Arya et al. (2013)
Boswellia serrata	Excised green zygotic embryos	Different concentration of sucrose and on MS medium containing 3 % sucrose, PVP (0-300 mg l^{-1}), GA_3, IAA, NAA, IBA or 2,4 D and BA or Kn	About 96% embryo germination and conversion into seedling on MS medium with 3 % sucrose and 200 mg l^{-1} PVP	Ghorpade et al. (2010)
	Cotyledonary node segments	MS medium with 0.5 mg l^{-1} BAP and 0.05 mg l^{-1} NAA.	By repeated subculture technique 90–100 shoots per node obtained after 88 d of initial culture. Approx. 80% rooting within 8–10 days	Purohit et al. (1995)

2.3 Seedling quality

The prerequisite of a hardy planting material at the time of planting is part of the art of being a good nurseryman. Studies on seedling quality highlight the importance of a good root: shoot ratio to reduce the transplantation shock in order to achieve good success of plantation program. Plants of larger size often show root systems restricted by the polybags/container (i.e., a poor root: shoot ratio) and the change in growing environmental condition can cause desiccation of the plant. A sound practice is to achieve planting stock of about 30-45 cm of top growth and a good first order lateral root system, but it should not out-grown the container. Seedling quality is assessed on morphological and physiological characters of the seedlings or planting materials (Mattson, 1997). Morphological quality is used more often to evaluate seedling quality. Height and stem diameter are the two characteristics most commonly examined on forest seedling stock (Rose and Ketchum, 2003). These two parameters should be defined along with acceptable minimum and maximum ranges. Workers on the grading line should be also trained to cull seedlings with physical deformities, mechanical damage, and signs of disease. Other parameter is root system size, which is well correlated with stem diameter, but measuring root quality is not as quick and simple as those for shoot quality (Jacobs et al., 2005). Another morphological aspect that should not be ignored while assessing seedling quality is seedling balance in which shoot should not be too tall as compared to the stem diameter. Physiological assessments are evaluation of cold hardiness and root growth potential (Radoglou et al., 2003).

For testing hardiness, groups of seedlings are placed in a freezer and the temperature in the freezer is decreased gradually from room temperature to a target subfreezing temperature and held for 2 hours. Four target temperatures are selected on the basis of their expected ability to create a given range of damage. Similar to the procedure described for assessing damage after a fall freeze, seedlings are then placed in a greenhouse with adequate moisture and warm temperatures for 6 d, after which damage to foliage, cambium, and buds is evaluated. If the cambium is dead in the mid- to lower section of the main stem or if more than 50 percent of the buds are damaged, the seedling is considered nonviable (Tanaka et al., 1997). Root growth potential (RGP) is useful for determining the percentage of live or dead seedlings in a particular lot, but there is some debate regarding its usefulness in predicting subsequent field performance (Simpson and Ritchie, 1997; Singh and Singh, 2007). RGP is generally determined after 3 week under ideal environmental conditions, though seedlings are rarely out planted to optimum temperature and moisture conditions. Other physiological tests to assess seedling quality are: (i) plant moisture stress, which is an indicator of xylem water potential and is often used to schedule irrigation and monitor water stress during lifting, packing and transporting process (Lopushinsky, 1990), (ii) bud development, which is related to seedling dormancy and shoot growth potential in the coming season; (iii) Chlorophyll fluorescence, which indicates a seedling's photosynthetic activity (Mohammed et al., 1995); and (iv) nutrient status, which governs many metabolic processes in the seedling.

3. PLANTATION TECHNIQUES

Prevailing climate conditions and limited supply or capture of light, water and nutrients than the optimal ones results in less productivity of most of the forest plantations in dry areas in comparison to their physiological potential (Goncalves et al., 2005). Further, maximum growth does not match up to the maximum wood value. It could be possible to identify and ameliorate factors limiting plant growth by soil cultivation, residue management, fertilizer/biofertilizer use, weed control, irrigation, coppice management, thinning and pruning (Goncalves et al., 2005; Szabó et al., 2014). Establishment of plantation on degraded lands plays a key role in harmonizing long-term forest ecosystem rehabilitation or restoration goals (Lamb, 1998). Forest plantations, using appropriate tree species can play an important role in the tropical ecosystem rehabilitation (Founoune et al., 2002). In such cases, planting of nursery raised seedlings either through seeds or by various means of vegetative propagation may accelerate regeneration and restoration of degraded sites (Yirdaw and Luukkanen, 2003). Successful seedling establishment and growth depends on the soil condition and the stored soil moisture to ensure survival into the next growing season (Warren et al., 2005). Because, seedlings of some trees are sensitive to drought, and may be killed by even short dry spells (Engelbrecht et al., 2007). Weeds (Richardson, 1993); vertebrates (Porteous, 1993); invertebrates (Gadgil et al., 1995) and seedling quality (Chavasse, 1980) also commonly affect the growth, survival and distribution of tree seedlings.

3.1 Site survey and selection

For plantation on farmlands, there is need to motivate landholders to consider and adopt this enterprise and provide access to adequate information on farm forestry. Information commonly required by landholders includes the biophysical requirements for commercial tree crops, the opportunity costs incurred, and the infrastructure available for farm forestry (Schirmer et al., 2000). Choice of the planting site in case of regenerating forest is however limited to the lands which are not suited for agriculture or livestock production. Therefore, survey and selection of a suitable site is more important in establishing a successful forest plantation. In such a case, reconnaissance information about the site gains importance. The major factors that affect the success of afforestation in the drylands are drought and moisture stress, soil fertility, infestation by insects and pests, biotic interferences from livestock etc. (Mahari, 2014). Greater the information available about the site conditions which is being considered for plantation, the better are the chances of selecting the tree or shrub species best suited to the region. The most commonly considered information while selecting a site are climate, soils, topography, vegetations, biotic factors, water availability (both underground and distant place), distance from the nursery, availability of labours and motivations amongst the local people towards the plantation activities. Quality of sites in terms of fertility and soil depth should also be assessed. For example, sites rocky in nature are in low fertility and little (<30 cm) or no top soil; whereas moderate to high fertility site is with >30 cm soil depth and can sustain growth of native species and production forestry. The required information is as follow:

3.1.1 Climatic conditions

This includes air temperature, rainfall (i.e., amount and distribution), relative humidity, and wind velocity.

3.1.2 Soil condition

Depth of the soil and its capacity to retain moisture, texture, structure, parent material, pH, degree of compaction, and drainage level.

3.1.3 Topography

It is an important factor modifying the effects of both climate and soil.

3.1.4 Vegetation

This includes the composition and ecological characteristics of natural as well as introduced vegetation. In absence of anthropogenic activities, the vegetation can provide an indication of the site conditions. Unfortunately, the vegetation has been so disturbed throughout the drylands that it is no longer a reliable indicator of potential planting sites. In such a condition, the site selection should be based on soil conditions.

3.1.5 Water table and water sources

Knowledge on the depth and variation of the water table during the wet and dry seasons is valuable and can be crucial in determining the tree and shrub species that can be planted. Water table can be estimated from the observations in the wells or by bore well made for this purpose. Availability of water sources like ponds, lakes, streams, well and other water sources is of great help for supplementary irrigation during drought or water stress period.

3.1.6 Other biotic factors and information

Past history and present land use also influences on the site, including fire, domestic livestock and wild animals, insects and diseases. Apart from these biophysical informations and socio-economic factors also play an important role. Among these factors are availability of labour, motivation of the local population and land ownership and tenure. Local community members are important actors in promoting re-afforestation activities. They can participate actively in tree planting in mountaineous region to prevent soil erosion in agricultural land, protection of river bank, and generating funds for management and maintenance of public facilities such as schools.

3.1.7 Protection measures

Once the area is selected, it should be marked with boundary posts and should be protected from any human and livestock interferences. In case of a danger of trespassing and damage by grazing animals, a boundary fence should also be established. Fencing could only be erected when other means of protection are not effective because of high cost involved in it. Although the fences can also be reused at another site after removal from the original site once a forest plantation is well established and the trees are sufficiently tall. In case of roads or other passage traverse the planting site, they should also be contained with fences for effective protection. In many cases, planting trees or shrubs are undertaken to protect fragile sites from degradation. However, in case of the fragile sites it may be better not to disturb the soil rather promote natural vegetation under direct seeding. Where gullies have been severely degraded by erosion, protective measures other than the planting of vegetation (i.e., building small checkdams) may be a better option.

3.2. Selection of planting species

Selection of appropriate plant species suitable for the natural environment of the region is imperative in order to make tree planting successful. The key for plantation success in dry areas is the selection of highly drought-tolerant tree species. However, standard of the selection is also based on the uses of the tree species in the region and its perception among the local people. Despite of thousands of indigenous species suitable for afforestation, about 85% of plantation forestry in the tropics is dominated by three genera, i.e. tropical pines, *Eucalyptus* and *Tectona.* Species of *Eucalyptus, Populus*, *Leucaena* and Bamboos appear with the greatest potential to provide supplemental fiber and has the potential to produce a biomass of 18 to 49 tons per ha per year (Prasad et al., 2009; Vance et al., 2014). The pulp yield from these species ranges from 40 to 49% of the wood biomass (Prasad et al., 2009). The concept of high density plantation system has gained immense interest in order to efficiently combine and utilize the land, labour and water resources for meeting immediate requirements of rural communities for fuel wood, fodder and timber and other minor forest produce. High density plantations of tropical species include Eucalyptus, Mesquite, *Leucaena leucocephala* and *Terminalia arjuna*.

Though the selection of indigenous tree species should be prioritized for sustainable forest management, and for effective use and preservation of water resources, but introduction of useful exotic tree species must be managed based on water use attributes of each species. For example, poplar (Populus), Casuarina, Acacia, Robinia and even Eucalyptus are considered for reclamation work, especially on eroded soils. They grow fast, have large root systems and are adapted to similar site conditions as the degraded land (Dean et al., 1986; Garvi, 1999). Thus selection of tree or shrub species should be through the use of analogous climates that must be amplified by an evaluation of localized factors like soil, slope, and biotic factors, which are more important. Therefore, trees species with multi-purpose uses are important plantation trees. As most of the multipurpose trees species are planted as part of agroforestry at present, it is necessary to understand the properties of the trees and consider planting and management methods to reduce competition with other plants over water. Selection should also focus on the species that are on the verge of depletion due to over exploitation as fuel wood and also the species retained intentionally by the local people for traditional uses. The important drought-tolerant tree species including both indigenous and exotic tree species are *Acacia senegal*, *Acacia tortilis*, *Acacia nilotica*, *Anogeissus rotundifolia*, *Alainthus excelsa*, *Azadirachta indica*, *Balanites aegyptiaca*, *Cordia myxa*, *Prosopis cineraria*, *Tecomella undulata*, *Eucalyptus camaldulensis* etc. *Celtis caucasica* is suitable species for afforestation of arid and semi-arid regions indicated by maintained leaf chlorophyll content under stress conditions (Kordrostami et al., 2014). Some suitable species for farmlands of dry areas are provided in Table 10.4.

3.2.1 Shifting sand dunes

A substantial portion of arid Rajasthan is covered by sand dunes of various types like longitudinal, transverse and barchans dunes with some further categories. Field studies on the soil moisture regime and micro climatic pattern over stabilised and shifting dunes reveal that high moisture concentration occurs below 1.5 m depth in shifting sand dunes throughout the year and below 4 m in stabilized dunes during summer months. Further, bare dune shows greater soil moisture as compared to the vegetated or stabilized/semistabilised dunes (Singh, 2004a; 2004b). Thus shifting sand dunes are the most suitable sites for afforestation even in low rainfall areas. Some suitable species are *Acacia tortilis* (Israeli babool), *Prosopis julifiora* (Vilayati babool), *Dicbrostachys cineria*, *Tamarix articulata*, *Colophospermum mopane, Zizyphus mauritiana* (Ber), *Acacia planifrons*, *A. nubica, Calligonum polygonoides* (Phog) etc mixed with shrubs and grasses to develop under canopy vegetation (Singh and Rathod, 2002).

Table 10.4 Species suitable for farmlands of drylands of India.

SNo.	Position/uses	Species
Boundary	-	*Tecomella undulata, Prosopis cineraria, Acacia tortilis, Eucalyptus camaldulensis, Acacia nilotica, Lawsonia inermis, Tamarindus indica, Pongamia pinnata, Prosopis juliflora, Azadirachta indica, Dalbergia sissoo* etc.
Live fence	Inner	*Parkinsonia aculeata Dalbergia sissoo, Carissa carandas, Prosopis cineraria, Pithecalobium dulce, Muraya coenigi, Gliricidia, Tectona grandis, Tecomella undulata, Azadirachta indica, Eucalyptus* spp. etc.
	Outer	*Zizyphus mauritiana, Prosopis juliflora, Zizyphus nummularia Opuntia spp., Lawsonia inermis, Eucalyptus, Agave spp.*
Trees on crop lands	Fodder/green biomass	*Acacia albida, Acacia nilotica, Ailanthus excelsa, Albizia lebbeck, Azadirachta indica, Cassia siamia,, Colophospermum mopane, Dalbergia sissoo, Dichrostachys cinerea, Hardwickia binata, Leucaena leucocephala, Pongamia pinnata, Prosopis cineraria, Tecomella undulata,* etc.
	Fruit species	*Zizyphus mauritiana*, *Phoenix dactylifera*, *Ficus carica*, *Syzygium cumini*, *Grewia* spp., *Annona squamosa*, *Mangifera indica*, *Punica granatum*, *Tamarindus indica*, Sapota, *Psidium guajava* etc.
	Wood/Fuel Wood	*Acacia tortilis*, *Parkinsonia aculeata*, *Acacia senegal*, *Acacia nilotica* var. *cupressiformis*, *Acacia nilotica*, *Eucalyptus* spp., *Acacia auriculiformis*, *Dalbergia sissoo*, *Tectona grandis* etc.

3.2.2 Sandy plains

Such sites comprise of deep sandy soils having soil depth ranging from 70 to 150 cm with kanker hard pan beneath. Soil working in such areas need not be done well in advance of planting as it would affect the soil moisture build up. Sturdy seedlings of 9 to 10 months old should be planted in the pits provided with a micro catchment/depression around the plants in plains or crescent shaped ridges of 15 cm high across the local slope if planting is done on slopes so as to arrest the run-off water during monsoons (Gupta, 1995; Singh, 2011b). *Acacia tortilis* (Israeli babool), *Prosopis julifiora* (Vilayathi babool), *Prosopis cineraria* (Khejri), *Azadirachta indica* (Neem), *Albizia lebbek* (Siris), *Acacia senegal* (Kumat), *Dicbrostachys cinerea*, *Cassia siamea* (Kasod), *Tamarix articulata* (Farash), *Holoptelia integrifolia* (Churel), *Colophospermum mopane, Zizyphus mauritiana* (Ber) etc. are some species suitable for such sites.

3.2.3 Shallow sandy loam soils

These soils consist of shallow sandy loam soils overlying deep hard calcareous pan. There is absolute need to perforate the pan to a depth of 90 to 100 cm using a post-hole digger, or by manual labour to provide a deep rooting medium for proper development of the planted seedlings. In this loose weathered soil should be filled in the pits before planting. With the onset of monsoons, sturdy nursery raised seedlings of 9 to 10 months old are planted providing saucer shaped depressions around the plant to store rainwater for a longer period. *Acacia tortilis*, *Acacia senegal* (Kumat), *Prosopis julifiora*, *Azadirachta indica*, *Albizia lebbek*, *Zizyphus nummularia* (Bordi), *Dichrostachys cinerea, Holoptelia integrifolia*, *Dalbergia sissoo* (Shisham), *Anogeissus rotundifolia,* etc.

3.2.4 Alkaline-saline areas

These are areas having highly saline soils with hardly any vegetative cover except for some salt bushes and little sparse tree growth on the elevated areas. Afforestation of such areas is only possible by ripping to open the pan to a depth of a meter by a tractor followed by cross harrowing. After the pan is broken, the area should be cross harrowed to break the crust formation. After this operation, ridges of 1 m wide at the base and 1 m high are constructed with the help of dosers. The inter-ridge spacing should be about 1.5 to 2.0 m. Planting is carried out on the crest of ridges in pits so that the salts get leached down from the ridges to lower depth providing better soil condition and rooting depth for increased transplant establishment and growth. *Aegle marmelos, Alangium salvifolium, Albizia lebbeck, Azadirachta indica, Buhinia variegataa, Cassia siamea Cassia fistula, Cordia dichotoma, Dalbergia sissoo, Ficus glomerata, Holoptelea interifolia, Pithecellobium dulce, Derris indica, Putranjiva roxburghii, Sterculia alata, Terminalia arjuna* etc are considered better for rehabilitation of sodic lands (Tripathi and Singh, 2005). Tree species like *Prosopis chilensis*, *P. juliflora*, *Tamarix troupii*, *Tamarix aphylla*, *Acacia nilotica*, *A. auriculeformis*, *A. ampliceps*, *A. stenophylla, Casuarina obesa*, *C. equisetifolia*, and *Eucalyptus camaldulensis* have relatively high tolerance to soil salinity (Aref et al., 2003). Tomar et al. (2003) ranked tree species in order of *Tamarix articulata*, *Acacia nilotica*, *Prosopis juliflora*, *Eucalyptus tereticornis*, *Acacia tortilis* and *Cassia siamea* based on order of survival, growth and biomass yield on a calcareous soil in a semi-arid part of northwest India after furrows irrigation with saline water (EC 8.5–10.0 dS/m) for initial 3 years (4–6 times/year) and there after once during the winter only. The other species are *A. tortilis* (hybrid), *Melia azedarach* and *Acacia farnesiana*. Tree species like *Acacia auriculiformis*, *Albizia lebbeck*, *Bauhinia variegata*, *Cassia glauca*, *Syzygium cuminii*, *Crescentia alata*, *Samanea saman* and *Terminalia arjuna* show satisfactory early growth and survival when these are supplied with supplemental saline irrigation but prove to be sensitive after the cessation of irrigation. *Cassia javanica* and *C. alata* are very sensitive to frost, whereas *Casuarina equisetifolia* could not survive drought due to the prevailing arid conditions. Some salt tolerant species are *Acacia ampliceps*, *A. stenophylla*, *Prosopis juliflora*, *Tamarix articulata*, *Salvadora oleoides* (Jal), *Salvadora persica* (Khara jal), *Suaeda nudiflora* (Untmarod), etc.

3.2.5 Rocky sites of sand stone

These are mostly hilly areas devoid of vegetation except for sparse growth of *Euphorbia* spp., *Acacia senegal*, *Anogeissus pendula* (Dhokra), *Zizyphus nummularia*, etc. Further, due to acute biotic stress such sites are just barren rocky with hardly any top soil for reforestation. It is necessary to select out spots having pockets of some soil depositions for plantations. By adopting effective soil conservation measures, such as rock bunding, contour dyke or contour trenches, such depleted sites can be planted with tree seedlings. Half of the pit can be refilled with imported soils (if no soil available) and the other half of the dugout soil is made into a crescent shaped ridge of 15 to 20 cm high across the slope to collect the run off rainwater. On shallow soil pockets and rocks crevices, seeds of good variety grasses or seeds of tree or shrub species can be dibbled to revegetate such patches. *Acacia tortilis*, *Prosopis juliflora*, *Acacia senegal*, *Butea monosperma* (Dhak), *Azadirachta indica*, *Albizia lebbek*, *Cassia siamea*, *Anogeissus rotundifolia*, *Comiphora wightii* etc are suitable species for such sites.

3.2.6 Degraded hills of Aravallis

Over-exploitation and unsustained vegetation removal induces land degradation in hilly tracts of Aravalli and Vindhyan regions of India. Many of the hillocks are exposed and devoid of any vegetation. Rehabilitation of these degraded hills is an essential requisite for eco-environmental improvement and to meet the basic needs of fuel wood and fodder in the region. Under rehabilitation of degraded hilly land with relatively better rainfall regime, sturdy seedlings of 9 to 10 months old should be planted in the pits provided with a crescent shaped microcatchment across the local slope or rainwater harvesting devices to arrest the run-off water during monsoons to make available soil water to the planted seedlings (Singh et al., 2013). *Acacia catechu*, *Gmelina arborea, Dalbergia sissoo* and *Bauhinia variegata* perform better whereas *Pongamia pinnata, Azadirachta indica, Dendracalmus strictus, Emblica officinalis* and *Holoptelea integrifolia* show moderate performance (Nandeshwar et al., 2006; Singh, 2013).

3.2.7 Degraded forestlands

Open or degraded forests with a canopy density between 10-25% or with large open gaps and are deficient in regeneration can be put under supplemental planting with high value native species. Besides the existing root stock of native species can also be nursed / nurtured to better health. Tree species suitable for dry deciduous forests are: *Azadiracta indica*, *Holoptelia integrifolia*, *Annona squamosa*, *Pongamia pinnata*, *Hardwikia binata*, *Albezia lebbek*, *Ficus bengalensis*, *Dalbargia sissoo*, *Ailanthus excelsa*, *Wrightia tinctoria*, *Steriospermum chelanoides*, *Boswella serrata*, *Emblica officinalis*, *Sterculia urense* and *Pterocarpus marsupium*. In relatively moist forests areas tree species like *Tectona grandis*, *Laegarstroemia lanceolata*, *Pterocarpus marsupium*, *Terminalia alata*, *Gmelina arborea*, *T. paniculata*, *Dalbargia latifolia*, *Dolichandrone falcata*, *T. belerica*, *Bambusa arundinasia*, *Butea monosperma*, *Madhuca latifolia*, *Santalum album*, *Emblica officinalis*, *Syzygium cumini*, *Grevia tiliifolia*, *Careya arborea* and *Terminatia chebula* can be planted. Suitable species for semi evergreen and evergreen forests are: *Pterocarpus marsupium*, *Dalbargia latifolia*, *Vateria indica*, *T. belerica*, *T. arjuna*, *T. paniculata*, *Bambusa arundinasia*, *Dendrocalamus strictus*, *Vitex ultissima*, *Machilus macranta*, *Veteria indica*, *Syzygium cumini*, *Artocarpus heterophyllus*, *Ailanthus malabaricum*, *Mangifera indica*, *Garcinia indica*, *Garcinia gummigatta* etc.

3.2.8 Mine-lands and overburdens

Mine areas like gypsum, bentonite, Fuller's earth, arid clay soils, limestones etc can be rehabilitated with species of trees, shrubs and grasses such as *Prosopis juliflora*, *Salvadora persica*, *A. tortilis*, *Albizia amara*, *Parkinsonia aculeata*, *Dichrostachys nutans* and *C. decidua* (Rao and Tarafdar, 1998; Sharma et al., 2000; 2001b, 2004). In this *Salvadora oleoides*, *Colophospermum mopane* and *Pithecellobium dulce* are calcium-loving plant and suggested for rehabilitation of gypsum mine spoil (Rao and Tarafdar, 1998). However, in the context of agro-and socio-economically relevant properties as well as with respect to environmental outcomes the highest frequency of occurrence have been reported for *Pongamia pinnata*, *Dalbergia sissoo*, *Albizia lebbeck* and *Azadirachta indica* in rehabilitating mined landscapes (Datar et al., 2011).

3.2.9 Avenue plantations

Avenue plantations along the high ways consist of planting 3 staggered rows of trees on either side of the road. For this, circular pits of 60 cm diameter and 90 cm depth along with a circular trench of 3 m diameter with dimension 60 cm width and 60 cm depth are very effective for road-side plantations but appropriate protection is must. The soil from the circular ditch is deposited on the berm. This operation should be completed before the end of June so that the dugout soil is thoroughly allowed to weather. Prior to the commencement of rains, these pits are refilled with the weathered soil mixed with 3 kg farm yard manure per pit. Planting is generally done on receipt of a good soaking shower. Immediately after planting 9 to 12 months old tree seedlings, each pit has to be watered at @ 18 litres per pit. In case of failure of rains after the planting is done, regular watering at 18 litres per plant/pit should be given once a fortnight till the plants are established. Complete protection against browsing animals has to be ensured by fencing individual plant with thorns or with tree guards. The plantings should consist of a shade row at 9.6 m away from the centre of the road. The second and third rows are successively planted depending upon the availability of the land and applicability.

3.3 Preparation of the planting site

Site preparation is directed towards giving the seedlings a good start with rapid early growth. In general, the methods used to achieve site preparation varies with the type of vegetation, amount and distribution of rainfall, presence or absence of impermeable layers in the soil, the need for protection from desiccating winds, and scale of the planting operations. Additionally, the value of the tree or shrub crop to be grown is important in determining the amount of expense that may be justified in plantation establishment. Site preparation includes removal of existing competing vegetation from the site; creation of conditions that enable the soil to catch and absorb as much rainfall as possible; reduction in surface runoff to increase the moisture in the soil, providing good rooting conditions for the plant including a sufficient soil volume and creation of conditions where danger from fire and pests is required to be minimized. Elimination of hardpans should also be taken care of.

Preparation of plantation site by hand is possible and economical only for relatively small-scale plantation, and where the labour of clearing the vegetation and working the soil is not too time-consuming. Under certain conditions, animal-drawn ploughs and harrows are economical for small-scale operations. Mechanical soil preparation is used in case of large-scale planting programmes. Some operations like deep sub-soiling and the breaking up of hard pans are carried out by use of machines/bulldoser. In 'steppe' method of site preparation, the surface of the soil is modified by breaking-up and stirring the deep layers of the soil with rooters, rippers, or large discs, and then building widely-spaced, parallel ridges following the contour line. The ridges are made with the topsoil and the seedlings of trees or shrubs are planted on the lower half of the ridges facing the slope, where the depth of moist soil is greatest because of accumulation of run-off water. The purpose of this method is to maintain sufficient soil moisture in the deep soil profile. Spacing between the ridges is greater with lower rainfall, as the catchment area between the ridges is increased.

3.3.1 Soil preparation

Soil preparation can be done in patches, strips or by complete cultivation. In this complete cultivation is more appropriate for tree and shrub species which are intolerant of competition from deep rooting grasses and woody growth, though spot preparation may also be sufficient sometimes, but such spots should be large (i.e., 1 to 1.5 m in diameter). Other methods of soil preparation are ash-bed method, tie-ridging, contour trenching and terracing, and the steppe method.

3.3.1.1 Ash-bed technique: In this debris from the harvesting or clearing of the land are piled into long lines or stacks. These debris are burned after drying and seedlings are planted in the ash patches. In some cases the lines or stacks of debris are covered with clods to obtain a more intense heat during burning. Advantages of this method are that it kills the competing vegetation and the area remains free of these vegetations for a considerable period of time, whereas ash provides a useful fertilizer for the planted seedlings.

3.3.1.2 Tie-ridge technique: This involves the cultivation of the complete area and the creation of soil ridges at specified intervals. The main ridges prepared along the contours are joined together by smaller ridges at right-angles to create a series of more-or-less square basins for retaining rainwater and preventing soil erosion. In general, the ridges are prepared 3 m apart though varies with slope gradient. In this seedlings of trees or shrubs are planted on the ridges. This method is relatively more suitable for flat or gently sloping area and can also be cropped during the initial years of plantation establishment.

3.3.1.3 Trenching techniques: Preparing trenches along the contours are also part of site preparation particularly in hilly regions. These trenches may be continuous, divided by cross banks, or consist of short discontinuous in lengths. These may be arranged in such a way that the gaps between the trenches in one row are opposite to those in the next row so that maximum runoff from rainfall could be harvested. The trenches are formed manually or mechanically depending upon the availability of resources and labour at the site.

***3.3.1.4 Terracing or gradonie ditches*: These structures are wider and flatter than trenches and can be created either manually or mechanically on the side of a hill by digging soil from the uphill slope area and depositing it on the downhill slope. In general, bottom of the terrace is made in such a way that it slope is towards the hillside (Afridi, 1951). The main objective of this technique is to retard the velocity of runoff and collection of rainwater between the terraces. These terraces provide improved conditions for establishment and growth of planted seedlings because of the increased soil water. Seedlings are planted on the ridge of the soil, at the base of the ridge, or in patches at the bottom of the trench depending upon the soil water conditions. These structures are used widely on moderate to severe slopes, i.e. 10-26% slope. Terraces can be 2 to 3 m or several hundred meters in length, but if short, they can be staggered on the hillside. Sometimes, crescent-shaped terraces are also constructed with the two tips of the crescent pointing uphill side for effective collection of the run-off.

3.4 Plantation density

Trees or shrubs are planted in such a way so that their root system does not compete with each other for soil water, soil nutrients and the light. Trees are planted at varying spacing (distance) depending upon types of plantation like blocks to develop woodlands, orchard, shelterbelt, boundary plantations or live fencing around a farmland (Kasera et al., 2003a; Singh et al., 2004). To ensure sufficient sunlight and airflow, it is generally suggested to plant the trees in an east-west direction particularly on farmlands. In case of alley-cropping system, trees or shrubs are planted at 10 m distance between the rows. Some trees/shrubs are also spaced in a line one meter or lesser distance in order to create a live fence. Trees are also planted to provide support for climbing crops such as pole beans, although only mature trees are used for this purpose as the vine growth can choke off the young plants. Plant spacing depends upon the types of species (smaller, medium or large size trees) and their utilization pattern. A spacing of 4 m x 4 m or 3 m x 5 m apart between rows and plants is suitable for the species smaller in size and are used for leaf, pod and seed production. For the tree species medium in size like *Ailanthus excelsa*, *Azadirachta indica* etc, 5 m x 5 m spacing will be sufficient that requires 400 plants per hectare (Fig 10.1).

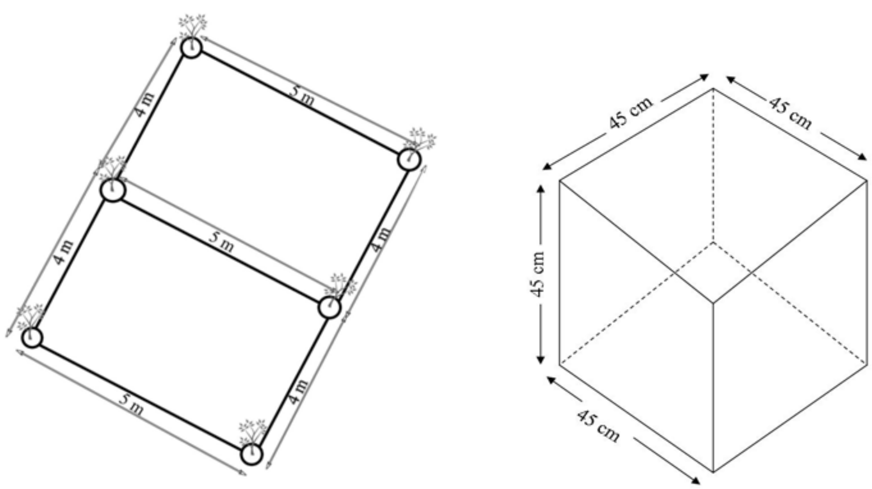


Figure 10.1 Layout and espacement between the planted seedlings (left) and pit dimensions for plantation (right).

For species having large and dense canopy architecture, such as *Madhuca indica*, *Ficus* spp., *Mangifera indica*, *Artocarpus heterophyllus*, *Dendrocalamus hamiltoni* etc., the spacing can be 7 m × 7 m accommodating 205 plants per hectare or even more go up to 10 m × 10 m or 100 plants per hectare (Table 10.5). In dry regions of western India, a closer spacing of 3 m × 3 m (1,100 plants per hectare) is considered better if the primary goal of plantation is soil stabilization or conservation. If the objective is to plant along riverbanks or to protect an area from landslides and avalanches, the spacing can also be 3 m × 3 m, 2.5 m × 2.5 m or even closer (Table 8.5). In such cases, a mix plantation of relatively fast-growing species will be more appropriate. Thus plant density depends upon the spacing finalized and can be calculated as:

$$\text{Total plant per ha (TPH)} = 10000/\ S_{wr}\ (m) \times S_{br}\ (m)$$

$$\text{At 4 m x 5 m spacing TPH} = 10000/20 = 500 \text{ tree}$$

Here TPH is total plant per ha, S_{wr} is spacing within the row and S_{br} is spacing between the row of plantation.

Table 10.5 Tree species, suitable pit size and espacement under plantation.

Species	Spacing(m)	Pit size (cm^3)	Manuring/Reference
Eucalyptus spp.	3 × 1.35	45 × 45 × 45	Neem based nutrients to avoid termite attack -50 g of phosphate and 250 g of Vermi-compost or FYM per pit
Guadua angustifolia, *D. asper* and *D. brandisii*	5 × 5	For offsets and rhizomes 60 × 60 × 60 to 100 × 100 × 100. For seedlings and branch cuttings 30 x 30 × 30 or 45 × 45 × 45	Approx. 5 kg FYM, 100 grams urea, 100 grams super phosphate, and 50 grams muriate of potash.
Mangifera indica	7.5 × 9	90 × 90 × 90	50 kg FYM + 1 kg SSP + 1 kg Neem Cake and 100 gm 10% Follidol dust per pit.
Shorea robusta		45×45×45	FYM 2 kg and Neem cake powder 100 gm
Tectona grandis	2 × 2, 2.5 × 2.5 or 3 × 3	45×45×45	Farm Yard Manure and insecticides. On poor gravely sites replacement of soils.
Ailanthus excelsa	4 × 2.5 or 10 × 10	45×45×45	Jat et al. (2011), Singh and Rathod (2002), Singh et al. (2004), Singh et al. (2013)
Acacia tortilis *Eucalyptus hybrid* *Acacia nilotica* *Dalbergia sissoo* *Zizyphus mauritiana* *Prosopis cineraria*	4 × 5	45×45×45 or 60 × 60 × 60	
Melia dubia	3.5 × 3.5	60 × 60 × 60	
Simarouba glauca	2 × 2, 2 × 4 2 × 10	45×45×45	http://ageconsearch.umn.edu/bitstream/43624/2/Simarouba%20brochure,%20UAS%20Bangalore,%20India.pdf
Madhuca indica	9 × 9 or 10 × 10	30 × 30 × 30	

3.5 Layout design of plantation

System of layout and distance among the plants is decided according to requirements. For laying out of a plantation on a level land is a matter of establishing a straight baseline, usually next to the fence or pathway. Then, lines at right angles to the baseline are established at both ends of the plot and one or two places in the middle. These lines can also be established using three ropes whose lengths are in 3:4:5 proportions (a right angle triangle). In this 4 m rope can be put along the baseline and 3 m rope at approximately a right angle, and finally closing of the triangle with the 5 m rope. The 3 m segment should be adjusted in such a way that it just touches the end of the 5 m rope piece, but it should also be ensured that the 3 m rope is at a right angle to the 4 m rope baseline. Subsequently, stakes should be placed along the baseline and the right angle line for sighting to extend these lines. From this point a desired row and tree spacing can be established using a measuring tape or knotted and measured rope at the proper intervals. When boundary lines are drawn, it becomes easy to divide the whole plantation area into squares or rectangles with their sides equal to the planting distance. In hexagonal pattern of layout, two chains equal in length to the planting distance are used. These chains are joined together by a ring. Two rings are also attached to the other two ends. Thus the connected chain is equal in length to double the planting distance with one ring at centre and two rings at either end. First of all stakes should be placed on the base line at appropriate distance. Then, the two rings at the ends are fixed in the two adjacent pegs on the base line and the chain is pulled tight holding the centre ring in hand. This tightened position is held and a stake is fixed in the centre ring. This way another row of trees can be marked out and this can be used as base line for marking out a third row. In triangular planting, the markings are made as in the square or rectangular systems, except that those in the even numbered rows are mid-way between, instead of opposition in old pattern.

A sloppy land requires contour layout using a surveyor's level and rod. The first row is at the highest elevation, and is staked out on the line at the same elevation. Next, the steepest slope along the first row is observed and the distance that has been selected as the minimum distance between the rows is measured down the slope. From that point the next row is laid out on a level line as staked before. Moving away from this steepest slope to less-steep slopes, the rows are wider apart. Wherever, the distance between two adjacent rows becomes twice the minimum distance, short contour row is laid out between them that point to the end of the plot.

3.6 Pit excavation and refilling

Proper digging and filling of pits in which seedlings have to be planted is one of the critical determinants of growth and productivity of forests or fruit tree species. After finalizing the plantation design, a wooden stick is pegged into the ground where a pit is to be excavated. The peg is used as the centre to mark out a square of required dimensions. Planting pits are dug to aerate and loosen the soil in which the seedlings are going to be planted. In general, pits for plantation should be kept ready before the onset of monsoon. Exposure to the sun's rays kills pests in the soil and facilitates soil weathering. In general, the width of the hole should be at least 3 times the diameter of the plant container. The earlier the pits are dug; the better will be the expected result. Following steps are follows while pit excavation:

- Pits of 45 cm x 45 cm x 45 cm dimensions are dug out. However, pit size varies with prevailing soil and environmental conditions and the types of species to be planted. For example, the dimension of 1m × 1m × 1m is suitable for the saplings of *Mangifera indica*, *Artocarpus heterophyllus* spp. etc., 0.6 m × 0.6 m × 0.6 m for cashew, and 0.3 m × 0.3 m × 0.3 m for many multipurpose tree species (Table 10.4).
- Digging is done according to the dimensions prescribed but while digging pits in poorly drained clay soil, it is important to avoid glazing, i.e. smoothening of the sides and bottom of pit affecting water movement.
- The dug up top soil is to be collected in a heap on the upper slope of the pit so that during the event of pre-monsoon rains, the fertile soil flows back into the pit with the rainwater.
- The wooden stick should be pegged on the heap of the soil as a mark of identification of the pit site.
- The gravel and stones portion of the dug out from the pit are piled separately, whereas the second layer of soil is heaped outside the pit on the opposite side of the first layer, i.e. downside of the slope.
- Care must be taken to maintain the length and breadth of the pit from the top to the bottom of the pit while excavating the pits.
- Pit-filling should be undertaken towards the onset of monsoon after the pits and the excavated soils have been exposed in the sun for sufficient period. If possible, biomass waste could be collected in advance and put in the excavated pits for making compost. Linden powder, neem cake, vermicompost/farmyard manure and bone meal could also be are also used while filling up pits for enhanced establishment and growth of the plantation.

Sometimes, round-bottomed pits of 1-m depth and 1 m width or pits of size 75 cm × 75 cm × 75 cm are dug out depending upon the types of species, i.e. horticultural species. The surface soil and other layers of soil are also disposed separately and the soils are put back at the bottom of the pit well before planting. About 50 to 100 kg of grass, manure and rubbish, 50 kg of organic fertilizer and 0.5 kg of phosphorus are mixed with the rest of the soil and put back in the pits. In hard and stony soils, a pit of size 1 m × 1 m × 1 m or 90 cm × 90 cm × 90 cm is excavated. Filling of the pit is done with top fertile soil or imported good soil. Well decomposed and powdered cow dung or compost at the rate of 12 kg and rock phosphate at the rate of 175 g per pit can also be mixed with the soils in the pit. In areas with exposed rock, artificial explosion or double blasting technique can be applied, where a pit of depth 1 m and a diameter of 2-3 m is blasted and the debris is taken out of the pit. The second blasting is done even deeper layer, but the debris of the second blasting left as such in the deeper portion of the pit. Then good quality soil mixed with organic manure is put into the pit into which a seedling is planted and watered. The nitrogen from the explosion powder remains in the pit after explosion thus increasing the nutrients for fruit tree growth. During refilling of the excavated pit following steps could be followed:

- First of all, insecticide/termiticide powder is sprinkled on all the sides of the pit to destroy termites in the soil.
- The top soil that had been dug out is added as the first layer. In case of poor quality soils, good fertile soil from the bank of a river/ stream or farmlands is collected and added to the pit for improved establishment and growth.
- Another mix of insecticide powder, FYM and soil is prepared and added into the pit followed by a mixture of Neem cake and soil.
- After filling up the pit, a wooden stake is pegged in the centre of the pit, which is the spot for planting the seedling.
- A heap of soil around 15 cm high is made around the peg so that this soil can settle in the pit with the rains.

3.7 Time of planting

In general planting season matches with the rainy season. Planting activity should be started as soon as a specified quantity of rain has fallen. This amount of precipitation must be judged on the basis of local knowledge and the people experiences. Planting can also be started when the soil is wet enough to a specified depth, i.e. 20 cm soil depth. Early planting, i.e. before monsoon may lead to summer desiccation. On the other hand, if planting is started too late, it may be difficult to complete a large planting programme in the scheduled time, and the plants will lose the maximum benefit of rains after planting. This is a matter of serious concerns particularly in the area where the rainfall is low and erratic as well.

3.8 Plantation

Seedlings generally provided for field planting are contained in either plastic bags or container or some time as bare roots. These seedlings are available in a predetermined number and species mix for the particular site. The plastic bags should be divided during packing to allow more convenient handling at the plantation site. Hand-planting using a small border spade is more appropriate. The use of planting machines however is a logical step. A quick-wood planter is also used for the shorter planting runs. In the case of metal or plastic containers, complete removal of the container in necessary. In the case of fiber containers, the sides may be split up, whereas the plastic bags should be removed carefully at the time of planting the seedlings. In all circumstances, disturbance of the soil-root association should be avoided during planting. While putting the root-balls of seedlings into the planting hole after removing the seedlings from the containers or polybags, the planting holes should be large enough to take the containers or the root-balls and seedling should be planted by placing the root collar at the soil surface line or slightly deeper (root collar is a spot located just above the roots identified by a change in color or slight swelling of the main stem). Too deep or too shallow planting and bending of roots in pits should be avoided. In case of bare root planting, the planting hole or slit should be deep enough to accommodate the seedling's root system properly, where the roots should hang freely in the planting hole and should not be bent or twisted. Once the seedling is seated in the pit, the original soil is then back-filled into the pit to the soil level of the collar zone and the surrounding soil should be firmed down immediately to avoid the formation of air gaps which can otherwise lead to root desiccation (Fig 10.2).

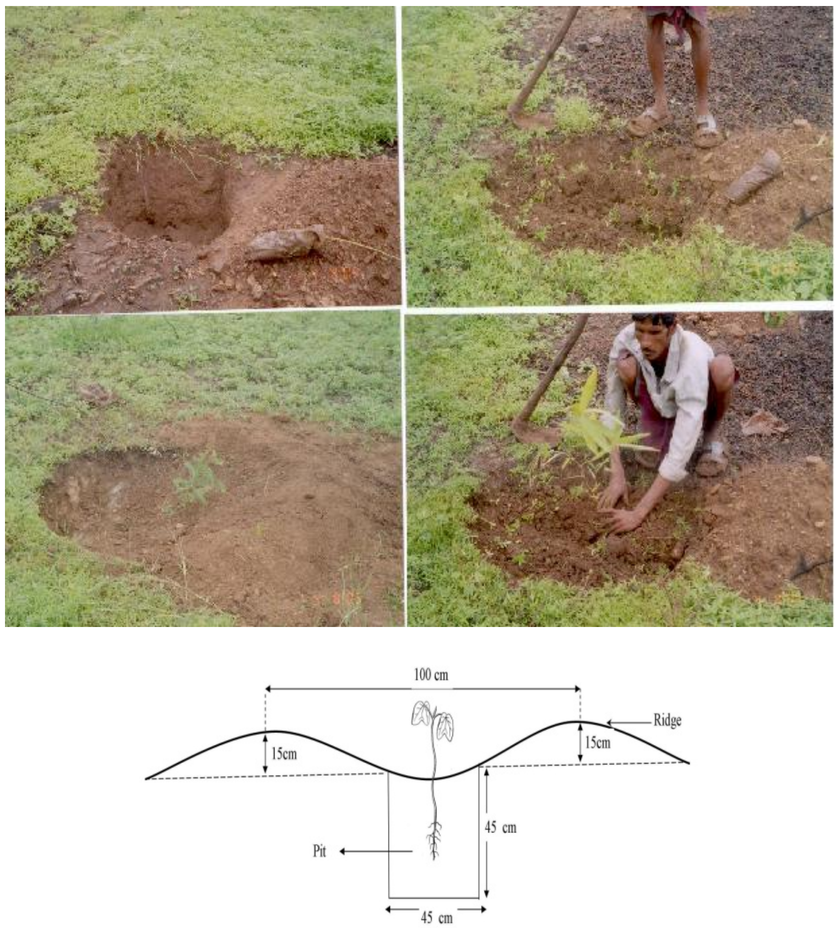
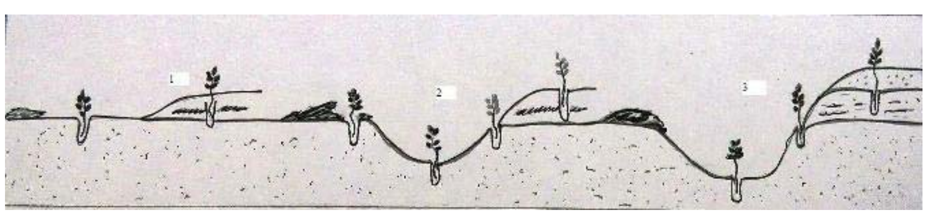


Figure 10.2 Pitting of size 45 × 45× 45 cm^3, refilling of pit with scraping of top soil and mixing with FYM and insecticide, planting of *Dendrocalamus strictus* seedlings and development of a micro-catchment for *in-situ* water harvesting (top). Pit size, plating position and surrounding micro-catchment in plain area (bottom).

It will be beneficial to prepare a small ridge (15 to 20 centimeters in height) of soil around the pit to obtain a small basin (about 80 to 100 centimeters in diameter); this is especially helpful when the plants are watered individually after planting. However, in sloppy area, a small basin/depression can be provided in upslope area of the planted seedling to accommodate rainwater to facilitate establishment and growth of the planted seedlings (Fig 10.2). A long-stem planting method is also in way that can result in higher survival and growth rates with minimal post-planting care. In this, seedlings are grown in pots for 10-18 months, so that they develop long woody stems and are then planted with about three-quarters of their length below the soil surface, i.e. 1 meter deep, where much of the woody stem is being covered with soil (Anon., 2010). The long-stem planting has been used in stabilizing sand dune with great success for both survival and growth of the plants (Bakewell et al., 2009).

3.9 Planting position

Choice of planting spot is crucial influencing seedling establishment and success of the plantation. Berm or hinge planting, mound planting or deep/furrow planting are different position where the seedlings are planted. Performance of the planted seedlings depends upon soil and climatic conditions of the site and availability of soil water and nutrient. High planting positions on a well drain mineral soil covered with humus berm or mound are often recommended because of improved nutrient supply, favourable soil temperature during the growing period, and better soil structure in the root zone compared with planting in mineral soil patches, pits and furrows (Örlander et al., 1991). On the other hand, mound planting or planting at the elevated positions at the same site results in post-planting water deficiency particularly during dry seasons (Fig 10.3). While seedling roots in mounds are exposed to lower and more fluctuating temperatures in winter, i.e. conditions associated with frost injury and frost heaving, a low planting position should be avoided in areas of water stagnation. Deep planting however, appears better alternative to mounding particularly in sandy dry areas because of higher soil water availability and reduced effects of desiccated hot winds and temperatures in the regions (Hallsby and Örlander, 2004), but deep planting or furrow planting may be harmful if soil is clayey because of compaction and water stagnation (Singh et al., 2006). Mound planting is generally preferred in area affected by waterlogging or water stagnation for a relatively longer period in a year (Gafni and Zohar, 2007; Roy Chowdhury et al., 2011). While testing various planting positions like furrow planting, hinge planting, planting without site preparation and mound planting, Karlsson (2009) observed lowest and highest mean tree height on control and mounded areas, respectively. Furrow planting affects survival and mean height in a negative way while hinge planting improves survival and mean height. Hinge planting offers an environment where seedlings are protected from wind, frost heaving and erosion while they at the same time are offered an adequate water and nutrient supply.



1-Patching 2- TTS trenching 3-Mounding

Figure 10.3 Planting positions of seedlings depends upon types of species and soil and prevailing environmental conditions.

4. POST PLANTING CARE

4.1 Mulching

The small basin prepared around the planted seedlings can also be covered with organic mulches of locally available vegetative materials (Gupta, 1995) or a plastic sheet (held in place on the ground with stones or soil), with an opening in the center for the plant. Such mulches impede evaporation of ground water from the planting hole. Through conservation of soil moisture, the plastic films facilitate more rapid establishment and growth of trees and shrubs during the initial years of establishment, while organic mulches improves microbial activities enhancing soil nutrient supply. Another benefit of opaque plastic films or thick organic mulches is that they inhibit weed growth by reducing light penetration. With the suppression of weeds in the immediate vicinity of the planted seedling, the labour component can also be reduced by doing so.

4.2 Water conservation and irrigation

A threat to newly-planted trees in dry area is the high rate of transpiration and evaporation as well. Unless the plants can establish themselves quickly and compensate for the transpiration by taking water through their root systems, they use to wilt soon after planting. Thus irrigation immediately after planting is generally beneficial unless there is rain during plantation or just after the plantation. In such a circumstance, containerized seedlings have a distinct advantage over bare rooted seedlings, where the earth ball surrounding the roots provides protection during transport and enables the plant to establish itself quickly and easily (Ken and Chikamai, 2014). Irrigation depends upon the time of tree planting, soil type and seasonal conditions. A combination of late planting, low rains and a light-textured soil suggest the need for watering. To prevent water stress and plant death, an observant skill is necessary to predict the timing of watering. A supplemental irrigation should be provided for as long as possible, perhaps at every fortnight for the first three months and then once a month for two summers. For limited watering, if plantation has been carried out during rain of July, there is no need to water just after planting; otherwise first watering of 30 liter per plant is done immediately after the plantation in dry region. Subsequent watering should be done in second to third week of October as temperature rises during post rain period. After taking protective measure for frost and heave during winter months of December to January, a third watering in second to third week of February boost the spring growth, while fourth watering in April to May is beneficial in protecting the seedlings from summer temperature and hot winds. Survival counts taken in December and June suggest that most seedling deaths occurs during summer, and that if a plant survives to mid-summer, then there is a good chance that the plant will continue to grow in the second year rains. Plastic bottles can be placed on the ground next to the base of seedling in an upside down position (the top must be covered to avoid the water getting hot and thus scotching the seedlings) for irrigation. Tests in the Colorado, Mojave and Sonoran deserts have proved the values of different methods of irrigating the planted seedlings, i.e. deep pipe, buried clay pot, wick, porous capsule, porous hose, perforated pipe etc. which also be applicable in other similar regions including

Indian desert (Bainbridge, 2001; Stein, 1998; Kurian et al., 1983; Mari Gowda, 1974; Bainbridge and Virginia, 1990; Bainbridge, 2007; Shiekh and Shah, 1983).

Various combinations of traditional planting holes, water-harvesting micro-catchments, stone or plastic mulches, small plastic sheets to increase water harvesting, dry wells, buried clay pots and deep irrigation can also be applied to enhance soil water availability, seedling survival and growth (Silva et al., 1981; 1985). Waterproof plastic sheets enhance water harvesting by 43% and soil moisture in the planting pit by 40% during low-intensity rainfall (Valdecantos et al., 2014). Application of composted sludge also improves seedling growth at the least water-stressed site. Conservation tillage and the subsoil planting rows along the contour facilitate trapping of run off on gentle sloping areas. On the other hands, use of water harvesting structures to concentrate water around the seedlings in W-shaped (in areas with minimal rains) or V-shaped (in areas with slightly higher rains) structures can be beneficial.

4.3 Weed control

Effective ground preparation provides a weed free planting environment. The plastic mulch used to control weed growth adjacent to the seedling increase plant vigour significantly and contributes slightly to increase survival. The plastic mulch is a sheet 1 m square and 0.075 mm thick and it has a 50 mm hole punched in the centre. It is laid after planting and formed into a saucer-shaped depression (i.e., about 15 cm deep) around the seedling. A small border spade is used to press the plastic into the soft ground. Alternatively, manual weed removal from vicinity of the seedlings (3 m diameter) can also be done particularly during September to October to avoid competitive effects of the weed on the planted seedlings.

5. COST OF PLANTATIONS

The estimated cost of plantation based on practical experience with regard to output of labour, cost of materials etc. in Rajasthan (Table 10.6). The estimate is presented below:

Table 10.6 Cost of planting and labour involvement in afforestation activities (Ist year) in dry areas of Rajasthan. Labour wages has been calculated on the basis of July 2015 for 1 ha area.

S. No.	Activities	Unit	Quantity	Amount	
			Labour	Labour	Materials
1.	Survey and demarcation of the plantation area	Man days	1	206	
2.	Cleanings	Man days	5	1030	
3.	Digging of Pits of size (45 × 45 × 45 cm)	Man days	45	9270	
4.	Filling up of planting pits with FYM up pulverized soil	Man days	15	3090	

S. No.	Activities	Unit	Quantity	Amount	
			Labour	Labour	Materials
5.	Cleaning the plantation area before planting	Man days	4	824	
6.	Local carriage of seedling				1500
7.	Transplanting of potted seedlings	Man days	10	2060	
8.	Infilling of vacancy created due to field mortality including carriage	Man days	4	824	
9.	Thawla making around pits (1m dia.) and cleaning and weeding	Man days	26	5356	
10.	2nd cleaning, weeding and hoeing	Man days	12	2472	
11.	Cutting fire lines 3 m wide to prevent accidental fire	Man days	6	1236	
12.	watch and ward	Man days	6	1236	
13.	Making livehedge fencing	Man days	3	618	
14.	Cost of insecticide, fertilizer including carriage	LS			5000
15.	Subtotal				
16.	Contingencies Rope/tin/watering can/thatch & carriage of seedling etc (5 %)	LS			
	Total			Rs. 28222	Rs.6500
	Grand Total			Rs. 34722	

6. CONCLUSIONS AND RECOMMENDATIONS

Plant production is brought out to deal with the issues of environmental protection, forest production, tree improvement, ecosystem balance, forest regeneration etc. A quality planting stock helps to influence field survival and productivity of plantation positively. The most appropriate species for a given site should be selected after reviewing survival and growth and availability of water as well. Further, knowledge about physical and environmental conditions of site, plant species water demand, labour skill and availability, resources and financial plan are some important criterion for a plantation programme. To meet the increasingly high demands of quality planting material, a number of methods are applied to propagate plants, i.e. through macro and micro-propagation. Under macropropagation, cuttings, layering, grafting, budding or by using plant modified organs can be used for plant production of desired characteristics. Micro-propagation provides an opportunity for large-scale multiplication of plants of various tree species. It has however, several limitations like involvement of high cost, requirements of skilled manpower and lack of effective protocols for the desired species.

Suitably selected tree species depending upon site conditions, soil preparation, plant espacement, pit size and different soil amendment help successful seedling establishment and plantation growth. Though there is always scarcity of water in dry areas but some trees or shrub species are more sensitive to drought or even short dry spells. For this providing good soil condition though amendments, soil replacements and soil preparation help store soil moisture to ensure survival in the next growing seasons. Planting positions like hinge planting, mound planting and deep or furrow planting can be suitably selected depending upon soil and environmental conditions. However, control or removal of existing weeds and intrusion of livestock is also necessary for a successful plantation.

Unless the plants can establish themselves quickly and counterbalance the transpiration by taking water through their root systems, they should be watered immediately after planting. Use of organic matter or plastic sheets reduces water loss and weed growth and speed up plants establishment. However, supplemental irrigation should be provided for as long as possible, perhaps at every fortnight for the first three months and then once a month for two summers or at least 4 irrigation under limited water supply. Various combinations of traditional planting pits, water-harvesting devices, stone, organic or plastic mulches, plastic sheets to increase water harvesting, dry wells, buried clay pots and deep pipe irrigation enhance soil water availability and facilitate seedling establishment and growth. Thus effective and efficient irrigation systems should be considered for much wider use in restoration forestry, agroforestry, agriculture, landscaping and revegetation programmes.

11

WATER MANAGEMENT AND IRRIGATION IN DRY REGION

Even with ample spatial and temporal variations, the rainfall sustains most of the prevailing ecological systems and societies on variety of dry lands throughout the world. For tropical situations like India, the rains happen to be the vital source of water to meet more than 75 % crop water requirements. The recent climate change have accelerated and magnified the water scarcity over large areas of the country, with which the extent of drylands is enhancing. On these lands, at one hand the vegetation cover is consistently depleting, while on the other hand more than 20-40% of rainfall is being lost in the form of runoff. This enhanced runoff led to high magnitude of sediment and nutrient losses from such degraded lands. The extent of uncertainties in climate and in particular the rainfall, adds fuel to the fire. One such growing scenario is decreased number of rainy days but in-spite of that increased magnitudes of rainfall intensities. This altogether gives a tremendous scope for more effective management of *in situ* rainfall, which remains equally sensitive both towards being a potential source for agricultural water demands on one hand and as an active agent for soil erosion/degradation. It all together requires different kinds of soil and water conservation measures to facilitate rainwater harvesting measures in different dryland regions of India. It encompasses variety of measures under the two broad categories of mechanical and vegetative measures to deliver the functions like rain water harvesting and its recycling, *in-situ* moisture conservation, micro catchment improvements, drainage line treatments, and also the groundwater recharging. Such conservation measures/structures are adopted either alone or in combinations, depending upon the prevailing patterns of rainfall, land use, vegetation cover, physiographic details, soils, hydrologic parameters, water availability, and socio-economic, infrastructure conditions for rehabilitation of degraded lands. Present chapter describes various kinds of *ex-situ* and *in-situ* rain water harvesting and conservation structure for their judicious utilization in restoration and rehabilitation of degraded drylands, ensuring improvements in vegetation covers, adaptation to climatic abrasions and thus enhanced livelihoods.

1. INTRODUCTION

Rainfall is an important source of freshwater worldwide but it is much more vital in drylands. Variation in rainfall at both spatial and temporal scale is high in arid region followed by semi-arid and dry sub-humid regions (Moral, 2010). In spite of such variability rainfall widely sustains many ecological systems and societies build up in drylands (Pachpute et al., 2009). About 78% of water consumed by crops comes directly from rainfall (De-Fraiture and Wichelns, 2010). It remains a potential source for feeding the current population of the world if managed properly, though there are limitations to further increase of the area under irrigation. More than 20-40% of rainfall is being lost however, in the form of runoff, and the enhanced runoff lead to high magnitude of sediment and nutrient losses from degraded dry lands (Ram and Davari, 2010). The extent of uncertainties in climate and in particular the rainfall, adds fuel to the fire. Harvesting of rainwater reduces risks of production failure due to water shortage associated with rainfall variability in dry regions, and helps cope with more extreme events. Rainwater harvesting (RWH) enhances aquifer recharge and enables crop growth (including trees) in rainfall limited dry areas. On the other side, land degradation reduces soil productivity because of loss of plant-available soil water and nutrients and by non-uniform removal of soil from the area (Gupta et al., 2010). Mismanagement of soil and water is further exacerbated with increase in desertification affecting distribution and composition of plant communities (Gong et al., 2008).

Best options to control land degradation and reduce run-off losses are land rehabilitation by afforestation and promoting natural regeneration by increased soil water availability (Ngachan, http://www.kiran.nic.in/pdf/publications/Rain-water-harvesting.pdf). This can be an important contribution to an integrated approach to the planning and management of land resources, which may increase the vegetation cover and may become the base of a sustainable supply of fuel wood and fodder and improve environmental quality and other services to the growing population of dry areas (Kobayashi, 2004). Rainwater harvesting is particularly useful in improving soil water storage, prolonging the period of water availability, enhancing seedling establishment and herbage biomass production and thus helps rehabilitate degraded forestlands or rangelands (Cater and Miller, 1991; Singh, 2013). Micro-catchment water harvesting is effective in crop production (Li et al., 2000; Narain and Khan, 2002), tree growth (Gupta, 1995; Anon., 2014a) and forage yield (Jia et al., 2006) also. Water harvesting (i.e., the use of surface runoff for agricultural production) can form a viable complement to irrigate agriculture and forestry.

RWH has also been considered as mitigation and adaptation measure for the climate change. IPCC report of 2007 expected a decrease of 50% in yield of rainfed agriculture in Africa by the year 2020. Moreover, an increase in 5 to 8% of arid and semi arid lands is projected under climate change by the year 2080. In the countries with highest areas under arid and semi arid conditions the climate change is going to result in an increase in drought frequencies and will pose the greatest risks to agriculture (Sivakumar et al., 2005). Salas et al. (2009) reported many successful stories where RWH provides adaptation opportunities to climate change. For instance, it reduces degradation of ecosystems, energy use and greenhouse gas emission, increases water supply and productivity of rainfed agriculture, releases capital needed in time of a disaster and realizes millennium development goals. Drought is considered frequent visitor to dry areas particularly in arid region, where ground water exploration, development and abstraction is expensive and is beyond the reach of most of the farmers. The world is currently enduring water crises and in that circumstance rainwater harvesting (RWH) appears better option that can augment water supply in all sectors including drinking water (Parmar and Patel, 2014).

2. NEEDS OF WATER HARVESTING

Low availability of water in drylands limits establishment and growth of plantation and productivity of crops and forests. While scarcity of water leads large areas of drylands remain barren and bereft of vegetation, a significant portion of rainfall losses in the form of surface run-off. About 8.82 percent of annual rainfall reported to loss in some semi-arid region (Mandal et al., 2012), but in some rainfall events runoff losses are as high as 85 percent from a bare land (Ren et al., 2009). Harvesting, conserving and utilizing this formidable amount of run-off water judiciously could be invaluable in the region of acute water scarcity (Dey and Sikka, 2010). Water harvesting applied strongly depend upon local conditions and include widely differing practices i.e., bunding, pitting, micro-catchments water harvesting, flood water harvesting and ground water harvesting (Prinz, 1996). Geddes, as quoted by Myers (1975), gave the first definition of water harvesting as ‘The collection and storage of any farm-waters, either runoff or creek flow, for irrigation use'. The widely differing practices like farming terraced wadi beds, growing trees on micro-catchments, tapping subsurface runoff, and storing runoff behind a dam vary with local conditions (Boers et al., 1986). These techniques benefit forest growth, agricultural productivity, animal husbandry and above all improve quality of water resources in the watershed. Marked spatial variability in infiltration of water into the soil is very much related to the distribution of plants and redistribution of water from ridges to adjacent flats indicated by low rates of infiltration into bare soil areas between groups of trees and shrubs in the shrub invaded *Eucalyptus populnea* woodlands (Johns, 1981). Further, the potential rate of evapo-transpiration from the *E. populnea* component of the woodland was 0.5 times that from a free water surface. Bare soil evaporation accounted for approximately one half of water losses. Herbage production was poorly related to soil water storage alone, but the regression between herbage production and the product of water and nitrogen availabilities accounted for 70% of the variance (Johns, 1981).

Rainwater harvesting employ inducing, collecting, storing and conserving local surface runoff for multiple use like agriculture or forestry. There are three types of water harvesting: a) Water collected from roof tops, courtyards and similar compacted or treated surfaces is used for domestic purpose or maintaining garden crops; b) Collecting surface runoff from a small catchment area and storing it in a basin in the root zone of a planted, a bush or annual crops and such structure is called infiltration basin as it facilitate water infiltration into deeper soil profile; and c) Harvesting from external catchments where runoff from hill-slope catchments is conveyed to the cropping area located at hill foot on flat terrain or diverted for agriculture irrigation in downstream. Flood water harvesting is the collection and storage of creek flow for irrigation use. Flood water harvesting may be classified into: (a) floodwater harvesting-within stream bed, the water flow is dammed and as a result, inundates the valley bottom of the flood plain and thus water is forced to infiltrate and wet the area, and is utilized for agriculture or pasture improvement; and b) floodwater diversion where water is forced to leave its natural course and conveyed to nearby cropping fields as irrigation. Groundwater harvesting is a rather new term and employed to cover traditional as well as unconventional ways of ground water recharging and extraction.

Water harvesting increases yields of crops under rainfed agriculture (Hoff et al., 2010; Li et al., 2006). Besides, it yields numerous social and economic benefits and contributes to poverty alleviation and sustainable development of drylands. The need for rainwater has been growing tremendously in the dry regions, not only for crop production but also for livestock and household use. RWH minimizes the risk of crop failure during droughts, intra seasonal droughts and floods (Barron and Rockstrom, 2003); it reduces women's burden of collecting water for domestic use, leaving time for other productive activities and gives opportunity for the girl child to attend school and provides a relatively safe and clean source of drinking water minimizing incidences of water borne diseases (Ubuoh et al., 2012). When applied at watershed level, RWH improves the environment and minimizes the effects of drought and floods. Local communities who have capacity to invest in labour and time can do it effectively; however the systems are varied and can therefore be built according to the ecological conditions of the particular region (Oweis et al., 2001; SIWI, 2000). Hatibu and Mahoo (2000) demonstrated the importance of RWH to domestic water supplies, livestock, watering and crop production using examples and data from Tanzania. The researchers describe effective use of rainwater, noting that 98% of the crop production in Tanzania is rain-fed, where RWH is important as about 71% of crop failures are caused by droughts (33%) and floods (38%). De-Fraiture et al. (2010) reported the reasons behind encouraging investment in rainwater management in rainfed agriculture like (i) the large untapped potential to increase productivity especially in African dry lands, where poor rural people depend on it; (ii) investment costs in rainfed agriculture are lower than that of the irrigated one; and (iii) the high environmental and social costs that are associated with irrigation development. However, the sustainability of RWH is based on reliable water supply and production, effectiveness of water use and minimal negative impacts on natural resources in the locality (Pachpute et al., 2009).

3. RAINWATER HARVESTING AND UTILIZATION

3.1. Concept of rainwater harvesting

A wide range of water harvesting technologies are used to collect, store and provide water with the particular aim of meeting demand for water by humans or human activities (Barron, 2009). Increasing water provisioning capacity at a specific location makes possible management and use of water for multiple purposes in order to bridge dry spells and droughts - a common feature in dry areas. Rainwater harvesting technologies are divided into two main types depending on the source of water collected like *in-situ* and *ex-situ* techniques. *In-situ* rainwater harvesting techniques are soil management strategies that enhance rainfall infiltration and reduce surface runoff, such as terracing, pitting or conservation tillage practices. The rainwater capturing area in this is within the field where the crop is grown and the soil serves as capture and storage medium at the same time. It is implemented to counter soil erosion, to recharge soil water for crop and other vegetation grown in the area, or to recharge shallow groundwater aquifers for drinking and other domestic uses (CSE, 2000). *Ex-situ* techniques involve the systems with capturing areas external to the point of water storage. The capturing area varies from being a natural soil surface with limited infiltration capacity (rocky surface) or an artificial surface with low or almost negligible infiltration capacity (cemented or paved surface). Commonly used impermeable surfaces represent rooftops, roads and pavements. Storage systems are often wells, dams, ponds or low lying areas. These rainwater harvesting interventions are primarily to increase land production or to provide domestic, public as well as commercial supplies of water. The most important variables to be considered in identifying areas suitable for rain-water harvesting include rainfall, land use and vegetation cover, topography and terrain profile, soil type and soil depth, hydrology and water resources and socio-economic and infrastructure conditions.

3.1.1 Rainfall

Knowledge on intensity and distribution of rainfall for a given area helps in designing a water harvesting system. For understanding rainfall-runoff process and determination of available soil moisture a series of rainfall data in space and time and its distribution is required. A threshold rainfall event (e.g. 5 mm/event) is generally used in many rainfall-runoff models as a start value for runoff to occur. Thus intensity of rainfall is a good indicator of which rainfall is likely to produce runoff. Useful rainfall factors for the design of a rainwater harvesting system include: (a) number of days in which the rain exceeds the threshold rainfall, either on a weekly or monthly basis; (b) probability and occurrence (in years) for the mean monthly rainfall; (c) probability and reoccurrence for the minimum and maximum monthly rainfall; and (d) frequency distribution of storms of different specific intensities.

3.1.2 Land Use or Vegetation Cover

Vegetation is another important factor that affects the surface runoff. The studies in West Africa and Syria (Prinz et al., 1998) have proved that an increase in the vegetation density increases interception losses, retention and infiltration rates, which consequently decrease the quantity of runoff. A high degree of similarity also exists between density of vegetation and suitability of the soil to be put under cropping. A significant difference has been observed in water distribution between bare and vegetated area, which increases the depth of soaking and soil moisture. Though there is a sharp decline in water storage after increasing from 8.8% to 36.4% slope, but water storage differe significantly between gradual slopes (8.8 and 17.6%) and steep (26.8 and 3.4%) slopes (Huang et al., 2012). Recharge coefficient also increases with increasing vegetation cover but it declines with increasing rainfall intensity, slope gradient and initial soil water status (Huang et al., 2012).

3.1.3 Topography and Terrain Profile

The land form along with slope gradient and relief intensity is other variables determining the type of water harvesting. The terrain analysis is used for determination of the length of the slope, a parameter considered very high importance for the suitability of an area for macro-catchment water harvesting. With a given inclination, the runoff volume increases with the length of the slope in general. The slope length can be used to determine the suitability for macro- or micro- or mixed water harvesting systems (Prinz et al., 1998).

3.1.4 Soil Type and Soil Depth

The suitability of an area either as catchment or as cropping area in water harvesting depend strongly on its soils characteristics. These are: (a) surface structure that influence the rainfall-runoff process, (b) the infiltration and percolation rate, which determine water movement into the soil and within the soil matrix, and (c) the soil depth including soil texture, which determines the quantity of water that can be stored in the soil.

3.1.5 Hydrology and Water Resources

Water harvesting practices involving the production, flow and storage of runoff within a particular area are called hydrological processes. The rain falling on a particular area can be effective (as direct runoff) or ineffective due to evaporation or deep percolation. The quantity of rainfall, which produces run-off, is a good indicator of the suitability of the area for this purpose.

3.1.6 Socio-economic and Infrastructure Conditions

The socio-economic conditions of an area being considered for any water harvesting scheme are very important for planning, designing and implementation. The chances for success of such schemes are much greater if resource users and community groups are involved in the programme from early planning stage onwards. The farming systems of the community, the financial capabilities of the farmers, the cultural behaviour together with religious belief of the people, attitude of the farmers towards the introduction of new farming methods, the farmers knowledge about irrigated agriculture/ forestry, land tenure and property rights are the crucial issues.

3.2 Estimation of potential runoff yield

For designing appropriate conservation structures such as check-dams, diversion ditches or waterways, it is important to make an estimate of runoff. Runoff expressed in terms of depth is not convenient to determine the capacity of disposal structures. If one is planning to design a channel or a spillway to discharge a given amount of runoff, then it will be necessary to know how much of the runoff could be accommodated by that channel. One has to know what quantity of the water to be conveyed and at what rate. In natural catchments, rainfall is either intercepted by vegetation, infiltrates into the soil, starts moving over the surface as runoff or is lost through evaporation. The proportion of runoff for a rainfall of a given duration and intensity depends mainly on the vegetation cover or crop residues, the soil infiltration rate, water content and storage capacity, and the land slope. Peak runoff rate and quantity needs to be determined to avoid the risk of designing low or high capacity channels, rupture and overtopping of dams, overflow of bunds, channels and rainfall multiplier systems. For instance, low capacity channels are not beneficial as they allow overtopping, whereas high capacity channels entail unnecessary costs.

There are two methods used for estimating runoff rate e.g. rational formula and Cook's method. The rational formula is expressed as follows:

$$Q = CIA/360$$

Where Q is peak discharge in cubic meter per second, C is rational method runoff coefficient (between 0 and 1), I is rainfall intensity (mm/hour) for duration equal to at least the time of concentration of given drainage area, and A is drainage area in hectare. It is used to calculate the peak discharge for small catchments. While using the above formula, the following points should be noted: runoff coefficient is the proportion of total rainfall that is expected to become runoff during the design storm. Runoff = Rainfall – Infiltration. It is determined from a table by looking into the watershed surveying results. The runoff coefficient depends upon land use and soil surface structure including vegetation (Table 11.1 and 11.2).

Table 11.1 Runoff coefficient values for use in rational formula in quantifying volume of runoff.

Land use	**Topography**	**Soil type**			
		Sandy loam	**silt loam**	**Clay**	**Tight clay**
Cultivated land	Flat land (0 -5 %)	0.30	0.10	0.10	0.40
	Rolling land (5 – 10 %)	0.40	0.16	0.25	0.50
	Hilly land (10 -30 %)	0.52	0.22	0.30	0.55
Pasture land	Flat land (0 -5 %)	0.50	0.30	0.30	0.65
	Rolling land (5 – 10 %)	0.60	0.36	0.35	0.65
	Hilly land (10 -30 %)	0.72	0.42	0.50	0.80
Forest land	Flat land (0 -5 %)	0.60	0.40	0.40	0.40
	Rolling land (5 – 10 %)	0.70	0.55	0.50	0.50
	Hilly land (10 -30 %)	0.82	0.60	0.60	0.55
Developed areas (villages)	Flat land (0 -5 %)	0.30	0.10	0.1	0.65
	Rolling land (5 – 10 %)	0.40	0.16	0.25	0.65
	Hilly land (10 -30 %)	0.52	0.22	0.30	0.80

Source: Hudson (1995).

Table 11.2 Effects of land uses and surface structure on run-off co-efficient.

SNo.	**Land use**	**Runoff coefficient (C)**
1	Lawn	0.05 - 0.35
2	Forest	0.05 - 0.25
3	Cultivated land	0.08 - 0.41
4	Meadow	0.10 - 0.50
5	Park, Cemeteries	0.10 - 0.25
6	Unimproved area	0.10 - 0.30
7	Pasture	0.12 - 0.62
8	Residential areas	0.30 - 0.75
9	Business areas	0.50 - 0.95
10	Industrial areas	0.50 - 0.90
11	Asphalt areas	0.70 - 0.95
12	Brick streets	0.70 - 0.85
13	Roofs	0.75 - 0.95
14	Concrete streets	0.70 - 0.95

Source: Sahoo and Choudhury (2012)

4. RAIN WATER HARVESTING AND CONSERVATION

Relatively wetter parts of an area in general are more prone to water erosion. Vegetation cover on farmland, forest or pastureland either as a consequence of conversion to arable land or plant succession has the greatest effects on rainfall infiltration capacity and soil erosion. Vegetation dynamics is a key factor in quantifying and interpreting the hydrological and erosion response of the land use and land covers (Nunes et al., 2011). Soil conservation measures are necessary parts of the system for combating erosion during critical times of the year and show certain effect on the environment (Kato et al., 2011; Adimassu et al., 2012). There are various measures adopted for soil and water conservation or diversion of water into natural and/or artificial ponds and reservoirs. These conservation measures include: (i) water harvesting and utilization, (ii) on site conservation measures, (iii) micro-catchments and trenches, (iv) drainage line treatments and, (v) recharge of ground water. Depending upon the rainfall in different regions, either alone or combinations of RWH and conservation measures are adopted.

4.1 Water harvesting and utilization

Harvesting and storage of rainfall and its release for multiple uses are age old practices. Rainwater is generally collected from existing structures like rooftops, parking plots, playgrounds, parks, rocky areas, flood plains, etc. and conveyed into pond, dam or below-ground tank where it is stored for non-potable uses or for on-site disposal or infiltration as storm water. This has some negative environmental impacts also compared to the other technologies for water resources development. Rainwater is relatively clean and the quality is usually acceptable for many purposes with little or even no treatment. It can co-exist with and provide a good supplement to other water sources and utility systems, thus relieving pressure on other water sources. Two types of collection and storage of rainwater are in practice in general.

Rainwater and floodwater delivered by surface runoff and overland flow are stored aboveground and in soil matrix. This means, that its application is limited to the rainy season, when rainfall occurs. To allow cropping outside the rainy season, a number of storage media are employed, ranging from ferro-cement tanks to large reservoirs, storing millions of cubic meter of water. In India and Sri Lanka, more than 5 lakhs tanks store rain water, sometimes supplemented by water from streams or small rivers. Tanks play several important roles e.g. as flood-control system and in preventing soil erosion and wastage of water in the form of runoff during periods of heavy rainfall (CSE, 2000). In western Rajasthan, about 40 -70% of the rural drinking water supply is sourced from nadi and tanka, 15-20% from wells/tube-wells and only 8-12% from other sources (Khan and Narain, nil; Singh, 2015). Almost 100 percent of villages of hyper arid districts of Rajasthan have ponds, wells and other water harvesting structures in their vicinity (Goyal et al., 2007). There are about 1436, 592, and 1822 number of 'Nadis' in drought affected Nagaur, Barmer, and Jaisalmer districts of Rajasthan, respectively (Plat 11.1). These water bodies meet about 37% of the water needs of the villages. Jodhpur town itself has about 25 numbers of 'Nadis' in and around it. Though, the water is not very suitable sometimes for human consumption but is important source of water for livestock and for irrigation. Besides, these Nadi's recharge the groundwater in surrounding areas. The larger ones, 10 to 30 hectares in size, feed several thousand hectares of irrigated land. They are equipped with sluices, which deliver water to an extensive canal system suitable for irrigated cultivation in large parts of the country (Agarwal and Narain, 1997). These rainwater reservoirs are not only employed for irrigation in extremely dry regions, but in semi-humid areas up to 1300 mm annual rainfall also.

A major disadvantage connected with surface storage of water in dry areas is high rate of surface evaporation. In addition to this, reduction in storage capacity caused by siltation, pollution problems and loss of agricultural land are the other drawbacks associated with surface storage of water. Underground storage of water is an effective alternative, where storage is done in near surface aquifers, calling for a conjunctive management of water resources. Traditionally, in Mediterranean houses, one cellar room is specifically designed to store rainwater. In north western India, particularly in Rajasthan 'Kunds'- a covered underground tanks with a plastered catchment is best example of underground storage (Agarwal and Narain, 1997). Other traditional systems of rainwater storage are 'Kui', underground Tanka etc. Construction of a series of 'Kuis' either in a dry riverbed, bed of Talab/Nadi or in depressions is common in western Rajasthan (Singh, 2003).

Jalkunds

Jalkunds are types of farm ponds excavated on the selected site before the onset of monsoon. The bed and sides of the Kund are leveled by removing rocks, stones or other projections to avoid damage of the lining material. The inner walls, including the bottom of the kund are properly smoothened by plastering with a mixture of clay and cow dung in the ratio of 5:1. After clay-plastering, about 3–5 cm thick cushioning is done with locally dry leaf (pine) (@ 2–3 kg per square meter) on the walls and bottom, to avoid any kind of damage to the lining material from any sharp or conical gravel, etc. It is followed by laying down of 250 mm light density polyethylene black agri-film to avoid seepage loss. The agri-film sheet is laid down in the kund in such a way that it touches the bottom and walls loosely and uniformly, and stretches out to a width of about 50 cm all around the length and the width of the kund. A 25 × 25 cm trench is dug out all around the kund and 25 cm outer edge of the agri-film is buried in the soil, so that the film is tightly bound from all around. The side channels all along the periphery of the kund help to divert the surface run-off, drain out excess rainwater flow and minimize siltation in the kund by allowing only direct precipitation. Silpaulin sheet 250 GSM can be also used for longer duration in place of LDPE black agri-film. Jalkund is covered with thatch (5-8 cm thick) made of locally available woodpoles/bamboo and grass. Use of Neem oil (10 ml per square meter) is suggested to reduce evaporation in off season.

Source: Ngachan, http://kiran.nic.in/pdf/publications/natural_resources.pdf

4.1.1 Traditional System of Water Storage

People of dry regions are well aware about the importance of rainwater harvesting and conservation traditionally since time immemorial (http://www.rainwaterharvesting.org/Rural/traditional2.htm). A variety of water harvesting structures available in the arid region of Rajasthan and Gujarat, India tells about the volumes and depth of traditional wisdom in the region (Borthakur, 2009). Numbers of RWH structures are running into thousands in Jaisalmer district alone (Narain et al., 2005). It demonstrates the dedication, devotion, hard work and social concerns of the communities toward harvesting and conservation of water. However, the shape and size of water harvesting structures vary widely depending upon requirement, utility, topography, physiographic feature, soil and rock types and climate. The efforts are such that each and every drop of water could be harvested and utilized efficiently. To meet the drinking water requirements, rooftop rainwater harvesting in individual Tanka and Kund are common across all villages and towns in the Thar Desert (Agarwal and Narain, 1997). Barmer is the major town in western Rajasthan where the art of rooftop rainwater harvesting is still in practice, whereas in Jaisalmer, there are thousands of different sizes of water harvesting structures. The names of water storage devices vary according to their size, structure and location such as 'Talab', Tal, Talai Bandh, Bandha, Nadi, Johad, Jahadi, Sar, Jheel, Khadin,, Bhe, Tanka, Dhari, Dei-bandh Jagah, Kua, Kui, Bavadi etc. Some of these structures are more than 100 years old. Diversion of every drop of rain to Kailana Lake and Takhat Sagar from the hills of Kailana and Mandor hills around Jodhpur city of Indian arid zone is such a remarkable accomplishment. The efforts of water harvesting system are true examples of decentralized water distribution where everyone has access to water.

4.1.2 Traditional Farming

The Khadin system in Rajasthan, India and Bandsar system in Iran are age old practices of water harvesting and cultivation. These lead to harvest wheat and gram and are thought to be developed in response to climate extremes and climate change (Kolarkar et al., 1983; Prasad et al., 2004; Samani et al., 2014). According to an estimate the number of traditional village tanks, ponds and earthen embankments are more than 1.5 million harvesting water in about 660,000 villages in India (Pandey et al., 2003). This wisdom of Indian Desert is in stark contrast to other deserts like those in African countries like Botswana, Tanzania, Ethiopia etc which are totally dependent on foreign aids not only for funds but also for technology and its execution. Unfortunately our strides to develop the network of modern water engineering projects are neglecting such traditional knowledge resulting in damage and disappearance of such ancient wealth.

4.2 On site conservation measures

In-situ water harvesting and moisture conservation are field based, low-cost and location-specific soil and water conservation technologies that are highly useful in drought mitigation and enhance land productivity. Land characteristics, farm size, plot size, slope, and location of the plots are important factors that affect the adoption of a particular soil conservation measure. Both positive (Norris and Batie, 1987; Bravo-Ureta et al., 2006; Amsalu and de Graaf, 2007) and insignificant or negative effects of farm size have been reported, but plot size is expected to influence conservation positively. Conservation structure needs a larger proportion of the plot thus reduction in the area may not be enough to compensate for the area lost when plots are small (Bekele and Drake 2003). Slopes have also a significant positive effect on conservation (Bekele and Drake, 2003; Nyangena and Köhlin, 2008).

4.2.1 Contour Farming

It is an important form of conservation tillage on slopes, where all farm husbandry practices are done along the contour by forming cross-slope barrier to the flow of water. Where this is not enough it is complemented with ridges which are sometimes tied to create a high degree of surface roughness to enhance the infiltration of water into the soil. The contour ridges are maintained for several seasons so that the work of construction could be minimized. Preparation of a seedbed along the top of the ridges is also carried out at the time of planting and in one operation. Residues are concentrated in the furrows where the water collects and infilters. Sometimes large numbers of mini-storages across the slope are prepared that help alleviate drought. To counter crusting of soil and its subsequent erosion from the agricultural fields a number of practices like contour bunding (low rainfall area) or graded bunding (medium to high rainfall area), contour tillage, contour sowing, etc. have been suggested (Singh, 1990; Dhruva Narayana, 1993). Contouring, strip cropping and high-value contour hedgerows of asparagus (*Asparagus racemosus*), pineapple (*Ananas comosus*), pigeonpea (*Cajanus cajan*) and lemongrass (*Cymbopogon flexuosus*) are quite effective in reducing soil loss compared with the farmer's traditional practice of up-and-down cultivation on slopes (Poudel et al., 1999).

4.2.2 Contour Bunding

This device is recommended for soil and water conservation for rain-fed farming in the semiarid region. Their specifications vary depending upon rainfall and soil but are found suitable for sandy soil with bunds of 0.3 to 0.6 m height. These bunds are placed in a series from the ridge to the bottom of a valley, one below another, to form terraced slopes with drainage. About 25 mm of rainwater is stored in 130-150 mm of soil depth for growing crops. On an average, contour bunds have 27 percent higher soil moisture and 14 to 181 percent higher fodder yield than flat surfaces on grasslands of western Rajasthan (Wasi-Ullah et al., 1972). Graded bunding (medium to high rainfall area), contour tillage, contour sowing, etc. are also adopted in different regions (Singh, 1990; Dhruva Narayana, 1993).

4.2.3 Contour Vegetative Barriers (CVB)

Locally adapted native, fast-growing perennial grasses or undershrubs with extensive root systems such as *Cymbopogon jwarncussa, Cenchrus ciliaris, Cenchrus setigerus, Barlaria* spp. and *Sacchrum munja* are planted 0.30 m apart on contours at 0.6-1.0 m vertical intervals to form a dense hedge against the slope. This convert the area into micro planes controlling erosion and conserving soil moisture by checking sheet flow. These are cheap and environmental friendly measures for *in-situ* soil and water conservation, and to improve the land productivity (Sharma et al., 1997; 1999). CVB also reduces runoff volume by 28 to 97 percent and help the soil to store about 2.5 times more moisture than the control sites.

4.2.4 Application of Crop Residue/Mulching

In the black soil areas ridge and furrow system help reduce the problem of waterlogging, while in the hard pan soils deep ploughing at 3-4 years interval ensure better infiltration and root growth. Mixing crop residues and organic matter with light textured soils also enhance the soil moisture and crop yield. In the areas where gravel forms a significant part of the surface soil volume, but the soil subsurface is less stony (e.g. Saurashtra upland and Kachchh peninsula), periodic tillage reduce the danger of water erosion, enhance moisture conservation and ensures better soil drainage. This is one of the reasons why farmers in the fringes of the uplands in these areas mix gravel with heavy textured black soils, while in the uplands they practice occasional tillage. Under afforestation, mulching the saucers area by locally available undershrubs or grasses appears beneficial in plant establishment and growth (Gupta et al., 1999). For example, performance of *Azadirachta indica, Acacia nilotica*, *A. planifrons, Albizia lebbeck*, *Prosopis cineraria* and *Tecomella undulata* has been better with mulching than the plants without mulching, attaining average girth of 23 cm for *T. undulata* to 43 cm for *A. indica* and height of 262 cm for former to 511 cm for the latter species.

4.3 Micro-catchments and trenches

To improve the early establishment and growth of plantations various techniques of *in-situ* water harvesting and conservation structures- known as micro-catchments have been studied (Krupnik, 2004; Ojasvi et al., 1999; Sharma et al., 1986; Sreedevi et al., 2008). These micro catchments reduce velocity of runoff water and allow the water to stay on ground for longer period and enhance the infiltration of the rain water in to the soil body (Fig 11.1). The *in-situ* water harvesting structures permit the storage of water around the vicinity of tree roots also (Gupta, 1995). Plant rhizosphere remains moist for longer part of the year offering favourable conditions of water and nutrient availability to trees resulting in better growth and biomass production.

4.3.1 Planting Pits

Planting pits are micro catchment techniques made on land with low permeability allowing runoff collection. They are known as Zai, Zay, Chololo, Matengo, Ngolo in different regions of the world. Indeed planting pits are holes dug to catch runoff and allow time for infiltration. They are usually fertilised with organic matter in the form of plant debris or compost to enhance yield. The Zai form are dug with approximately 80 cm apart to a depth of 5 to 15 cm, with a diameter of between 15 and 50 cm, but the planting pits also exists in much greater size and with different spacing. The planting pits are suitable for semi-arid area to enable crops to survive dry spells. They are used on a wide variety of soil types but most suitable are silt and clay soils, where runoff can be generated due to limited permeability. This technique works on land with 1-15% slope.

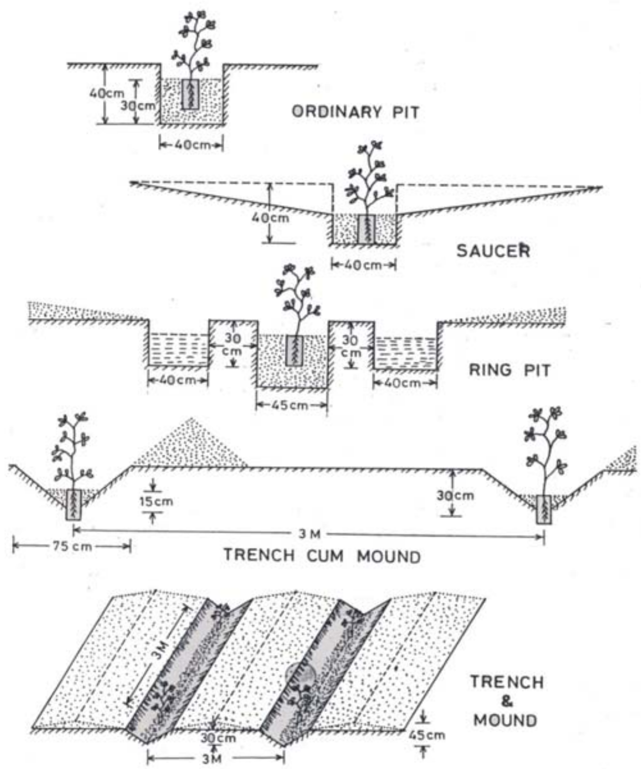


Figure 11.1 Different micro-catchment for rainwater harvesting and utilization in afforestation programmes (Source: Gupta, 1995).

RWH structures like ring trenches (40 cm wide and around 52.5 cm radius) and big saucers of 3.0 m diameter with 10-20% slope are beneficial for plant growth and biomass production in plantation forests (Plate 11.2) as they prevent runoff losses by 30-50% and maintain higher soil moisture regime, facilitate root system and improve water and nutrients use (4-7 times) efficiencies thus give a good start to young plantations (Gupta et al., 1993). Among this, ring pits (trenches) are widely applied along road side plantation in dry areas, where it not only able to harvest sufficient rainwater for its utilization by the planted seedlings but the ring pit around the planted pit is also beneficial in terms of protection from the domestic and wild animals. Only needs an improvement is to provide a way to collect water from the adjacent area otherwise it collect only direct rainwater. In case of fruit plants like aonla, apple and mango, saucer type planting pit induces better growth as compared to the ring or shelved trench type pits (CAZRI, 2008).

4.3.2 Semi-circular bunds or Demi-lunes or half moons

Semi-circular bunds are earth embankments in the shape of a semi-circle with the tips of the bunds on a contour line. These are constructed in staggered lines with runoff producing catchments between structures in rainfall region of 200 to 750 mm and land slope of 2 to 5%. Semicircular bunds in name of "demi-lune" used in Africa, are quick and easy method of improving rangelands (Fig 11.2 left). These bunds are more efficient in terms of impounded area to bund volume than other equivalent structures like trapezoidal bunds. Depending on the site and the catchment: cultivated area ratio, it can have a short slope or long slope catchment technique. A catchment: cultivated area ratios of up to 3:1 are generally recommended for water harvesting systems used for rangeland improvement and fodder production. Larger ratios would require bigger and more expensive structures, with a higher risk of breaking. Semi-circular bunds can be constructed in a variety of sizes, with a range of both radii and bund dimensions. For tree growing and production of crops semi-circular bunds of small radii, i.e. 2 to 3 m and bunds height of about 25 cm are commonly used. Soil for the bund is either drawn from within the hoop by creating a furrow inside or outside the hoop.

4.3.3 Negarims

Negarim micro catchments are diamond-shaped basins surrounded by small earth bunds. Each micro catchment consists of a catchment area and an infiltration pit (Fig 11.2 right). The shape of each unit is normally square, but the appearance from above is of a network of diamond shapes with infiltration pits in the lowest corners (Hai 1998; Critchley and Siegert 1991). Runoff is collected from within the basin and stored in the infiltration pit. The area of each unit is determined on the basis of a calculation of the plant water requirement. Size of micro catchments (per unit) range between 10 m^2 and 100 m^2 depending on the tree species to be planted but larger sizes are also feasible, particularly when more than one tree will be grown within one unit. In case of increase in land slope over 2.0% the bund height should increase as well near the infiltration pit. A common variation in this structure is building micro-catchments of either "V" or semi-circular shape. Advantage in alternative structure is that surplus water can flow around the tips of the bunds, though the storage capacity is less than that of a closed system. These types of bunds are particularly useful on broken terrain, and for small numbers of trees around homesteads. Manure or compost is applied to the planting pit to improve fertility and water-holding capacity. If herbaceous vegetations are allowed to grow in the catchment area, the runoff reduces to some extent; however, the fodder obtained gives a rapid return to the investment in construction. However, regular weeding is necessary in the vicinity of the planting pit. Planting of two seedlings are recommended in each micro catchment - one in the bottom of the pit and one on a step at the back of the pit. If both plants survive, the weaker can be removed after the beginning of the second season. For some species, seeds can be planted directly, which eliminates the cost of a nursery. This technique is recommended in rainfall as low as 150 mm per annum, soil depth of 1.5 to 2.0 m and land slope of up to 5.0%. In uneven topography a block of micro catchments should be subdivided. Negarim micro catchments are suitable for both in village afforestation or homesteads plantation, where a few open ended "V" shaped micro catchments provide shade or support to the trees.

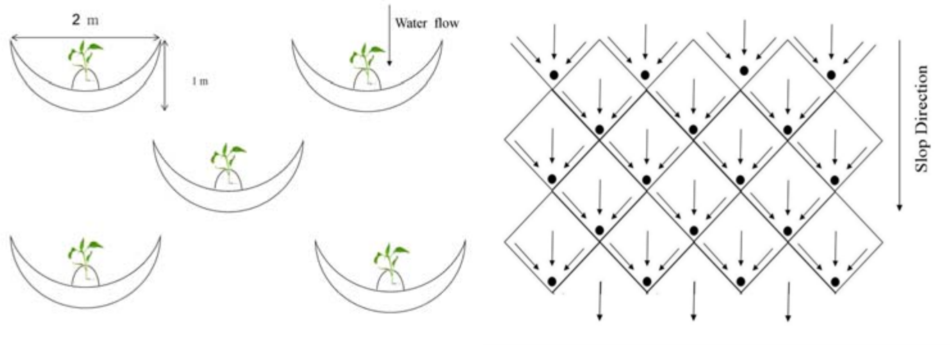


Figure 11.2 Semi-circular bunds (left) and negarins (right) micro-catchments for plant establishment under afforestation.

4.3.4 Tied Contour Ridges (furrows or bunds)

Contour ridges is a micro catchment technique, sometimes called contour furrows also. The ridges follow the contour at a spacing of usually 1 to 2 m for agricultural crop and at wider distance for tree plantation. Runoff is collected from the uncultivated strip between the ridges and stored in a furrow just above the ridges. It is simple and can be constructed by hand or by machine and is less labour intensive than the conventional tilling of a plot. It is applicable in annual rainfall zones of 350 mm to 750 mm and land upto 5% slope and to all soils but heavy and compact soil should be avoided. This technique is used in a variety of climatic and soil conditions and can be adapted to rainfall by adjusting the distance between contours and also the area of cropping/plantation. Water harvesting potential is reduced or lost if the catchment area is planted (Fig 11.3). In a mean annual rainfall of about 700 mm, a catchment to cultivated area ratio of 2:1 can be adopted. An estimated 32 person days/ha (approx. $1.5/day) is required for preparing this structure. Use of machinery reduces the time requirement but increases the costs up to $100/ha.

A further variation of the contour ridging technique is use of an external catchment (fallow land, rock surfaces or roads) and incorporation of a stone spillway into the contour bund for excess runoff to flow around the structure. Bunds are made of soils or stone and are usually covered with a layer of stone on the top and back slope. The area impounded by the bund is planted with tree seedlings. In general, the catchment to cultivated area ratio is 2:1 but it reaches up to 5:1 in Kenya where off contour bunds are used as collection systems to channel runoff into cultivated plots. For full utilization of the cropping area, the spillway heights are leveled with the base of the spillway on the next contour uphill. Leveling off the ground between contours assists in water spreading when runoff is collected. The spillway height determines the depth of water retained and is usually about 10 cm. It is useful in areas with low and unreliable rainfall, with an annual precipitation of 350 to 650 mm. It is also well-suited for use in the reclamation of degraded land. Estimated construction cost is about 100 person days/ha for bunds, land preparation and fertilizer application (UNEP, 2010).

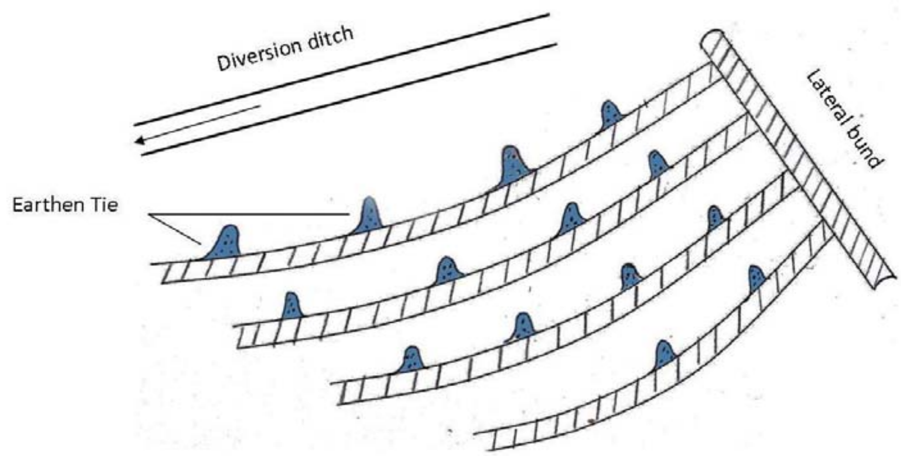


Figure 11.3 Field layout for contour ridging which varies according to the catchment to harvest area ratio (Critchley et al., 1991).

4.3.5 Terracing (Fanya juu and Bench)

Fanya-juu terraces are constructed by putting soil up slope from a ditch to form a bund along a contour (Plate 11.3 left). The trench is normally 60 cm wide by 60 cm deep, and the bund of 50 cm high by 150 cm across at the base. The enlarged fanya juus are about 1.5 m deep and one meter wide. Through gradual erosion and redistribution of soils within the fields, the terraced land is leveled, forming a structure like terraces. Soil and rainwater are conserved within the bunds, and the bunds are usually stabilized by planting fodder grasses. A cutoff drains may be prepared to protect the terraces from surplus runoff. Wherever stones are available, stone terrace walls are relatively better as they allows surplus water to pass through and overtop the walls. Distance between the bunds ranges from 5 m on steeply sloping lands to 20 m on more gently sloping lands (Ngigi, 2003). It is used in growing horticultural crops like bananas, papaya, citrus and guava planted in the ditches, whereas fodder grasses or scrubs are planted on the bunds. This technique is suitable for regions with about 700 mm annual rainfall or above with sufficient soil depth ranging from gentle slopes to greater than 5%. Cost of construction of this structure is estimated at 150 to 350 person days/ha for terraces and cutoff drains.

Bench terracing is applied in nearly level steps along contours normally by half cutting and half filling procedure (Plate 11.3 right). It is an earthen embankment or a ridge and channel, constructed across the slope at a suitable location to intercept surface runoff. It can be constructed with an acceptable grade to an outlet or with a level channel and ridge. By adopting bench terracing, both degree and length of the slope are reduced which help in conserving soil moisture and enhance crop production. Bench terracing is recommended for slopes from 10 to 30%. Design of bench terraces depends upon soil depth and uniform spreading of top soil, slope gradient of land, amount of rainfall, farming practices in the region and proposed crops to be grown in the area, terrace spacing, terrace grade along the width and length and terrace cross section. In general, terrace spacing is the vertical distance between two successive bench terraces. It is equal to the double the depth of cut and depends on the soil depth and land slope. The width of terrace should be such that it enables convenient and economic agriculture operations.

4.3.6 Contour Stone Bunds/Dykes

Use of stones in making bunds is a traditional practice in Sahelian regions of West Africa. Improved construction and alignment of stone bunds along the contour makes the technique considerably more effective (Fig 11.4). Such bunds are used to slow down and filter runoff, thereby increasing infiltration and capturing sediment. In addition to less maintenance the great advantage of this system is non-requirement of spillways, where potentially damaging runoff is concentrated. The filtering effect of the semi-permeable barrier along its full length provides a better spread of runoff than earth bunds are able to do so. This is effective in rehabilitation of barren and crusted soils by using a combination of stone bunds and planting pits by keeping the water spread throughout the area. It is often started at the lower points of a field and work upslope rather than the conventional wisdom which would suggest starting at the higher points in the catchment and working down slope. It is most appropriate for crop or tree production on gently sloping land. Stone bunds of a single line following the contour are laid across fields or grazing land. The resulting structures are up to 25 cm high with a base width of about 35 to 40 cm. To increases stability these are set in a trench of 5 to 10 cm depth. The spacing between bunds varies depending largely on the amount of stone and labour available. Bund spacing of 20 m for slopes of less than 1% and 15 m for slopes of 1-2% observed effective.

Figure 11.4 Rock bunding and contour dykes in conserving soil and water.

A common error is the use of large stones only, which allow runoff to flow freely through the gaps in between. Hence a mix of large and small stones is recommended and the bund should be constructed in such a way that smaller stones are placed upstream of the larger ones to facilitate rapid siltation. Similarly, permeable rock dams are typically long, low dams of loose stone constructed in gullies and across valleys. Because of lack in spillway, the dams force flood water to spread over their length reducing erosive force and force water to infiltrate in fields resulting in large quantities of sediment being deposited favouring conditions for growing crops.

4.3.7 Earth Bunds with External Catchment

Earthen bunds are essentially an external catchment with long slope technique of water harvesting. In this typically a U-shaped structure of earthen bunds is build on the cultivated lands to harvest runoff or sometimes floodwaters from adjacent upslope catchments. This can be categorized into graded bunds, which are constructed in rainfall area of 600 mm and above rainfall annually and useful in the soils with poor permeability or those having the crust formation tendency. In area with annual rainfall of less than 600 mm the contour bunds are constructed in light textured soils. The bases of the bunds follow the contour line and impound the runoff. Two outer arms act as conveyance structures which direct water to the cultivated lands. A shallow channel is left on the inside of the bund to support the drainage and circulation of runoff. Excess water is generally drain along the tips of the outer arms which are sometimes reinforced with stones, brushwood etc. The bunds are usually 0.5 m high and 2 m deep at the base, but these dimensions vary greatly depending on both the slope and the amount of runoff expected in the area. The base can be between 50 to 300 m long, while the arms are usually 20 m to 100 m long. The size of the cultivated area serviced by such a structure is about 0.2 to 3 ha. This is useful for cultivation of crops in the areas with short duration intensive rainfall in mountainous regions. Catchments are generally 2 to 3 times the cultivated area in regions of 150 to 400 mm annual rainfall.

Other earthen bunds are also recommended depending on the slope of the land and size of the field. It helps in conserving the water in the field and maintain *in situ* moisture. By dividing the field into several units, bunds control the volume and velocity of runoff in each such unit. The distance between the earthen bunds varies from 30 to 80 m depending upon the slope of the land.

4.3.8 Ridge and furrow catchments

Ridge and furrow structures are designed to increase the available soil water in order to improve the establishment and growth of plantations and stabilization of yield of agro-pastoral system (Feng et al., 2012). Use of crop straw, plastic film, gravel–sand or stone materials to mulch the soil surface reduces soil evaporation, increases water availability and decreases soil erosion (Li et al., 2000; Feng et al., 2012). Plastic mulching increases topsoil temperature during winter, promoting plant growth, whereas during hot summer, straw mulching can moderate soil temperature, preventing the topsoil from temperatures that inhibit plant growth. Ridge furrows with plastic mulching on the ridges and crop straw covering the furrows channelize water to the furrows, and enhance soil water infiltration and water availability to the crop. Mulched ridges and furrows favour soil microbial activity, increase soil biodiversity, increase crop yields (20–180%) and improve environmental benefits (Gan et al., 2013). Different methods of water harvesting and moisture conservation viz. Control (T_1), weeding (T_2), weeding with oil working (T_3), weeding and saucers of 1 m diameter (T_4), weeding and saucers of 1.5 m diameter (T_5), weeding and saucers of 1 m diameter + mulching (T_6), microcat-chment structures by raising bunds around each tree in checker board design (T_7), and ridge and furrow structure (T_8) with 20% slop (Fig 11.1) were tested with *Azadirachta indica, Tecomella undulata* and *Prosopis* cineraria, where ridge and furrow method found the best by improving the growth of all three species (height by 58%, 35% and 40%, collar circumference by 73%, 56% and 63% and crown diameter by 111%, 51% and 131%, respectively). Biomass accumulation increased by 3.8-fold and 4.6-fold in *A. indica* and *T. undulata*, respectively (Table 11.3). Mulching with locally available weed was also beneficial to *A. indica*, whereas weeding improved growth of most of the species (Gupta, 1994a, 1995).

Table 11.3 Influence of rainwater harvesting and conservation practices on growth of 26-month old trees of different species in Indian Desert.

treat ments	*A. indica*				*P. cineraria*			*T. undulata*			
	Hei-ght (cm)	Collar girth (cm)	Crown dia. (cm)	Bio-mass (g)	Hei-ght (cm)	Collar girth (cm)	Crown dia. (cm)	Height (cm)	Collar girth (cm)	Crown dia. (cm)	Bio-mass (g)
T1	216	13.8	127	1016	119	7.3	65	151	150	9.4	230
T2	301	21.3	210	2060	138	9.5	100	186	162	14.1	601
T3	295	20.0	213	2004	145	9.4	85	190	170	14.0	572
T4	308	22.0	197	2296	151	10.6	95	176	180	13.7	630
T5	319	23.6	222	2465	156	10.8	175	193	210	14.7	919
T6	315	23.1	245	3329	148	10.5	90	200	204	15.8	942
T7	299	22.4	255	1953	138	9.5	140	176	146	12.8	699
T8	342	23.9	268	3836	166	11.9	150	211	227	14.7	1061

Source: Gupta (1994a, 1995). Treatment as in above para.

4.3.9 Continuous Contour Trenches

Contour trenches are ditches generally dug along a hillside in such a way that they follow a contour line and run perpendicular to the flow of run-off water. The soil excavated from the ditch is used to form a berm (a narrow shelf) on the downhill edge of the ditch (Daniel, 2007). Contour trenches are used to slow down and collect runoff water, which then infiltrates into the soil. It reduces soil erosion and salinity in ground water, assists in recharge of shallow wells and prevents pollutants from draining into water bodies. Ploughing is not allowed as it induces evaporation (Plate 11.4 left). Some decision support system is recommended in designing and laying out of continuous contour trenches or staggered contour trenches under varied land forms and climatic conditions (Kurothe et al., 2014). Continuous trenches of 60 x 30 cm^2 cross section (sometimes 45 cm x 45 cm cross section) spaced at 5 to 6 m horizontal interval observed to control the runoff effectively leading to uniform *in-situ* rainwater and soil conservation to the extent of 96 to 97% (Dalvi et al., 2009). Trenches primarily favour plant growth and increase agricultural productivity rather than just as a means to increase groundwater levels (Singh et al., 2013a). In general contour trenches are applicable in the soils with sufficient infiltration capacity and potential sub-surface storage capacity. It is generally avoided in the area with slopes greater than 10%. In region sensitive to very heavy storms it may be dangerous to prevent the water completely from flowing down a slope. In such areas building of waterways or drains at a slight angle so that the excess water could safely channeled away. The excavated soil of the trench can also be used to fill up the existing gullies and the trenches can also be connected to the wall of a sand dam. Small scale contour trenches can also be used at field level.

The water that infiltrates can be used as soil moisture for crops cultivated after a rainfall event, directly for pumped irrigation, or extracted from shallow wells in the area for irrigation. The major limitations of contour trenches are errors occurring in contouring over long distances resulting in water flow from the high point to the low point, cutting a path and increasing soil erosion. In such a condition intermittent plugging of the trenches is recommended to avoid accumulation of stored water in limited area. The berm can also be planted with permanent vegetation like native grasses or legumes to stabilize the soil and for the roots and foliage in order to trap any sediment that would overflow from the trench in heavy rainfall events. Labour cost can be calculated at the rate of about 1.5 m^3 per person per day manual earth movement or cost of laying out contours and digging of trenches of 60 cm x 30 cm size are 210 manday/ha (Sadgir et al., 2006).

4.3.10 Staggered Contour Trenches

Staggered trenches on a contour line (SCT) are prepared in medium rainfall region with highly dissected topography and slope between 10-25%. The length of the trenches is about 2-3 m and the spacing between the rows vary from 3 to 5 m. Size of the trench depends on the depth of the soil and other factors. In general, the most popular size used in the watersheds is 50 cm (depth) × 50 cm (width) though trench dimension of 45 cm x 45 cm is also adopted (Plate 11.4 right). The soil excavated is piled up 20 cm away, downstream of the trench. The gap between the trench and soil, called berm is essential so that the soil does not fill up the trench again. The chances of breaches of staggered trenches are less as compared to continuous contour trenches. This appears better as compared to contour trenches because of invariably errors occur in contouring over long distances resulting in water flow from the high point to the low point, cutting a path and increase in soil erosion. For this one can dig trenches of 2 m long on a contour line giving a gap of 4 m. The gaps in the contour line should fall below the trenches in the higher contour line. Chains of staggered trenches could be made along successive contour lines so that water left by one line of trenches is captured by the immediately lower line. In areas where there is an abundance of trees and vegetation, gaps in excavation are in any case essential to allow space for the roots of the trees to spread. Wherever there are hard rocks underneath the soil, trenches must be staggered. In some cases contour staggered trenches supported by vegetative barriers like *Tripsacum laxum* and *Cymbopogon flexuousus* are more efficient in soil erosion control and are effective in reducing run-off and soil loss compared to vegetative barrier of *Eragrostis curvula* with SCT, *Vetivera zizanoides* with SCT and a control (Madhu et al., 2011). If grass has to be planted along the trenches, then the excavated soil can be piled up in a 10 cm high rectangular layer, whereas for plantation purposes, seedlings can be planted either in the space after the trench or on either side of the trench (Rejani and Yadukumar, 2010). In fact, it will be more appropriate to plant the seedlings downside of the trench to fully utilize the stored water in the trench (Singh et al., 2011).

4.3.11 Gradonie and V-ditches

Gradonie and V-ditches are across the contour and 1800 cm^2 in cross section area [(30 × 120)/2], but differences were only in vertical cut of 30 cm height. Gradonie ditches are constructed and bunds are made out of the excavated soil from the ditch. The vertical (height of 30 cm) cut is upside of the slope but the excavated soil is heaped towards the down slope (Plate 11.5 left). They are excavated at different contour levels to reduce velocity of surface run-off and facilitating infiltration of stored water underground and utilization of stored soil water by the seedling growing in or along the ditches. The V shaped ditches across the contour are constructed and bunds are made out of the excavated earth in the form 'V' ditch. The vertical (height of 30 cm) cut is downside of the slope. Ditches are of 1800 cm^2 cross section area to conserve the run off in the ditch facilitating infiltration and its utilization by the growing seedling. The excavated soil is heaped towards the down slope to form a bund of about 20-25 cm height (Plate 11.5 right).

4.4 Drainage line treatments

Check dams or gully plug are temporary or permanent dam constructed across a drainage ditch, swale, or channel to reduce the velocity of runoff, while minimizing channel erosion and promoting sediment deposition (Ruffino, 2009). Stormwater entering a swale or vegetated ditch is ponded temporarily behind the check dam in the sediment control basin. Ponding allows sediment and other pollutants to settle out, while allowing some water to infiltrate and evaporate (Malesu et al., 2007). Small and medium gullies are reclaimed through clearing and leveling of gully bed, followed by construction of check dams and ramps with suitable grasses (Plate 11.6). Gully plugging, planting of grass species like *Dichanthium annulatum* on gully heads and sides, and plantation of tree species like *Prosopis chilensis*, *Acacia nilotica*, *Dendrocalamus strictus*, etc. help control erosion (Dhruva Narayana, 1993). Checkdams are of the following types:

4.4.1 Brushwood Check Dams

These are constructed using brushwood/vegetated material to conserve small gullies up to 1.2 m to 2.1 m deep. These are further classified into; (i) single row brushwood checkdams, which are a single row of posts erected across the channel with brushwood laid along the flow of water. The brushwood is kept in position by tying it to the posts; and (ii) multiple row brushwood checkdams, which are used for 7 or 8 feet deep and about 29 feet wide gullies. The posts about 6 inch diameters are driven in two rows across the flow of water and brushwood are tied with galvanized wire. It can also be constructed by planting bamboo across the drainage line to have dense rows of bamboo.

4.4.2 Semi Permanent Dams

These structures are more stable than brushwood checkdams and are further categorized like (i) dry/loose stone checkdam, and (ii) log dam. The dry/loose stone checkdams are made up of dry stones without mortar. It is constructed in the form of an arch with convex side facing the water current. The walls are built leaving a step of 6 inch on the down streamside without deviating from the arch so that the top width could gradually reduce. After reaching 0.60 m above bed level, a notch is use to left in the middle. Notch is half the span long and 0.30 m deep. Apron and wind walls are also built of stones. At the back of checkdams, earth brushwood and stones are piled upon the notch to make it more effective. It should consist of at a minimum of 1-foot layer of 1-inch washed stone over a 1-foot layer of 3 to 6-inch clearstone, free of fines and sand, underlain with a geotextile fabric. Size of the structure depends upon the site with 0.30 to 1.5 m in height and a minimum width of 0.6 m. Besides, the slopes should have a maximum ratio of 2:1 as greater slopes may become unstable and will require excessive maintenance. The center of the check dam should be at a minimum and 15 cm lower than the edges to allow water to flow over the top of the structure. The **log dams** are types of dams where timber is used in its construction in case where timber is available at cheaper rate. Logs of at least 10 cm in diameter and 2 m in length are driven in side by side to form a wall of logs. If the gully has steep sides, a rectangular notch is made in the center. Lashing and bolting cross members to vertical posts provide extra rigidity to these structures (Ruffino, 2009).

4.4.3 Permanent Checkdams

These structures are built in deeper and wider gullies where other measures are unable to stop erosion. These are generally three types: (i) Drop spillway is an efficient structure for controlling relatively low head upon 3 m and discharge capacity of up to 3 cubic meter per sec; (ii) Chute spillways is useful in high overflows where a full flow structure is required and where the site condition do not permit to use a detention type of structure; and (iii) Gabions are pre- fabricated rectangular basket made up of galvanized wire netting. Stone-filled gabions are very flexible structures able to withstand significant movements from undercutting or land slippage. They can be constructed on a better or level drainage. Gabions work well in unimproved channels because they provide surface roughness more in harmony with natural channels. Gabions can also absorb significant deflections when undercut by the stream. In this, the basket is placed in position and filled with stones, and then the lid is wired down. Basket has size of 4 m × 1 m ×1 m. Baskets are built up on top of each other and can form large and small structures. The main advantage of these structures is that there is sufficient flexibility for the structure to adjust to settlement resulting from scouring of foundation and posses high friction and provide channel aeration during high flow, which makes them very desirable for limited repair of unimproved channels. A well graded stone of 3 to 8-inch size, clean and hard is specified and increases density. Stones must distributed evenly by hand to minimize voids and ensure a pleasing appearance along the exposed faces. Baskets should be square and diaphragms straight. The fill in adjoining cells should not vary in height by more than 1-foot. Leveling of the final stone layer allow the diaphragms tops to be visible.

There are varying results of different types of checkdams in terms of live, maintenance, ease of construction depending upon the types and materials used in its construction (Table 11.4). Standard height of brushwood, log, loose stone and gabion checkdams are 1 m, 1.5 m, 2.0 m and 5.0 m, respectively. To discourage concentrated flow, water velocity in the channel can be reduced by using multiple check dams. The distance between check dams will depend upon the slope of the drainage line, but should be spaced so that the base of the upstream check dam is even with the peak of the downstream structure. Thus increase in the slope of the drainage line will require increased number of check dams to prevent concentrated flow in the channel (Table 11.5). As a result, check dams used in drainage line with slopes greater than 6% may not be practical. The construction costs range between US $200-400 for temporary check (brush wood, rocks, soil) and US $1,000- 3,000 for permanent dams (made from stones, bricks, cement), depending on the length and height of the structure. Such variation is because of differences in materials used and size of the gully (AKVOPEDIA, 2012). Early intervention to stop gully erosion is advisable as it is more economical than the late ones.

Table 11.4 Principal characteristics of check dams (Source: Seng, 2011).

Type	Expected life (years)	Material used	Water retention effectiveness	Frequency & cost of Maintenance	Relative cost	Ease of constr-uction
Short term	<1 year	Earth/sand -Without bags	Poor	High	Low	Easy
		-Filled in bags	Poor	high	Low	Easy
	<2 year	(b)Timber logs	Poor (average if layer of imper-meable sheet is provided)	High	Average	Average
Medium-term	2-5 years	Loose stones/rocks	As above	High	Average	Easy
		Stacked rocks or gabion type	As above	High	Average	Easy
Long-term	> 5 years	Precast concrete stacked blocks	Good	Low	High	Average
		Precast concrete Post panel system	Good	Low	High	Difficult
		Cast *in - situ* concrete	Very Good	Low	High	Difficult

For effective stabilization there needs of gully bed plantation, where plantation of water-loving or moist tolerant trees, shrubs and grasses like *Paraserianthes lophantha*, *Salix* spp., *Acacia nilotica, D. melanoxylon*, *Syzygium* spp., *Terminalia arjuna*, *Phalaris aquatica*, *Sesbania* spp. and grasses like *Pennisetum clandestinum*, *Pennisetum riparium*, *Pennisetum purpureum* and green gold grass breaks the flow and velocity of water run-off, traps the sediment, and protects the gully bed from erosion. For long-term stabilization, the gully sidewalls require the establishment of woody perennials like *Dodonea* spp., *Krignella* spp., *Acacia nilotica* etc. Excellent results can be achieved by planting grasses rows across the gully slope. Direct sowing or broadcasting seeds on gully beds and into cracks on sidewalls during the rainy season may result in an almost immediate cover of these fragile areas. Seeds of *Sesbania sesban*, *Accacia saligna*, *Pegeon pea*, common vetch and other can be mixed together and sown on different sections of the gully. The gully offset is the area that extends from the top edge of the gully wall up to five meters away and off-set plantations is adequate stabilization of this to prevent the sideway extension of the gully and further encroachment of arable land. In general, the gully offsets are moisture deficient, where drought tolerant multi-purpose species of trees, shrubs, grasses, and fodder legumes are suggested for stabilizing this fragile area. Recommended species include: *Medicago sativa*, *Coronilla varia*, *Atriplex nummularia*, *Teline canariensis*, *Acacia saligna*, *Acacia abyssinica*, *Acacia ferruginea*, *Diospyros melanoxylan*, *Chamaecytisus palmensis*, *Grevillia robusta*, *Sesbania sesban*, *Lupinus arboreus*, *Tephrosia vogelli*, *Leucaena leucocephala* and *Tamarix* spp etc.

Table 11.5 Spacing between the check dams depending upon the slope gradient of the drainage line.

SNo.	Slope of the drainage line (%)	Approx. spacing between checkdams (m)
1	1	61.1
2	2	30.5
3	4	15.3
4	6	10.1
5	8	7.6
6	10	6.1

4.5 Ground water recharge

4.5.1 Subsurface dams and Sand Dams

In ravines or heavily gullied areas, small earthen check dams with drop inlet spillways are prepared. These check dams generally have a small pondage, which helps in retention of the silt load, supplements irrigation, contributes groundwater recharge and enhances the overall biomass production. Water harvesting dams have also been constructed across ephemeral streams at several locations in western Rajasthan and other dry areas (including degraded Aravallis) in India under watershed management programs to impound 40,000 to 800,000 m^3 of water behind each structure.

A sub-surface dam is a vertical, impermeable barrier put a cross-section of sand-filled, seasonal river bed observed generally in the drylands (Nissen-Petersen., 2006a). In this a ditch is dug at right angles across the river and into each bank, preferably where a rock dyke stick outs. This provides a solid, impermeable base onto which a simple masonry wall can be built within the trench. In some situations, the wall is raised gradually as sand from upstream accumulates behind the structure, forming a sand dam (Nissen-Petersen, 2006b). Water is extracted through a shallow well in the sand bed, or through a filter box using a gravity pipe which runs through the dam to the point of use downstream (Fig 11.5). For effective water supply and enhance soil conservation, it is better to build a series of small dams along the same stream, rather than building one large dam. A sequence of small dams increases alluvial deposition and improves infiltration more than a single large dam.

Storage volume = Height of dam/2 × (100 × Height of dam/slop of river (%)) × river width × porosity (0.3).

This is useful in the area with erratic rainfall with wide seasonal variation in normal water availability, where no perennial water sources and groundwater potential are available. It is most suitable for use in sandy, seasonal rivers prone to sedimentation and remotely situated area where access is relatively difficult. Limitations to subsurface or sand dam are: (i) acceptable with seasonal riverbeds and floods event only during the wet season; (ii) rivers with less coarse sand will not have sufficient water storage capacity; (iii) river slope range between 1 and 5 % only; (iv) river bed should have solid rock without fractures, and (v) availability of construction material at local level.

Figure 11.5 A constructed sand dam in Indian desert. Arrow indicates stone masonry wall constructed across river bed.

4.5.2 Anicuts

An anicut is small water harvesting masonry dam constructed across a stream to hold sufficient water and submerge the upstream area during the rainy season (Plate 11.7). The stored water is used for lift irrigation and for recharging groundwater in adjacent wells. If the submerged area is large, bed cultivation is practiced using the stored soil profile moisture like in a `Khadin'. A study conducted on artificial recharge of groundwater in Jodhpur district of Rajasthan, reveals an annual increase in water level of 1.8-2.2 m in the zone of influence of anicuts as against a 0.5 m rise in outside wells, whereas in Pali district, the increase in recharge in the zone of influence of anicuts was 68.5 percent higher than that outside the zone of influence (Khan 1996a; Khan 1996b).

4.5.3 Percolation tanks

To achieve artificial recharge on a much larger scale, construction of percolation tanks is a widely practiced technique. This is more or less similar to check dams or Nala bund with a fairly large storage reservoir (Plate 11.7). Percolation tanks are formed for collecting runoff water from catchments ranging between 10 to 50 km^2 areas. Because of high evaporation rates of surface water in the summer months, storage in ground water reservoir is a preferred method. In this runoff water of many seasonal channels of a large watershed is impounded by constructing earthen bunds across the streams. The collected water percolates down during the months of the winter season and by the beginning of summer the tank becomes dry. This leads to better recuperation of wells in the downstream areas. Percolation tanks enable to increase the water table in command area and per day yield and duration of the water in the wells (Pawar, 1989, 2003). Studies conducted on ground water recharge through percolation tanks constructed in hard rock and alluvium formations in Pali district of Rajasthan indicated the rate of percolation at 14-52 mm day^{-1} (Table 11.6), where water loss from percolation tanks was 65-89 % and evaporation loss was only 12-35 % of stored water.

Table 11.6 Percolation and evaporation losses from percolation tanks constructed in different locations in Pali district of Rajasthan (Source: Khan and Narain, nil).

Location	Basin	Formation	Capacity (m^3)	Av. percolation rate (mm day^{-1})	Percolation rate (%)	Evaporation (%)
Sablipura	Guriya	Hard rock	35,400	18	77	23
Dhaneri	Lilri	Hard rock	25,700	14	65	35
Sojat	Sukri	Alluvium	3,80,000	52	88	12
Sheopura	Sukri	Alluvium	64,300	38	83	17
Dhabar	Phunpheriya	Alluvium	29,500	33	89	21
Mev	Guhiya	Hard rock	67,000	27	81	29

4.5.4 Farm Ponds

This is an innovative approach to dug-out farm ponds in individual fields to ensure maximum collection and percolation of rainwater (Plate 11.8). In this ponds of 9 × 9 × 3 m^3 size are dug at strategic locations to harvest excess runoff from the fields and can harvest about 250 m^3 of water at a single filling. Most important benefit created by this device is sufficient labour employment in the region (Das et al., 2014). Water harvested in these ponds is used for protective watering of the plantations established in the area. These ponds help increase percolation and subsequent leads to maintenance of a better soil moisture regime, which in turn helps better tree growth. This measure also results congenial microclimate reducing aridity and crop losses due to moisture stress. Besides, trench-cum-bund across the slope helps to retain silt and water *in-situ*. A series of farm ponds can be constructed on contour lines and are located in such a way that the field 'trench-cum-bunds' act as conducting channels for excess water from each pond to be conducted to the next pond in the same contour. Once a pond is filled with rainwater the excess water flows horizontally to the next pond through the conducting channels. The last pond in the chain discharges to a check-dam in the drainage line. In a line normally there can be 5 to 15 ponds. The ponds are not lined with any impervious material. Instead the ponds are regularly desilted to encourage maximum percolation.

4.5.5. Earth Dams and Water Ponds/Pans

Earth dams are semi-circular or curved banks of earth, 3 to 4 meters in height and 100 meters in length. Water ponds or pans are naturally occurring or excavated water storage structures without a constructed wall or dam (Plat 11.8 right). In this the reservoir should have a greater depth to surface ratio to store maximum water behind the smallest possible dam. The best catchment area could be a relatively steep and rocky landscape with no erosion and the dam can be placed in gentle sloping land in a wide shallow channel or broad depression. It is generally preferred to build it using manual labour and animal tracking. An outtake pipe system can be constructed to abstract drinking water from the reservoir. Runoff coefficient of 0.25 is used in catchment area for steep terrain with many rocky outcrops and 0.10 for gentle sloping hills mainly covered with soil though it vary with region and could be considered accordingly.

$$\text{Storage volume} = \tfrac{1}{2}\pi \times W \text{ (width of dam)} \times D \text{ (maximum depth of reservoir)}$$

It is very useful in arid and semi arid regions with limited water resources and where groundwater potential is low or problematic (quality unacceptable). Remotely situated areas are more suitable for this as the harvested water can be utilized by seasonal herders. Important limitation to this are areas with substantial soil erosion, high probability of torrential rains/floods and non-availability of construction material at the site.

5. IRRIGATION WATER MANAGEMENT

Because of low availability of surface and ground water plantation and allied sectors mainly depend on rainfall. At the same time erratic rainfall affects the success of afforestation programmes if supplemental irrigation is not provided. Plant survival and growth are adversely affected and biomass production is drastically reduced where intensity of water stress is relatively high. Soil water stress significantly influences the growth of the planted seedlings. For example, height and collar diameter of *Azadirachta indica* declined to 49% and 41% respectively under 30-60% available water and to 69% and 54% respectively under 5-30% available water compared to 90-100% available water (Pandey, 1999). There are reduction in height, collar diameter, leaf size and area, root volume and total biomass of *Dalbergia sissoo* seedlings with increasing levels of soil water stress (Singh and Singh, 2011a). The reduction was >32% in growth, >50% in leaf, and >77% in biomass when seedlings were grown with <50% of soil field capacity on aridisols. The need of supplemental irrigation during the establishment phase arises from the fact that the soil water content of the predominantly sandy soil profile remains below the availability limit for a long period. Applying irrigation to the plantation significantly enhances survival, growth and productivity of the plantation. Watering at field capacity at 1 and 2 weeks interval brought about the maximum increase in height and stem diameter of *Azadirachta indica* seedlings (Burman et al., 1991). If not properly cared, the longer dry spells causing more intense stress could not be alleviated at any level of irrigation in latter stage.

Irrigation to plantation has for long been recognized as a basic necessity for sustaining high productivity particularly in drylands, the soils of which are more prone to water deficit. Several fold increase in biomass production recorded under irrigation than that of control under rainfed conditions (Mathur and Upadhaya, 1990, Gupta, 1994a). Both growth rate and mean annual increment have been observed highest under irrigation in IGNP area at 3 years age, where it was highest for *Eucalyptus camaldulensis* and lowest for *Prosopis cineraria* among different species under plantation (Upadhyaya et al., 1991). The indigenous desert species like *Prosopis cineraria, Zizyphus mauritiana* and *Tecomella undulata* known for extremely slow growing (2.8 to 3.1 m in 14 years) have responded well both to irrigation and fertilizer application. In some of the cases *Prosopis cineraria* and *Tecomella undulata* have attained more than 3 m height in only 18 months (Mathur and Upadhaya, 1990). However, the excellent performing *D. sissoo, Acacia nilotica* and *Eucalyptus camaldulensis* plantation raised under irrigation to increase green cover during first five years has become victim of over-irrigation as plantation started drying after discontinuing the irrigation and has resulted in large-scale mortality in the command area plantations coupled with development of water logging and salinity in some of the pockets. Ground water table has risen at an alarming rate of 0.5 m per year in IGNP stage-I. Excessive watering in early phase of plant establishment resulted in development of shallow root system, which could not succeeded in taping water from deep soil layer after discontinuance of the irrigation (Gupta et al., 1995c).

5.1 Methods of irrigation

Spot method of irrigation has been observed very effective for *Prosopis cineraria, Zizyphus mauritiana*, *Tecomella undulata* and *Acacia tortilis* plantation, where *D. sissoo, Acacia nilotica* and *Eucalyptus camaldulensis* respond well to furrow method of irrigation. Under liberal watering, frequency of irrigation has been recommended at 9, 9, 6, 6, 3, 3, 2 and 2 from 1st to 8th year for increasing green coverage of canal side in a minimum period (Upadhyaya et al., 1991). Gupta et al. (1995c) suggest spot irrigation method for initial 1st year and furrow method in 2nd year onwards for optimum growth of *Dalbergia sissoo* plantation, where best initial growth is obtained with 45 mm of water added at the interval of 10 days in summer, 20 days in monsoon and 30 days in winter months (Gupta et al., 1995c). Increasing the frequency of watering after certain level has not been found beneficial. Performance of *Acacia nilotica, Eucalyptus camaldulensis* and *Dalbergia sissoo* under three irrigation levels (W_1=30 mm and W_2=45 mm) and cumulative pan evaporation to irrigation level ratio (I_1 = 0.2, I_2 = 0.3 and I_3 = 0.4) in arid region of Rajasthan suggests that quantity of water per irrigation is more important than the total quantity of irrigation as evidenced by better performance of the plants in I_3W_2 as compared to I_3W_1. Because I_3W_2 treatment provided more soil volume with favourable moisture condition for roots where wetted rooting zone was more and thus resulted in better growth (Bala et al., 2003, 2008).

Irrigating above 50% field capacity appears beneficial for rapid growth and biomass production of *D. sissoo* in loamy sandy soil in arid environment (Singh and Singh, 2009). *D. sissoo* does not follow the trend of water use efficiency (WUE) observed in most xerophytic species, where water use efficiency increases with increase in water stress. *D. sissoo* shows the highest water use efficiency at mild water stress. Growth and biomass production depend upon species, and quantity and frequency of irrigation. For example, *E. camaldulensis*, *A. nilotica* and *D. sissoo* produced 31.05 kg seedling^{-1}, 18.07 kg seedling^{-1} and 25.88 kg seedling^{-1} dry biomass in four years when irrigated at 36.2 mm per irrigation. Total water used was 4632.8 mm, 3691.6 mm and 3040.0 mm and number of irrigation was 120, 94 and 76 number for the respective species. At irrigation level of 26.5 mm, the biomass production was 21.5, 12.6 and 18.5 kg seedling^{-1} dry mass for *E. camaldulensis*, *A. nilotica* and *D. sissoo*, respectively at the expense 2551.0 mm, 2153.5 mm and 2021.0 mm of water in four years. There is decrease in biomass production with decrease in the level of irrigation. Minimum biomass was at live saving irrigation (i.e., six irrigations of 75 mm each) as only 1.51, 3.62 and 0.74 kg seedling^{-1} dry biomass was recorded in four years. Balance between evaporation and transpiration of irrigation water vary widely among the species as total water used in *E. camaldulensis* plot irrigated at the rate of 36.2 mm per irrigation was 4.75 mm day^{-1} (19 lit day^{-1}) during summer as compared to 3.45 mm day^{-1} (13.8 lit day^{-1}) in *A. nilotica* and 2.62 mm day^{-1} (10.56 lit day^{-1}) in *D. sissoo* plot. A simple mulching saves the water loss by 0.15 mm day^{-1} (Table 11.7). The partitioning between transpiration and evaporation uses of water was 66% and 34% in *E. camaldulensis*, 54% and 46% in *A. nilotica* and 39% and 61% in *D. sissoo*, respectively.

While application of phosphorus (10 mg P per kg soil) to the planted seedlings alleviates the soil water stress, accumulation of sulfur compounds in *Calligonum polygonoides*, *Capparis decidua*, *Salvadora* spp. etc plant parts enhances the tolerance levels to drought and soil water stress. Phosphorus application enhances stems and leaf biomass and nutrient accumulation at all level of irrigation in *D. sissoo* by alleviating drought stress. Phosphorus responses to growth and biomass production increased with irrigation levels and 20 mg P per kg soil appeared beneficial at sufficient soil water availability and a lower dose (i.e., 10 mg P per kg soil) has been recommended under high soil water stress conditions to benefit growth and productivity of *D. sissoo* (Singh and Singh, 2011a).

Table 11.7 Partitioning of water loss between surface evaporation and transpiration by plants of different tree species irrigated at 36.2 mm level during March to June 2002 (Source: Singh and Rathod, 2012b).

Variables	Control		Planted species		
	No mulch	Mulched	*E. camaldulensis*	*A. nliotica*	*D. sissoo*
Number of days	91	83	99	94	97
Total irrigation (mm)	144.8	144.8	470.6	325.8	253.4
Irrigation intervals (day)	22.8	20.8	7.6	10.4	13.9
PET* (mm day^{-1})	1.75	1.60	4.75	3.45	2.62
PET (lit day^{-1})	7.00	6.40	19.00	13.80	10.40
Transpiration loss (lit day^{-1})	-	-	12.60	7.40	4.00

*PET: potential evapo-transpiration (evaporation + transpiration).

5.2 Drip irrigation

The actual water required by the planted seedlings is often less than what we are applying under conventional methods of irrigation. Plant use only 1-2 liters per month (rather than 1-2 lit per hour); but more water is better and will improve survival and growth (Reddy and Rao, 1980). In case of crops water requirements are higher, but on a per hectare basis may only be a few cm per month (Bainbridge et al., 2011). Farming a shallow basin around the tree help, but it must be reconstructed and much of the water remains near the surface and quickly evaporates. It is also better to bury an old mud pot (Matka) with drainage holes just outside the root zone of the seedlings. While watering one can quickly fill the pot once or twice a month and all the water is channeled directly into the soil near the root zone. A pinch of fertilizer can also be put into the pot to boost the growth of the seedlings. The moistened area favour soil microbial biomass and diversity, which are observed higher in the middle and base of a dune than the top part of the dune, boosting the growth of forest trees as both trees and soil microbial diversity index are positively correlated (Jin et al., 2013). The idea of using used mineral water and drip bottles (from hospital) was applied irrigating *A. indica* and *P. pinnata* seedlings along New Pali road of AFRI, where the bottles were hung up on iron/wooden rods with water dripping down to the planted seedling of more than 500 in number. The result was quite successful in generating a greenbelt along the road.

Efficient way of irrigation is the use of either drip or sprinklers. Drip irrigation can be beneficial for the plants of dry areas, and can run longer than sprinkler systems because it delivers water more slowly as compared to the sprinkler. Use of drip irrigation are mostly recommended for irrigating trees, shrubs, vines, vegetables, and any individual plant. On the other hand, micro sprinklers are best to be used on ground cover, flower beds, groups of plants, hillsides and on very sandy soils as water will percolate downward before it can spread far enough horizontally. Sprinklers should be avoided at day time (or sunny days) and in areas where it is windy as high winds disturb the sprinkler spray pattern. General schedule is provided in Table 11.8, however, it could be rescheduled based on the soil and plant conditions and existing climate in a region.

Table 11.8 Watering scheduling of dripper and micro-sprinkler for different categories of plants in varying climatic regions.

Plant type	Watering time	Watering frequency		
		Hot climate	Warm climate	Cool climate
Flowers, vegetables	30 minutes to 1 hr	1-2 days	3 days	3-4 days
Small trees or shrubs	1-2 hours	1-2 days	2-3 days	3-4 days
Vines	3-6 hours	1-2 days	2-3 days	3-4 days
Medium trees or shrubs	5-7 hours	2-3 days	2-3 days	4-5 days
Large trees or shrubs	6-8 hours	1-2 days	2-3 days	5-6 days
Pots up to 15"	3-5 minutes	1-2 days	2-3 days	4-5 days
Pots over 15"	5-10 minutes	1-2 days	2-3 days	4-5 days
Flower beds, ground cover	30 minutes to 1 hr	1-2 days	3 days	4-6 days
Small trees	1-2 hours	2-3 days	4-5 days	5-6 days
Medium trees	2-3 hours	2-3 days	4-5 days	6-7 days
Large trees	2-5 hours	2-3 days	4-5 days	5-7 days
Greenhouses or hothouses	5-10 minutes	2-4 times/day	2 times/day	1 time/2 days

Source: http://www.dripirrigation.com/drip_irrigation_chapters/9/drip_irrigation_pages/38.

Deep pipe irrigation is also useful and it uses an open vertical or near vertical pipe to concentrate irrigation water in the deep root zone of the planted seedlings (Bainbridge and Virginia, 1990). Experiments in dry areas demonstrate that the deep pipe drip system is much more efficient than surface drip or conventional surface irrigation (Sawaf, 1980). Grape vine weight on a deep pipe drip system is more than double the weight found with surface drip and more than six times the vine weight of conventional surface irrigation. Root spread reaches 100 cm horizontally with conventional surface irrigation, only 60 cm with surface drip, but 178 cm with deep pipe irrigation. Thus deep pipe irrigation develops a much larger root volume than other forms of irrigation and helps develop a plant that is better adapted to survive after watering is terminated after establishment. Deep pipe irrigation is commonly done with 1-3 cm diameter pipe placed vertically in the soil 30-50 cm deep near the seedling or tree with a screen cover (1 mm hardware cloth) to keep away the wild animals. The top of the pipe may be set close to the ground to minimize visual impact, or may extend above ground 20-40 cm. A series of 1-2 mm holes should be spaced about 5-7.5 cm apart down the side of the pipe nearest the plant to facilitate root growth in the early stages of development. If shallow rooted plants from containers are planted next to a deep pipe the roots may not make contact with the wetted soil unless these holes are drilled and the pipes are filled with water. If a drip just moist the soil in the bottom of the pipe the young seedling can be left high and dry. Several pipes may be used for older trees fitted with a drip emitter and can be a very effective system (Bainbridge, 2007).

6. EFFECT OF SOIL AND WATER CONSERVATION

In-situ rainwater harvesting (RWH) practices have modified the landscape functions in African dry land, RWH practices have improved hydrological indicators such as infiltration and groundwater recharge, enriched soil nutrients, and increased biomass production with subsequent higher yields (Vohland and Barry, 2009). High biomass production supports a higher number of plants and animals, although native species might have been replaced by crops as the landscape might change as a whole. Farmers applying *in-situ* RWH practices have been profited from higher food security and higher income. However, some aspects are only poorly covered within the scientific literature, where more integrative research concepts require to be investigated. Likewise, some on-going debate about the adverse effects from afforestation in dryland areas and corresponding soil drying up is damaging to the success of forest restoration, whereas the water yield reduction from watershed is harming to the regional development. Some studies show a possibility that these adverse effects can be diminished more or less by properly designing the system structure and spatial distribution of forest/vegetation in a watershed (Wang et al., 2012).

Adoption of moisture conservation techniques such as mulching, tillage, weeding, etc. have enormous potential in success of afforestation by conserving soil available moisture which are utilized by the plants (Ludwig et al., 2005; Yu et al., 2008). Moisture conservation practices such as mulching with local under shrub like *Crotalaria burhia*, soil tillage and intercultural operations in dry zones adequately demonstrate their utility in plantation establishment and early growth of *Azadirachta indica* seedlings by increasing height by 24% and collar circumference by 27% (Gupta, 1994a). This impact is attributed to the prevention of evapo-transpiration losses and consequently high soil moisture regimes and moderation of thermal regimes (by 5°C) in the vicinity of roots and consequently maintaining better microbial activities resulting in transformation and availability of nutrients (Gan et al., 2013). Coir pith mulching together with application of 50 g of single superphosphate and 25 g urea per plant of *Peltophorum pterocarpum*, *E. camaldulensis, A. nilotica* and *A. plantifrons* enhances survival (by 12 to 37 percentage), growth and biomass of these species (Gupta, 1991).

Soil working, weed removal and conservation tillage also show profound effects in improving soil water that facilitates plantation growth (Gupta and Meena, 1993; Gupta and Limba, 1995). Effects of deep ploughing and weed removal facilitate infiltration of rainwater that is conserved into deeper soil profile. The conserved soil water in deeper soil profile is utilized by deep planting (15 cm deep from soil surface) seedlings under capillary action (Fig 11.6) that help in enhancing seedling survival even with one liter of water application that is only to affirm soil contact between seedling soil clog with the bulk soils. No further watering is required except hoeing around the tree sapling. In traditional method watering is done after 20-25 days interval in summer and 30-35 days interval in winter. Growth and survival of relatively greater adapted species like *A. indica* are better as compared to *Ailanthus excelsa*, *P. cineraria*, *T. undulata* and *Holoptelea integrifolia* (Anonymous, 2014a).

This technique is useful in sandy loam well drained soil and for fast growth species like *A. indica* and *A. excelsa*.

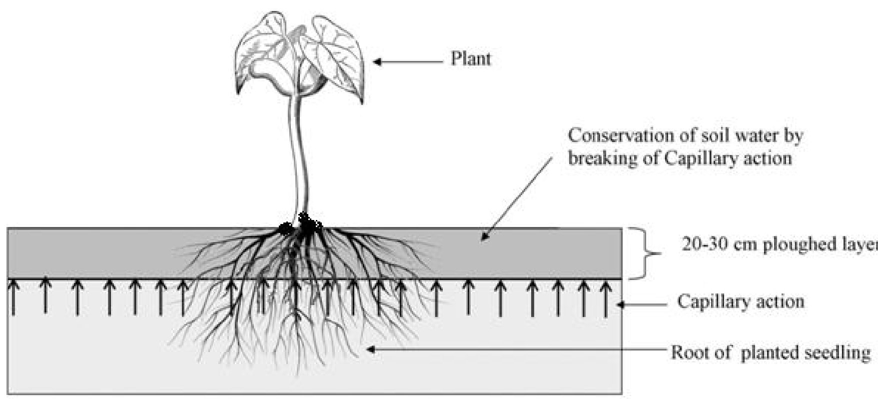


Figure 11.6 Functional aspect of deep ploughing and its effect on plant establishment and growth.

With an additional 10% cost mulching enhances the biomass by 35% (Gupta and Meena, 1993; Gupta and Limba, 1995). The study also highlights the necessity of weeding in arid zone plantations as it prevents unproductive loss of water and nutrients and allows their utilization by plantation thereby improving their growth (Gupta, 1994a; Singh and Rathod, 2012a). Weed clearing conserve 20% higher moisture, improve tree height by 26% and double the biomass production in *A. indica* as compared to the plants growing without any amendments (Gupta et al., 1993). Effects of different conservation measures like weed removal, weed removal and soil working, weed removal + soil working + Saucers of 1 m diameter, weed removal + soil working + Saucer of 1.5m diameter, *in-situ* water conservation structures in checker board design, weed removal + soil working + mulching in saucer round the plants, and water conservation by making inter row slope of 20% showed that inter row slopes of 20 per cent gave highest survival, growth and biomass (Gupta et al., 1993; Gupta, 1994a) because of significantly higher soil moisture in the root zone (i.e., 40% higher than the control). Weed removal alone enhances tree height by 26% over control. The practices of mulching and making saucers also enhances soil water content promoting tree growth considerably (Gupta, 1995). Singh and Rathod (2012b) has observed depletion in soil water from bare soil as 7.0 lit day^{-1} indicating substantial amount of water loss. Simple mulching with locally available *Crotalaria burhia* under shrub save the water loss by 0.15 mm day^{-1}. Thus surface evaporation contribute significant amount of water loss that can be reduced by weeding and surface mulching with locally available under-shrubs or grasses.

6.1. Micro-catchment and plantation

The most important services provided by native forests, when compared with the bare soil are carbon sequestration and prevention of sedimentation. Conversion of native forests into urban areas, forestry plantations, agriculture and pastures reduces these services of forest ecosystem. An estimate indicates that 7624 ha of lands around reservoir in Brazilian Atlantic forests can store additional 864 569 tons of carbon biomass in 30 years and prevent 244 511 tons of sediment delivery into the reservoir per year (Ditt et al., 2010). Applying micro-catchments over traditional methods of planting improves growth of plant to a varying degree depending upon the amount of water harvested and the response of the species planted. It was shown by experiments conducted involving traditional method, traditional method + microsite catchment, and planting in 15 cm × 50 cm pit with one liter water (one liter plantation technique) and *D. sissoo*, *Hardwickia binata* and *A. nilotica* as the tree species (Singh and Singh, 2004). In this, slope of microsite catchment is constructed to accumulate rainwater for the saplings that enhances survival of trees up to 58.8% after five years compared to traditional method (38.0%) and one liter plantation technique (38.8%). Similar pattern has also been observed in growth of these species under improved soil water availability to the localized root zone. Basal diameter, tree height and survival percent have been observed highest in *D. sissoo* followed by *A. nilotica* and *H. binata.*

Among water capturing structures like ordinary pits of size 45 cm × 45 cm × 45 cm, saucer pit of 2.0 m diameter, ring pit, trench cum mound, trench and mound, deep ploughing + pitting, trench and mound and bigger saucers of 2.5 m diameter have caused dramatic improvement in tree growth and root development. These practices facilitate establishment of plantations and give them good initiation boost which developed into healthy vigorously growing stands in subsequent years, besides imparting resistance against drought and famines (Gupta et al., 1995a, b). Micro catchment rain water harvesting and deep ploughing also improve two to three fold growth and survival of *H. binata*, *P. cineraria* and *A. indica* (Jat et al., 2002; Singh and Singh, 2004). A vigorous root system under micro catchments explores larger soil volume and increases the availability of water and nutrients to the trees. Such techniques also enhance survival and growth of *D. sissoo, E. officinalis, Z. mauritiana* and *S. cummini* planted at 3 m × 4 m spacing (Annon., 2000). Interestingly, some species like *A. nilotica, Z. mauritiana, S. cumini* and *D. sissoo* perform well in saucers, whereas, *E. officinalis, C. mopane, A. lebbeck* and *E. camaldulensis* perform well in trench cum mound RWH structures at the end of 33 months (Table 11.9). Likewise *Dichrostachys nutans, D. sissoo*, *Acacia nilotica* and *Prosopis cineraria* have observed as better performer to 3 m diameter saucer as compared to the other structures.

In a study of the effects of moisture conservation practices like (i) control, (ii) ring ditching, (iii) straw/ residue mulch (iv) ring ditching + straw mulch, and (v) soil mulch, where ring ditch is made around the 15 years old *P. cineraria* tree in a 15 cm wide and 15 cm deep trench, show higher moisture content in deeper soil layer than the surface soil (Jat et al., 2002). Ring ditching + straw mulch indicates more than 35 percent higher soil moisture content than the respective control enhancing height and diameter growth of the trees.

Table 11.9 Effect of rainwater harvesting on the growth parameters of different plant species at Jodhpur (Source: Anon., 2000).

Tree species	Height (cm)			Collar (cm)			Crown dia (cm)		
	Control	T & M	Saucers	Control	T & M	Saucers	Control	T & M	Saucers
A. nolotica	250	292.0	321	4.1	5.4	7.7	54	69	90
Z. mauritiana	338	333	396	4.6	4.7	4.9	152	162	197
E. officnalis	129	145	143	3.1	3.7	3.5	68	44	33
C. mopane	223	253	186	4.4	4.4	4.9	45	154	197
A. lebbeck	386	392	121	6.0	7.0	5.2	169	172	129
E. camaldu-lensis	266	410	343	4.2	7.0	4.8	115	193	137
S. cumini	67	62	68	3.5	3.1	3.7	23	17	21
D. sissoo	198	253	296	4.3	5.7	5.5	118	123	129

6.2 Run-off control and soil improvement

Rainwater harvesting coupled with afforestation has tremendous potential in rehabilitation of degraded hills (Singh et al., 2010a; Singh, 2009b; 2013). Restoration practices with water harvesting and plantation of multiple tree species not only reduce water, soil and nutrient losses, but also improve soil water, nutrients and growth and biomass of herbaceous vegetation as well as plantation (Table 11.10). About 400 running meter RWH structures per ha could able to control only 2% of the annual rainfall in Banswara area. In such a condition its length can be increased significantly. In addition, it helps sequester carbon in both plants and soils and improves biodiversity in the region as well. Different rainwater harvesting structures show different responses towards water storage, tree seedling establishment and growth and improvement in soil water status (Plat 11.9). Restoration of a degraded hill involving Contour trench (CT), Gradonie (G), Box trench (BT) and V-ditch (VD) rainwater harvesting devices along with a control in an area with slope gradient of <10%, 10%–20% and >20% in 2005 have showed a decrease in SWC from December to June and it is linearly related to rainfall and vegetation height (Singh et al., 2013a). Interception in photosynthetically active radiations (PAR_{int}) by tree, vegetation and tree-vegetation combine have been observed 30.0%, 54.6% and 84.6%, respectively. SWC, plant and vegetation growth and PAR_{int} due to tree are lowest, whereas herbaceous biomass and PAR_{int} due to vegetation are highest in 10–20% slope (Singh et al., 2013a).

Vegetation height and SWC are linearly related to biomass indicating improvement in micro-climate and herbaceous growth. Highest SWC in <10% slope promotes plant growth and mean annual increment (MAI) in height and collar diameter, which enhance PAR_{int} due to tree and PAR_{int} due to tree-vegetation combine. These variables are highest in CT/BT treatments and lowest in control plots. Characteristic root distribution of *Acacia catechu* and *A. indica* promotes their growth in V-ditch, whereas *E. officinalis*, *Z. mauritiana* and *H. integrefolia* perform best in CT treatment. RWH enhances herbaceous biomass between 22.4% and 60.7% over control. These findings indicate importance of VD/GD structures for growth of herbaceous vegetation as well as *A. catechu* and *A. indica* plants, whereas that of CT/BT structures for growth of other tree species (Singh et al., 2013).

Table 11.10 Effects of rainwater harvesting and afforestation of soil, water and biological variable during 6 years of observation recording. (Source: Singh, 2011b).

Variables	Trend after work initiation
Run-off losses	Decrease (by 2.1% of total rainfall)
Soil losses	Decrease (from 3.43 to 0.19 g l^{-1})
Nutrient losses	Decrease
Soil water	Increase
Soil bulk density	Decrease
Fine earth fraction	Increase (greater in higher slope)
Soil nutrients (NH_4-N, NO_3-N & PO_4-P)	Increase
Soil carbon	Decrease (lower slope)/increased (upper slope)
Plant growth	Increase
Herbaceous diversity	Increase (39 to 92 species)
Regeneration diversity	Increase (22 to 42 species)
Diversity of fauna	Increase
Fodder availability	Increase
Fuelwood availability	Increase
Water availability	Increase

The existing gradient due to soil texture and topographic features affects soil pH, EC, SOC, NH_4-N, NO_3-N and PO_4-P also in hilly tracts, where these variables decrease with application of RWH techniques (Singh, 2012). Such improvements in soil status promotes vegetation growth and biomass in higher slope also. Soil water, species diversity and herbage biomass increase from upper to lower position, and RWH techniques have positive role in improving SOC, nutrients, vegetation population, evenness and growth downside of the RWH structures. Despite of lowest soil water, regular rain and greater soil water usage enhances green and dry herbage biomasses in higher slopes as compared to the foothills. Area with contour trenches exhibit higher vegetation diversity and herbaceous biomass, which enhance concentrations of SOC and PO_4-P further. Rainfall influences SWC, but RWH help conserve soil and water, promotes plantation and herbaceous growth and facilitates restoration process, and thus promotes restoration of degrading hills. This indicates that applying suitable RWH technique depending upon site conditions and types of species promotes regeneration, increases herbage biomass and helps rehabilitate degraded hills.

6.3 Rainwater harvesting and biodiversity

Diverse communities of plant on the earth are the result of many abiotic and biotic factors including water (Ellenberg, 1988; Thompson et al., 1993; Schaffers and Sykora, 2000). Ecological and hydrological processes interact strongly in landscapes, yet these processes are often studied separately. Most experimental evidences in which production has been increased by enhancement of soil resource availability have shown a corresponding decline in species diversity (Goldberg and Miller 1990). This was because of the confounding effects of environmental factors including resource availability, which has strong control over both diversity and productivity in natural systems and may conceal any positive effects of diversity on productivity (Huston, 1997; Fridley 2002; Sutton-Grier et al., 2011). Increase in soil resource availability promotes regenerations of many species either from root stocks or seeds available in soil seed bank (Singh et al., 2010a; 2011). However, this is not only the soil water but also nutrients availability, which play important role in promoting and sustaining number of species in a region (Fig 11.7). For example, number of species increases exponentially with soil NO_3-N concentration, though it varies due to variations in species response to different nutrients and soil water availability (Leishman and Wild, 2001; Dangwal et al., 2012).

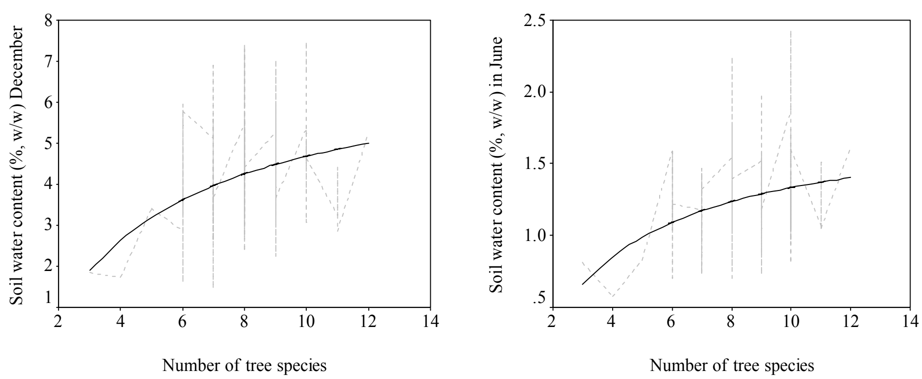


Figure 11.7 Relationship between soil water content (R^2=0.139, $F_{1/73}$= 11.71, P<0.01 in December and R^2=0.238, $F_{1/73}$= 22.82, P<0.001 in June) and number of tree species under rainwater harvesting.

During restoration of a degraded hill, number of species, population and species dominance increased with time, i.e. from 39 in 2005 to 92 in June 2010 (Singh et al., 2011). However, species diversity and richness decreased to the lowest value in 2010 because of increasingly higher dominance of *Heteropogon contortus*- a C_4 grass species with relatively higher adaptability towards environmental stresses. Total numbers of herb/ grass species identified in these years were 151 indicating significantly higher number of species confined to about 17 ha area under restoration. Pooled data for the dry biomass of six years ranged from 275.4 to 535.2 g m^{-2}. The lowest biomass was in <10% slope and the highest was in >20% slope area (26.7% increase over <10% slope), whereas the plots without water harvesting was with lowest values. The increases in herbage biomass over the control plots were 28.2% in CT, 34.9% in Gradonie, 23.95% in BT and 18.84% in VD plots (Singh et al., 2013). A positive relationship between species diversity of herbaceous vegetation and water storage capacity of RWH devices has been observed by greater diversity in CT plots and the lowest diversity value in the VD plots indicating the negative effects of water deficit on diversity of herbaceous species (Anon., 2011). But most interesting is the positive relation of species dominance (which increased with time with negative relation with species evenness) with herbage biomass and vegetation height. In general harvesting of grass increased from 15 tons in 2005 to 36 tons in 2010 in about 17 ha area (Singh, 2012). Among diversity variables, number of species, species population, species diversity and species richness were highest in <10% slope area, whereas species dominance was highest in >20% slope area, and species evenness was highest in 10-20% slope area. There has been a significant increase in number of regenerated/ seed sown tree/shrubs plants/seedlings, which increased from 18 in 2005 to 45 species in December 2010 (Anon., 2011).

7. CONCLUSION AND FUTURE PLANS

Rainfall is prime source of water in drylands, many parts of which remain barren and bereft of vegetation because of water scarcity. At the same time, a significant amount of rainfall is lost in the form of runoff. Different methods of water harvesting and soil and water conservation measures are in practice traditionally as an adaptation to climate and many of them have been designed based on the local requirements to increase water availability and land productivity. Most of them can be categorized into: (i) water harvesting and utilization, (ii) on site conservation measures, (iii) micro-catchments and trenches, (iv) drainage line treatments, and (v) groundwater recharge. Various techniques of *in situ* water harvesting and conservation structures known as micro-catchments have also been adopted to improve early establishment and growth of plantations in dry areas. These micro catchments reduce velocity of runoff water and allow the water to stay on ground for longer period enhancing infiltration in to the soils. Because of dependency on the quantity and frequency of rainfall, topography, vegetations status, regional hydrology and the socio-economy of the regions, these RWH and conservations measures should be applied but carefully.

Because of trans-boundary in nature, water management in dry areas is complex that needs to be resolved through the involvement of government departments, research institutions, NGOs and other stakeholders particularly the villagers in participatory mode. Cooperative effort among governmental agencies and private partners may be there in pursuit of common goals. Such collaboration can range from very informal, adhoc activities to more planned, organized and formalized ways of working.

Centuries old practices of water harvesting prevalent in dry regions throughout the world, which are still viable and cost-effective, needs to be revived and popularized with a new movement as an adaptation towards climate change and drought. In addition, modern rainwater technologies such as anicuts, percolation tanks, injection wells and subsurface barriers should also be propagated to rejuvenate the depleted groundwater aquifers.

There need to improve RWH system depending upon terrain conditions and rainfall and document it for further replications. Some of these include reducing seepage rate, evaporation losses, tank sizing, cost of constructing tanks and ponds. In built programme involving tree plantation for providing shade and reducing wind influence and water losses may also be considered.

RWH techniques could only be effective if related to livelihood. Either *ex-situ* or *in-situ*, rainwater harvesting provides reliable soil moisture and in turn increases crops yield and help adopting diversification. Thus benefits of RWH should extend beyond the rainfed farming to the whole ecological system, as the success in agricultural produce will minimize encroachment into forestry system.

Farmers applying *in situ* RWH practices are benefited from higher food security and higher income. Soil and water conservation through various agronomic and engineering measures including contour cultivation, different kinds of bunding, bench terracing in conjunction with cover cropping and appropriate land-use practices including mulching needs to be integrated to enhance soil and water conservation and enhance land productivity.

Laying out of rainwater harvesting structure on a contour line should be cautiously done so that water level should be same throughout. Otherwise, intermittent plugging of trench could be done to avoid water accumulation at one place resulting in damage of the structures.

Responses of species towards rainwater harvesting structures depend upon types of species and their rooting pattern. Hence selection of species and RWH devices should suitably match for a region. For example, most of the *Acacia* spp. showing spreading roots response better to V-ditch, whereas species with deep rooting performs better under contour trench.

Increased water availability through RWH help enrich soil nutrients and increase biomass and production with subsequent higher yields. Higher biomass supports a higher number of plants and animals, i.e., increased biological diversity and food security.

Relatively greater resource availability through rainwater harvesting or higher use of water could promote ill effects, like invasion by other species (because of limited resource use by the indigenous species), salinity development, species replacements etc. This needs to be researched upon to cope up with such regenerating problems. Science-based and sustainable forestry policy could harmonize the forest-water interrelation and beneficial in forest development.

Drought is a common phenomenon having many facets although water is the most crucial factor in its mitigation. Huge funds are available in MNREGA and are utilized in developing water resources, but these structures need to be monitored properly and should be developed based on some scientific principles.

Land-use systems should match water availability in the region. Therefore, there is a need for the continuous education of farmers in order to adopt water efficient practices, low water requiring crops, conservation irrigation and deficit irrigation, to economize and save more water.

An assessment about the available water resources, current demand and future projection and technological options for water management are required to improve water availability and management efficiency for various uses and to mitigate the effects of drought and climate change in the drylands.

Plate 11.1 Nadi (left) and Kuan in a Talab bed (right) –rainwater harvesting devices in dry areas of western Rajasthan.

Plate 11.2 Different micro-catchment rain water harvesting structures like saucers pit (left), ridge and furrow structure (centre) and ring pit (right).

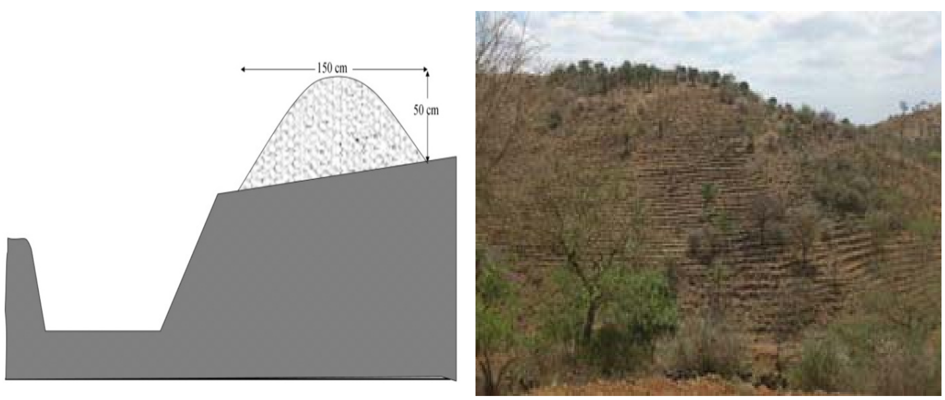


Plate 11.3. *Fanya-juu* terraces (left, construction of a bund) and contour terracing of hillslopes for conservation of soil and water for cropping (right).

Plate 11.4 Contour (left) and staggered/box (right) trenches for rainwater harvesting and rehabilitation work.

Plate 11.5 Gradonie (left) and V-ditch (right) rainwater harvesting structures under rehabilitation of degraded lands.

Plate 11.6 Masonary checkdam (left) and loosstone checkdam (right) for treating drainage line.

Plate 11.7 Anicut (left) and percolation tank (right) for ground water recharge and multiple uses.

Plate 11.8 Farm ponds (left) and earthen ponds (right) for ground water recharge and multiple uses.

Plate 11.9 Influence of rainwater harvesting structure on soil water retention and its availability seepage in hilly area in Banswara, Rajasthan.

12

ASSISTED REGENERATION AND SEED SOWING FOR DRYLANDS RESTORATION

In addition to current changes in environmental conditions and human activities that lead to degradation of tropical dry forests, natural regeneration is generally influenced by site resources like soil and microclimate of the site, competition with existing vegetation, site disturbance, occurrences of established woody plants and their propagules, and seed dispersal by varying agents influencing seed bank. Assisted natural regeneration, directs sowing, planting and a mix of these provide options to restore these degraded forests. In general, small wind-dispersed seeds are better able to colonize degraded areas than large seeds dispersed by animals. Collecting seeds at the end of the dry season and sowing them at the time when soil has sufficient moisture increases seed germination, seedling establishment and reduces the time of exposure to seed predators. Depending upon the size and condition of the area and availability of resources, direct sowing could be done by aerial seeding, mechanized seeding or spot seeding after effective site preparation and protection. Nitrogen fixing indigenous and multipurpose species may be a better option, where large-seeded and late-successional or climax species can be established in degraded and successional forests. However, beneficial character of higher establishment and growth rates of the early-successional and small-seeded trees can be utilized for planting as these species ameliorate the environmental conditions more quickly and can help enhance establishment of later-successional or climax species. Sometimes prevailing harsh climatic conditions for germination and early establishment in the field are ameliorated under existing trees or bushes which can be utilized for seed sowing. The increased competition for both above ground and below ground resources should be minimized by weeding vegetation around the established seedlings. However, use of direct seeding as a complimentary measure of planting fast-growing and multipurpose nitrogen fixing trees could be more beneficial approach for restoration of degraded and successional forests.

1. INTRODUCTION

Beneficial changes towards environment recovery programs are the attempt made to restore the complex interactions of plant communities with intrinsic characteristics in ensuring the perpetuation and evolution of the natural ecosystems (Rodrigues and Gandolfi, 2004). Natural recovery is possible only when there is still some resilience in the environment which can enable the system to regenerate on its own. Human disturbance also influence regeneration as resprouts are the most prevalent individuals following a recent disturbance, but individuals of seedling origin become more important in forest composition when disturbance has taken place over a longer interval. Along an increasing rainfall, the proportion of regeneration accounted by seedlings increases, while the proportion of coppicing individuals decreases after regular cutting. However, an equal contribution by seedlings and shoots to regeneration after cutting has been reported to occur at sites with a total annual rainfall of 1400 mm or more and approximately 19-20 years following cutting (McDonald et al., 2010).

Natural regeneration is a simple method of low cost, which may promote the formation of productive forests in the areas already degraded or under the process of degradation (Shono et al., 2007; Singh, 2008). National Forest Commission (India) report 2006 indicated that around 41% of the total forest in the country is already degraded, 70% of the forests have no natural regeneration, and 55% of the forests are prone to fire hazards (Gubbi, 2003; Kittur et al., 2014; MoEF, 2006). Highly fragmented forests coupled with a more severe degradation caused by human interferences have many physical, chemical and biological barriers that reduce the resilience of these forests and affect natural regeneration processes, i.e. *Boswellia serrata* and *Lannea coromadelica* tree species in Rajasthan (Pachauri and Sridharan, 2003; Yadav and Gupta, 2009). Regeneration and establishment of many woody species in arid and semi-arid areas are rare event. Significantly low number of saplings recorded in different land uses in western Rajasthan is the example (Table 12.1). This is mainly due to the occurrence of excessive water stress caused by low rainfall and/or high evapotranspiration rates and soil conditions (Jat et al., 2011; Rathore and Verma, 2013). However, the establishment of these woody species would be possible after years of above normal and well-distributed rainfall (Pelaez et al., 1992). In the conditions of reduced natural regeneration, human interventions are necessary where artificial means like seedlings plantation or direct seed sowing are applied to start processes of soil covering and vegetation restoration. The method of direct seed sowing in restoration of degraded ecosystems has become a viable alternative for this purpose, as opposed to the conventional method of planting seedlings (Ferreira et al., 2007).

There is traditional practice of sowing seeds of *Artocarpus heterophyllus, Madhuca indica, Syzygium cuminii, Butea monosperma, Phoenix sylvestris, Zizyphus* spp., *Mangifera indica, Azadirachta indica* and many other species in Vindhyans and Aravallis in Rajasthan. Direct sowing requires simple technique for rainwater harvesting in combination with soil manipulation to prepare seeding beds before sowing. Depending upon the locality factors such as soil conditions, aspect, soil moisture, slope and availability of natural rootstocks, a combination of practices are followed. These are: (i) direct seeding; (ii) direct seeding and facilitation of rootstocks/rootsuckers to resproute, (iii) seeding, sprouting, and minimal planting, and (iv) utilization of facilitative effects of trees and shrubs. Out of all these, the least costly and most useful model is direct sowing or in combination with assistance to the natural regeneration through sprouting of the persistent rootstock.

Table 12.1 Population (numbers ha^{-1}) of tree saplings influenced by land-use and forest ranges in Jodhpur district. Values are mean ±SE of five replicate plots.

Forest range	Land use				
	Agriculture	Forest	Oran	Pasture	Roadside
Baap	11.20±4.95	15.00±8.90	9.40±4.35	3.60±0.81	5.00±2.72
Balesar	17.80±11.83	9.80±4.16	10.60±4.93	3.20±0.66	9.60±3.49
Bhopalgarh	50.20±33.45	9.20±2.92	13.60±3.59	6.20±2.85	7.20±4.31
Bilara	17.60±9.27	8.00±3.45	8.80±2.22	11.60±3.67	41.80±14.54
Luni	16.60±4.80	6.60±1.78	6.20±2.20	5.20±1.46	6.40±2.50
Mandor	39.80±13.65	23.40±8.21	11.40±2.01	8.20±2.24	47.20±17.17
Osian	13.60±7.03	4.40±1.50	14.20±0.97	12.40±3.08	10.20±3.10
Phalodi	15.80±6.20	19.80±11.51	7.80±1.16	8.20±3.26	8.40±2.93
Shergarh	8.00±5.09	10.60±4.71	13.60±4.96	25.60±5.83	5.80±2.08
Mean	21.18±4.60	11.87±2.07	10.62±1.07	9.36±1.34	15.73±3.36

2. ASSISTED REGENERATION

Assisted natural regeneration (ANR) is a cost effective method of reforestation, which encourages natural establishment of indigenous trees and shrubs by countering particular limiting factors, such as insufficient dispersal of tree seeds into cleared areas, lack of beneficial shade or excessive competition from weeds etc. (Hardwick et al., 2004; Shono et al., 2007). However, ANR is applicable for restoring areas where some level of natural succession is already in progress. The most important condition is sufficient availability of root stock so that regeneration could be accelerated. For example regeneration of *Beilschmiedia* spp., *Prunus cerasoides* and *Engelhardia spicata* in deforested areas is limited by various factors operating at different stages of the life-cycle. A rapid establishment of a nurse crop, either by weeding around naturally established trees and shrubs or by planting fast growing trees is suggested as an effective way of assisting a diverse range of species by overcoming limiting factors like thick grass litter accumulation, lack of habitat for birds and lack of shade (Hardwick et al., 1997). Sometimes seedlings of pioneer tree species are often present among and below the unwanted vegetation, but the minimum required number of preexisting seedlings to implement ANR depends on the acceptable length of time for restoration for the forest to be restored and site-specific conditions influencing the rate of recovery of the forest ecosystem. According to the existing literature (Jensen and Pfeifer, 1989) on dry tropical forests a density range of 200 to 800 seedlings (>15 cm height; counting clumps in 1 m^2 as one seedling) per hectare is suggested for ANR reforestation. Further, at least 700 seedlings/ha are required during the early treatment period in order to achieve canopy closure within three years. Proximity relic forests facilitate successional development by supplying seeds. Additional planting is suggested only when the density of natural regeneration is not sufficient. However, most important is the prevention of further disturbances such as fire, grazing, and illegal removals as the success of ANR ultimately depends on the continued protection of the site. Under this the work plan should remain flexible, and the treatments are adjusted according to how the vegetation responds to interventions.

Resprouting is an important mechanism of regeneration in most of the species in dry areas and must be considered for restoration (Vieira and Scariot, 2006). However, species loose re-sprouting ability under sequential cutting, fire, and intensive tractor use. Reduced number of sapling and young trees of *Prosopis cineraria* and other trees in agriculture lands of north-western India is a burning example where tractorization has caused a massive loss of indigenous vegetation. Sprouting from root suckers are more common as compared to the above-ground sprouts in the species of tropical dry zones, where hardwood species are better sprouters because of slower rates of decay in their roots and stems than the respective part of softwood species. The slow rates of decay in these plant parts have been described as the factor responsible for greater resprouting in dry forests than in the rainforests (Ewel, 1980). Further, species with high root to shoot ratio- a characteristic of the trees or shrubs of dry regions and species with high starch concentrations, particularly carbohydrates in roots, are also strong resprouters (Bond and Midgley, 2001). However, there are variables reports on the resprout capacity depending on the types of the species and the age of the trees (Kammesheidt, 1999). In Paraguay, the percentage of resprouts declined from 76% in the young forest fallows (2–5 years old) to 48% and 14%, respectively in 10 to 15 year old and mature forest, whereas in Venezuela, the proportion of resprouts from the youngest logged stand (5 year old) to the oldest logged stand (19 year old) and mature forest increased slightly from 10% to 16% and 17%, respectively (Kammesheidt, 1999). A field level assessment made on natural regeneration treated under ANR showed only 1500 plants/ha in the formation year 1996 that enhanced to 4,971 plants/ha in 1999 under the protection from grazing and fire (Prasad and Kotwal, 2001). These are the varieties of technical methods, which could be used in applying ANR to make dry forest more dense and productive (Fredericksen, 2011).

In some of the cases, natural regeneration is provided by cutback to degraded stock (*Anogeissus pendula*, *Prosopis cineraria*, *Salvadora oleoides* etc.), cultural operation in bamboo clumps (soil working and water harvesting), making saucer-shaped micro-catchments around germinating seedlings from persistent soil seed bank, stem singling in multiple coppice and circular trenching for inducement of root suckers around the trees of suitable species like *Azadirachta indica*, *Prosopis cineraria*, *Tecomella undulata*, *Boswellia serrata, Diospyros melanoxylon* etc (Fig 12.1).

Figure 12.1 Resprouting from root suckers of *A. indica* after trenching around tree (left) and facilitative effects of *E. caducifolia* on growing *Sarcostema acidum* (right) under ANR.

This combination enhances productivity and biodiversity in restoration area. Depending upon the stated preference of the local people, species for timber, fodder, fuel, fruit, oil, medicines and other non-timber forest products are chosen for direct sowing. In the past, only spiny and xerophytic species were tried. However, now about 50 species are directly sown. Some of the multiple-use species that are giving good success include *Madhuca indica*, *Syzygium cuminii*, *Butea monosperma*, *Phoenix sylvestris*, *Zizyphus* spp., *Mangifera indica*, *Azadirachta indica*, *Pongamia pinnata*, *Tamarindus indica*, *Terminalia arjuna*, *Terminalia bellerica*, *Acacia catechu*, *Acacia nilotica*, *Acacia leucophloea*, *Acacia senegal*, *Aegle marmelos*, *Emblica officinalis*, *Holoptelia integrifolia*, *Annona squamosa*, and *Boswellia serrata* among others. Sample count in 2 to 10 years old plantations over 20,000 ha area in Aravallis suggests about 50% survival of directly sown and germinated seedlings in the long-term (Pandey and Prakash, 2014).

3. DIRECT SEEDING

Direct seeding is a regeneration method of sowing seeds directly to the soil resulting in a forest stand after germination and establishment. Direct seeding is a commonly used method for long time ago by farmers in generating crop and wild plant, where seeds are directly sown to the soil either after pretreatment or without pretreatment (Hossain et al., 2014). It involves collecting seeds from local sources, storing them until sowing, identifying the germination niches or preparation of site to optimize the germination, and sowing seeds at the onset of monsoon season for best results (Fig 12.2). By focusing greater on the sites where natural regeneration or seedlings plantation cannot be performed, direct seeding offers various possibilities like the ability to rapidly increase the area being forested and has ability to provide rural people with an inexpensive method to obtain benefits from trees (Mattei, 1995)**.** Besides that, it shows favourable results in degraded areas of difficult access and steep terrain slopes (Barnett and Baker, 1991). Though the sites which are relatively dry or have high erosion potential are generally avoided under direct seeding; but it has been applied across a range of tropical forests with varying degree of degradation (Hardwick et al., 1997; 2004; Pandey and Prakash, 2014). However, performance of seed sowing also depends upon site conditions as well as species suitability. The experiment conducted on the species *Ruagea glabra*, *Otoba novogranatensis* and *Garcinia intermedia* indicates that former two species showed relatively high mortality in pastures and secondary forests between year 1 and year 2, but performed well in plantations, whereas *Garcinia* consistently showed high survival in all habitats and appeared well suited to direct seeding in a range of conditions (Cole et al., 2010).

Direct seeding from the air has been widely used in China where more than 15 million ha were reforested during 1956 and 1985 (Xinhua and Jingchun, 1988). Direct seeding has also been engaged on a large scale for regenerating *Acacia nilotica*, *A. seyal, A. melifera* and *Balanites aegyptiaca* and is the best method for regenerating doum palm *Hyphaene thebaica* (Ochsner, 2001). In India, a field trial on coalmine-spoils investigating several species of trees, grasses and herbs found seedling emergence between 20% and 85 % (Jha and Singh, 1993), where species that produced most biomass was found to be pigeon pea (*Cajanus cajan*). This technique fulfils the goals of producing biomass economically by conserving water, nutrients, and provides a backup in case of mortality of the planted seedlings etc (Lohrey and Jones, 1983; Beaufait et al., 1984). However, direct seeding is recommended only for some initial pioneer and secondary species in areas lacking vegetation, and also for late secondary and climax species, for the enrichment of secondary forests (Kageyama and Gandara, 2004).

Figure 12.2 Direct sowing through broadcasting *C. mopane* (left) and hole preparation for seed sowing.

4. SEED SOWING VS. NURSERY RAISING

Sowing seeds help overcome the limitations of seed availability or absence of soil seed bank - a potential constrain in many dry areas (Sitters et al., 2012). By comparison raising seedling in nurseries put additional cost in the form of soil preparation and amendments, plastic bags, required watering, transport of the seedlings to planting sites and labour to look after the seedlings (Table 12.2). Besides, use of pesticides, fertilizer and plastic bags pollute the environment. While direct seed sowing has economic and time-saving benefits, especially in remote areas, mechanical injuries and desiccation damage to seedlings during handling and transport can also be avoided (Gerhardt, 1996). Cost analysis of one hectare plantation (2500 plants) in New Zealand indicates a range between NZ$ 13955 and 23535 as compared to direct sowing cost of NZ$ 4915 to 14300 (Douglas et al., 2007). In another study cost for direct seeding has been found 10 to 30 fold less per 100 seedlings after 2-year as compared to the nursery-raised seedlings planted at the same sites. Though planting nursery-raised seedling is effective to rapidly establish canopy cover and restore large areas but is costly, whereas direct seeding is a more efficient way to enrich an existing degraded ecosystem (Cole et al., 2011).

Direct sowing provides benefits of selecting large number of species for which raising seedlings in the nursery will not be practical. By using a large number of species per unit area direct sowing helps in enhancing not only species richness but also help in developing multi-tier forest stands diversity (Pandey and Shukla, 2001). Besides this direct sowing is also advantageous in maintaining species mix and extensive root system of the seedlings which is more likely to be able to reach deeper soil layer where possibility of soil moisture is relatively higher, particularly after the rainy season (Fig 12.3).

Table 12.2 Advantage of direct sowing vs. planting, where '+' indicates advantages and '–' indicates disadvantages.

SNo.	Activities/aspects	Direct seeding	Planting
1	Time in revegetation	+	
2	Labour involvement	+	
3	Seed/seedling handling		
4	Initial costs	+	
5	Root system	+	-
6	Species mixture	+	-
7	Remote areas	+	-
8	Deep, non-wetting sands or heavily textured soils	-	+
9	Establishment	-	+
10	Weed competition and herbicide application	-	+
11	Mechanical weed control	-	+
12	Survival chance	-	+
13	Predation risk	-	+
14	Nursery costs	+	-
15	Risk of drying up before planted		-

An experiment conducted in Indian arid zone indicates significantly higher growth of roots than shoot, i.e. about three fold in *A. indica* and 4-fold in *C. mopane* (Table 12.3). Direct seeding promote natural root development 100 times larger root volume than in container grown plants and have lesser height to collar diameter ratio. In direct sown seedlings, there are potentially lesser root deformation providing optimal root-soil contact and undisturbed taproot for effective anchoring and tolerance to wind (Saifuddin and Osman, 2014). Anchoring strength of root depends upon stem volume, tree height to diameter ratio, and root plate width (Moore, 2000). This indicates that decrease in tap root diameter negatively affects the anchoring power of the root for the seedling as whole. Thus the seedlings that originally have been directly sown may compensate for their less advanced develop-ment stage by the absence of planting and field stress. In addition, direct sowing can either be used as a stand-alone restoration programme or can be combined with advance closure, assisted regeneration, and plantations depending upon site conditions and cost involved.

However, major difficulties related to direct sowing are inconsistency concerning emergence, survival, and growth of plants under varying climatic conditions that require a fair analysis of the results and the cause of such variations (Winsa and Bergstein, 1994). Some factors may be associated with the difficulty in applying this method to large areas because of high diversity of the existing vegetation in the tropical forests. Further, little knowledge about the species demands in the environment as to the essential factors to the emergence and development of seedlings, such as light, temperature, and required soil water. Another problem is related to the explanation about the relation between the survival of the seedlings and quantity of seeds that will be sown in order to assure a good recovery and good development of the species. For example 1.2% and 9.7% seedling establishment for

A. indica and *C. mopane*, respectively in Table 12.3 indicates wide variability in the quantity of seeds to be used under direct sowing.

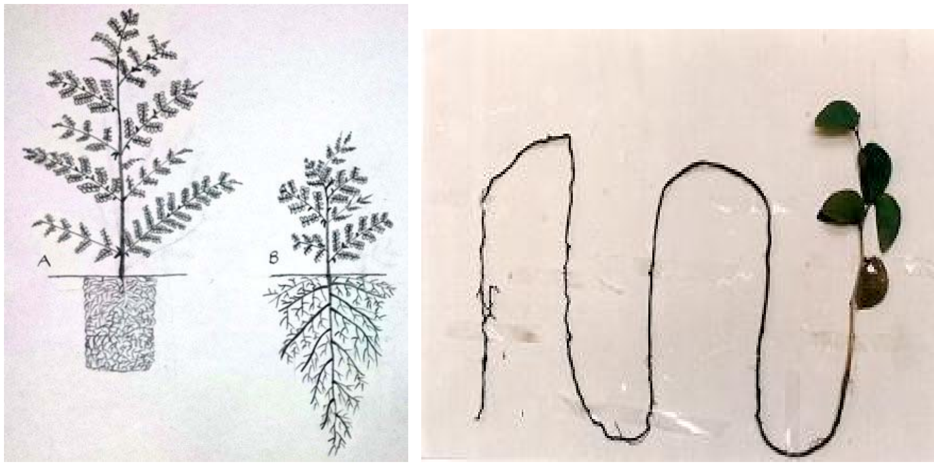


Figure 12.3 Diagrammatic differentiation in root and shoot growth of the seedling grown in nursery (A) and direct seeded (B) in field condition (left) and 9 months old field grown seedling of *C. mopane* (right).

Table 12.3 Seed germination, survival and growth of germinated seedlings of *Azadirachta indica* and *Colophospermum mopane* under direct seeding. (Source: Singh and Rathod, 2006a).

Parameters	*Azadirachta indica*		*Colophospermum mopane*	
	8 April 02	17 July 02	8 April 02	17 July 02
Number of seeds sown	1530	–	955	–
Seeds germinated (nos) 25 July 01	825	–	903	–
Seedling survival (Nos)	21	9	91	87
Seedling survival (%)	–	1.2	–	9.7
Height (cm)	11	23	18	28
Collar dia. (cm)	0.28	0.31	0.42	0.49
No. leaves	14	17	7	24
No. branches	1	1	1	3
Root length (cm)	–	60	–	121

5. SOIL SEED BANK

Soil seed bank is as an important component for resilience of climatic vegetation, particularly in dry areas. It is one mechanism that allows plant species to persist in highly stochastic environments. Frequent disturbances are more common for persistent seed banks (Abernethy and Willby, 1999; Holzel and Otte, 2004; Reubens et al., 2007), and also occur in some dryland areas that have highly episodic resource pulses, like scrublands of desert (Guo et al. 1999). In an experiment, Olano et al. (2012) observed nearly 24% of the seed bank density due to secondary dispersal, where 66.41 – 71.33% seeds died before emergence, 14.08 – 15.48% emerged and remaining 14.59 – 18.11% persisted in the soil. Recovery is based mainly on the seed rain at small scales together with secondary dispersal from intact seed banks in the vicinity emphasizing the relevance of processes occurring on short spatial scales. Persistent seeds are smaller than transient seeds, but a clear separation have been observed within the persistent seed group like smaller-diaspored hydrophytes and larger-diaspored xerophytes (Stromberg et al., 2008). In most of the cases (Birhane et al., 2007; Kellerman and Van-Rooyen, 2007; Teegalapalli et al., 2010), soil seed banks are dominated by grasses, sedges, or forbs (including invasive ones), with limited number of woody species. The study of Daïnoua et al. (2011) also indicates that out of the seeds of 43 species, only three were of tree species. Here seedlings emerged from the soil samples were mostly from weedy and short-lived pioneer species, where climax species predominated in the extant vegetation, leading to a very weak similarity between soil seed flora and the surrounding vegetation. This shows that the soil seed bank contribution to the resilience of mature tropical forests is low as very few tree species could benefit from soil seed stocks for their regeneration. In such a circumstance enrichment techniques using soil seed bank as a source of tree regeneration may not be useful rather harmful in the form of unwanted growth enhancing management cost.

However, there are reports where soil seed banks have sufficient number of seeds of trees species in soil seed banks (Teegalpalli et al., 2010). Sapkota et al. (2009) related varieties of diversity measures and regeneration attributes to gap characteristics in a forest in Nepal. Stem density of tree and shrub components were higher in the gap than in the intact vegetation. Seedling densities of *S. robusta* and *Terminalia alata* (B. Heyne ex Roth.) were higher in the gap than in the intact vegetation, while contrary result is observed for *T. bellirica* (Gaertn. ex Roxb.) and *Syzygium cumini* (L. Skeels) in term of seedling density. Gaps created by multiple tree falls in different years had higher seedling density of *S. robusta* than gaps created by single and/or multiple trees falls in the same year. Thus gaps maintain species diversity by increasing seedling density, and favour regeneration of Sal forests. In another study (Khare and Kahre, 2012) on species diversity and density of soil seed bank in top 10 cm of soil in tropical dry deciduous forests in Central India indicates seeds of total 34 species (a total of 17 species of trees, 4 species of shrubs and 13 species of herbs). The highest density in upper layer (0-5 cm) was of *Anogeissus pendula* (density of 800 seeds per sq meter) under the canopy zone. Maximum densities in case of shrub and herb species were contributed by invasive *Lantana camara* (175 seeds per sq meter) under the canopy zone and *Cassia tora* (850 seeds per sq meter) in inter canopy zone (Khare and Kahre, 2012). Favourable microsite and edaphic factors also play an important role in seedling emergence from soil seed banks (Gad and Kelan, 2012) as observed on sand dunes, where soil seed bank and seedling emergence varied with location, direction, level of sand dunes, and micro climate play an important role in soil seed bank.

6. TARGET SPECIES

Direct seeding is recommended primarily to use the species which occur naturally in the region, or native species that may be associated with different ecological groups, and have the socioeconomic importance for the local communities within the areas under restoration. Many species have a wide range of geographical distribution, with genetically adapted characteristics to different environmental conditions found within their historic range. Populations of such species show a differential provenance related germination, seedling growth, disease resistance, responses to frost and resilience to water and environmental stresses (Khurana and Singh, 2001). Performance of seed sown seedlings of *Acacia catechu*, *Acacia senegal*, *Azadirachta indica*, *Zizyphus mauritiana* and *Jatropha curcas* were compared with the planted ones at 65 months of age under varied slopes and rainwater harvesting (RWH) treatments. Performances of seed grown plants of *Acacia catechu, A. senegal* etc. were equally good or out performed than the planted seedlings, but plantation of *Z. mauritiana* and *A. indica* performed better than their seed sowing counter parts (Singh, 2011). RWH facilitated growth, whereas increase in slope gradient affected growth negatively depending upon soil conditions and soil water stresses. Direct sowing can be used both for implementation of pioneer species in areas without forest covering, and for the implementation of slow-growing species (i.e., late secondary and climax species) in the enrichment of secondary forests (Kageyama and Gandara, 2004).

Most commonly recommended species for seed sowing are of genus *Pinus, Eucalyptus, Acacia* and *Prosopis*, even in the countries or regions where these species do not occur naturally (Maury-Lechon, 1993). This is because of their associated use with positive socio-economic impacts, adaptation to the climatic conditions, and that they do not compromise the local ecological balance. Legume seeds typically have tough, smooth seed coats, making them resistant to desiccation and predation. Besides, the nitrogen-fixing capability of many of the legume species provides them a competitive advantage over the weeds (Elliot et al., 2013). However, there should be a careful planning for gradual replacement of these species by development of the native species with time advancement. In such a condition, the exotic species are also initially recommended in view that these species may play the role of pioneer species particularly in the areas where the extent of degradation is high, which require a long-term recovery (Durigan, 1996). Because of their ability to grow rapidly, the early-successional and pioneer species are more suitable for direct sowing. However, late-succession and climax tree species can also be successfully established by direct sowing. Indeed, by virtue of their large seeds and food reserves, the seeds of climax forest trees provide much better result in tropical dry forests (Elliot et al., 2013). Species with large seed mass (>0.1 g dry mass), spherical in size and medium in moisture content (36–70%) establish successfully under direct sowing because large food reserves make the seedling robust with advantages of growing even in association with existing vegetation (Kumar and Mishra, 2009a; Elliot et al., 2013; Owoh et al., 2011). Therefore it is very pertinent to identify the context-specific species for direct sowing based on following criteria (Cole et al., 2011; Douglas et al., 2007; Mulawarman et al., 2003) that are in coherence with ecological, economic and social sustainability:

- Indigenous to the region with multiple benefits to support livelihoods of the local communities. This includes cultural and ecological keystone species and sacred species as they are ecologically important and socio-culturally adopted.
- Relatively faster in growth with dense canopy to compete with herbaceous exotic species or with nurse effects to promote autogenic regeneration through facilitation.
- Easy to collect and store seeds, but without compromising the intended diversity and mixture of the species.
- Adaptation to direct sowing under open area with low to moderate fertile soils without affecting the regional biodiversity.
- Tolerant to browsing by domestic and wild animals but preference to the species producing edible and useful produce for wildlife
- Show good association with biological status of the soils, e.g. mycorrhizae, rhizobium, promoting soil development and growth of other saplings growing in their vicinity.
- Rate of seedling establishment, particularly time from sowing to germination and seedling growth rate within the first 6–12 months.

Table 12.4 Tree species for seed sowing tested under aerial seeding in different region of India.

Species	Tested Location	Reference
Acacia tortilis	Barmer	–
Acacia nilotica	Many parts of India	Afridi (1951), Joshi (1986)
Acacia senegal	Indian dry zone	–
Colophospermum mopane	Barmer, Bikaner, Jodhpur	Singh and Rathod (2006b)
Dichrostachys nutans	Bikaner	–
Prosopis cineraria	Bikaner	–
Zizyphus rotundifolia	Bikaner	–
Prosopis juliflora	NWF, Pakistan	Afridi (1951), Joshi (1986)
Prosopis glandulosa	NWF, Pakistan	Afridi (1951)
Acacia modesta	NWF, Pakistan	Afridi (1951)
Acacia arabica	NWF, Pakistan	Afridi (1951)
Parkinsonia aculeata	NWF, Pakistan	Afridi (1951)
Dalbergia sissoo	Chambal Ravines	Joshi (1986)
Holoptelea integrifolia	Chambal Ravines	Vedant (1954)
Acacia catechu	Chambal Ravines	Joshi (1986)
Butea monosperma	Degraded hills, Banswara	Singh (2012)
Terminalia belirica	Degraded hills, Banswara	
Azadirachta indica	Degraded hills, Banswara	
Emblica officinalis	Degraded hills, Banswara	
Zizyphus mauritiana	Degraded hills, Banswara	
Salvadora oleoides	Indian dry zone	–

However, to restore tropical dry forests the 'framework species method' or agglomerating seeds of a large number of species (30 to 40 indigenous forest tree species from different families) have been observed more useful which enhances seedling emergence and growth many fold together with maintaining biodiversity (Madsen et al., 2012). Thus multiple use trees, shrubs, and herbs suitable for direct seeding should form the pool of species for direct sowing. Pelleting of agglomerated seeds may be more beneficial in spot sowing in dry areas. Using large number of species from both early and later successional stages as well as leguminous and non-leguminous species will result into higher initial diversity that may also be supplemented by colonization from nearby remnants forests (Eklinder-Frick, 2014).

7. NURSE PLANTS AND THEIR EFFECTS

Many trees and shrubs species can have a net positive effect on germination and recruitment of other species, i.e., target species. The establishment of later species in arid environment depends completely on their so-called nurse plants (former species), a phenomenon which has been studied better for Cactaceae (Valiente-Banuet et al., 1991; Godínez-Alvarez et al., 2003). In arid areas temperature, soil moisture, soil nutrients and radiation regimes are different under tree/shrub canopies in comparison of with open spaces (Belsky et al., 1993; Belsky and Canham, 1994; Singh et al., 2008). Experimental evidences indicate that some of these conditions like shading and higher nutrient levels, improve survival and growth of seedlings of target species under canopy plants as compared to those in open areas (Carillo-Garcia et al., 2000; Singh et al., 2003b). Nurse plants are those which facilitate the growth and development of other plant species (target species) beneath their canopy because they offer compassionate microhabitats that are more favourable for seed germination and seedling recruitment than their surrounding environment by ameliorating light, temperature, soil moisture and nutrient, as well as avoiding grazing (Bruno et al, 2003; Padilla and Pugnaire, 2006). Nursing effects not only vary between the species of different plant habit but also with sex (dioecious trees) as most of the young seedling were observed underneath female *Juniperus thurifera* trees than the male ones. Attraction of frugivorous birds by reproductive female junipers and improvement of environmental conditions beneath tree canopies were described as the main factors responsible for the variation in seedling density among these microhabitats, i.e. highest underneath female trees and lowest in open interspaces (Montesinos et al., 2007). Nursing effects can be shortly described in to following points (Kos and Poschlod, 2007; Ren et al., 2008):

- This phenomenon takes place mostly on the early stages of restoration in degraded ecosystem or succession in plant community.
- Nursing effect on the earlier stage of restoration or succession is mostly observed as shrubs nursed by grasses and trees nursed by shrubs.
- Nursing effects usually occur among the native species in corresponding pairs.
- Some exotic leguminous species can serve as good nurse plants by ameliorating nitrogen in soil and providing shade for target species either shrubs or trees.

- Nurse plants have better adaptation than those of the target species, including being light-dependent, fast-growing, infertility resistant and drought tolerant.
- The individuals of target species are generally smaller than those of nurse plants in the early stage.
- Seedlings can successfully be established around the adult plants in forests for the amelioration of some extreme ecological factors.
- Nurse plants are considered not only to play a key role in recovering the properties and functions of the primary ecosystem, but also to drive succession in poor environments on the early stage of restoration.

Nurse plants can be used to restore vegetation in arid and semi-arid zones because of their positive interactions with the established seedlings of target species. Unpalatable species are also used as nurse plant in heavily grazed sites, because these nurse plants provide refuges for small animals and target species (Padilla and Pugnaire, 2006; Sánchez-Velásquez et al., 2004). Legumes species are potential nurse plants which can improve the survival and growth of target species in desert and Mediterranean semi-arid habitat for their amelioration in soil nitrogen and overshadow function, *Acacia auriculeformis*, and *Acacia mangium* are the examples (Ren et al., 2008). Some of the important nurse plants of Indian arid zone are *Prosopis cineraria*, *Euphorbia caducifolia*, *Suaeda nudiflora* etc which supports many species growing in their vicinity (Table 12.5). However, the effect is undesirable when both nurse and target plants are legumes (Gómez-Aparicio et al., 2004). Likewise some species like young trees and seedlings of *Ougeinia dalbergioides* need a moderate amount of shade, but once established requires full sunlight for its best development (Orwa et al., 2009).

Table 12.5 Some nurse plants and the target species of Indian dry regions.

S.N.	Nurse plant	Target species
1	*Prosopis cineraria*	*Salvadora oleoides, Azadirachta indica, Lycium barbarum, Zizyphus nummularia, Cocculus pendulus*
2	*Prosopis juliflora*	*Azadirachta indica*
3	*Capparis decidua*	*Zizyphus nummularia, Ephedra foliata, Rivea hypocraterformis, Lycium barbarum, Abutilon bidentatum*
4	*Acacia tortilis*	*Aadirachta indica*
5	*Maytenus emarginata*	*Ephedra foliata, Zizyphus nummularia*
6	*Euphorbia caducifolia*	*A. indica, Acacia senegal, Anogeissus sericea, Grewia tenax, G. villosa, Commiphora wightii, Vernonia cinerescence, Anogeissus pendula*
7	*Calligonum polygonoides*	*Cassia angustifolia*
8	*Suaeda nudiflora*	*Salvadora oleoides*
9	*Panicum turgidum*	*Carulina edulis*
10	*Acacia mangium*	*Castanopsis hystrix*, *Michelia macclurei*, *Manglietia glauca*
11	*Acacia auriculeformis*	*Castanopsis hystrix*, *Michelia macclurei*, *Manglietia glauca*

In desert, shrubs usually act as better nurse plants for other seedlings, especially cacti. Traditionally people of Rajasthan, India have used *Euphorbias* bushes to act as a host for directly sown seeds. Before the onset of monsoon a small patch of soil under the Thor bushes is dug up with an iron rod or wooden tool and few seeds of the desired species are sown. Since *Thor* bushes are evenly spaced and distributed over the large tracks, sowing automatically gets spaced and sapling can easily be traced for subsequent silvicultural operations (Fig 12.1). Further, pioneer shrubs facilitate the establishment of woody late-successional species and thus help positively in reforestation success in many different ecological settings (Gomez-Aparicio et al., 2004; Kos and Poschlod, 2007). In forest, seedling establishment may be enhanced in the vicinity of adult plants that improve some extreme ecological factors (Cavieres et al., 2006; Fajardo and McIntire, 2011).

8. FACTORS OF DIRECT SEEDING SUCCESS

8.1 Seed size, dispersal, and seed bank

Forests of dry areas are characterized by a relatively large number of tree species producing large amounts of small and dormant seeds able to form a persistent soil seed bank dominated by wind–dispersed seeds as compared to vertebrate-dispersed seeds (Bhuyan et al., 2000, Teegalapalli et al., 2010). Seed traits like seed weight and size have been found to influence seed output and variations in germination (Henery and Westoby, 2001; Gunaga et al., 2011) in tree species like *Alangium lamarckii* Thwaites (Ahirwar, 2012), *Leucaena leucocephala* (Lam.) De Wit (Alam et al., 2005), *Jatropha curcas* L. (Singh and Saxena, 2009) and *Azadirachta indica* A. Juss (Kumar, 2007). Large seeds are generally associated with tall tree species (Grubb, 1998), shade tolerance species at the intergeneric level (Mehlman, 1993; Metcalfe and Grubb, 1995), nutrient-poor sites (Milberg et al., 1998) and the site with an abundance of insects and pests (Coley and Aide, 1991). In contrary, Haig and Westoby (1988) suggested that resource limitation does not increase the production of large size seeds rather plants use to alter their seed number rather than seed mass. Among the fruits of a plant, trade –offs between seed number and seed mass indicate the inability of the plant to readjust but all seeds equally well under resource-limited conditions (Mehlman, 1993). Response to daily temperature fluctuations also influence to change the seed size as small-seeded species do not use this as gap detection cue, whereas large-seeded species do it as in pioneer rainforest trees (Pearson et al., 2002). This indicates that small-seeded species are more affected by daily temperature fluctuations than the large-seeded species as small seedlings are less tolerant of environmental hazards like drought (Leishman et al., 2000). Species with very small seeds (<2 mg) are generally triggered for germination by light, as they require to photosynthesize soon due to limited internal resources, whereas the larger seeds (>2 mg) are stimulated by temperature alternation because of the larger amount of internal resources under which the seedlings reach the soil surface even when the seeds are buried in deeper soil layers (Pearson et al., 2002). Temperature alternation appears to be a more important stimulus for the species with larger seeds as increase in seed mass adheres to a decrease in the need for light and an increase in the tolerance to alternating temperatures (Aud and Feraz, 2012; Sotomayor et al., 2014). Literature shows that inhibition of germination at temperature regimes characteristic of high radiation of open area are observed in fleshy-fruited species of widely divergent taxonomic groups, where germination mechanisms to detect canopy shade based on temperature signal have been observed in many species depending on nurse plants, especially bird-dispersed species (Leishman et al., 2000). A positive correlation exists between seed size and survival across various types of tropical forests. This suggests large-seeded non-pioneer species are more suitable for direct sowing as compared to small-seeded species (Camargo et al., 2002; Laborde and Corrales-Ferrayola, 2012). For instance, the 34 species recommended for direct seeding in Amazonia had predominantly large seeds (Knowles and Parrotta, 1995).

Wind-dispersed seeds of the species of dry areas are smaller and drier, that help them to reach a larger distance. For example, anemochoric seeds are 47 times more frequent than animal-dispersed seeds (3 vs. 141 seeds m^{-2} $year^{-1}$) in open pastures up to 250 m from the adjacent forest (Holl, 1999). Further, high number wind-dispersed seeds are better able to colonize degraded areas as compared to the vertebrate-dispersed seeds (Zimmerman et al., 2000). Small seeds and those with low water content are less susceptible to desiccation, which is a major barrier for establishment in open areas. The seed dormancy overcomes by environmental conditions like high irradiation with an increased proportion of red light, i.e. available in open areas, high or alternating temperatures or a combination of these factors. This is only to provide favourable environment to seedling growth as seeds with small nutrient supplies are not able to sustain development for long periods in a shady habitat (Souza and Válio, 2001), though some species can germinate even in diffused light under a dense canopy or at constant temperature (Pearson et al., 2002).

In general, high seed availability in the soil at the end of the dry season in tropical forests is only to maximize the time to germinate and grow during monsoon rains. However, seed production and its availability in soil seed bank are highly influenced by highly variable precipitation and frequent dry spells leading to mortality in seeds as well as the germinated seedlings (Yadav and Gupta, 2009). Small seeds have a comparatively better potential to enter into the soil and facilitate a persistent soil seed bank, necessary for autogenic and spontaneous regeneration during monsoon rains. The factors that extend seed longevity and persistence of soil seed bank are small seed size, seed dormancy, and the dry condition in the field (Aud and Feraaz, 2012). Isolated trees or shrubs present in degraded areas provide perches for birds and bats and increases the number of vertebrate-dispersed seeds up to more than hundred times relative to the open areas (Slocum and Horvitz 2000). Further, some species are successfully colonized by cattle or wild animals particularly the large seeded ones (Janzen, 1981; Aide et al., 2000). However, due to reduction in population of seed dispersers some species do not colonize areas even after decades of secondary succession (Marcano-Vega et al., 2002; Beckman and Rogers, 2013).

8.2 Seed collection, storage and treatments

Many species have a wide range of geographical distribution, with genetically adapted characteristics to different environmental conditions found within their historic range. Populations of such species show differential provenance related germination, seedling growth, disease resistance, responses to frost and resilience to water and environmental stresses particularly in dry areas (Khurana and Singh, 2001). In practical seeds should be collected locally or from the isoclimatic regions, but from phenotypically superior trees, so that advantage of context-specific local adaptation, developed in the long-term evolutionary period could be utilized (Kumar and Mishra, 2009a). Some criterion (Commander et al., 2013) for selecting the tree for seed collection could be:

- Collection of seeds of a particular species should be from 10-15 trees which are preferably 100 m or more apart to cover the largest possible number of widely dispersed trees.
- Stands with numerous heavily laden trees should be preferred for seed collection, whereas sparse seeded trees or heavy seed trees restricted to isolated conditions should be avoided.
- Seed collection should be from vigorous trees of good form.
- Seed collection should be across the range of site conditions preferably after stratification like ridges, gullies, soil types, aspect etc.

Careful observation of tree phenology like fruit ripening, seed fall and the amount of seeds visible on the trees before seed fall will help in deciding the time of seed collection, i.e. the second fortnight of March is optimum time for collection of seeds of *Anogeissus latifolia* and May to June for *Salvadora* spp. (Anon., 2010; Mathur and Sharma, 2015). Seeds of the majority of species of dry tropical forests possess orthodox character which tolerate relatively long storage periods, and hence have inherent primary seed dormancy and can be stored for longer duration (Orwa et al., 2009). These species belong to genus *Acacia*, *Gmelina*, *Eucalypts*, *Flacourtia* etc and can be stored for a longer period (Akinnifesi et al., 2007). However, some species also have recalcitrant seeds which are sensitive to desiccation injury and have a short storage period (Berjak and Pammenter, 2004; UmaShankar, 2012). Some of these trees are Salvadora, Mango, Coconut, Rubber, Jackfruit, Jatropha, etc. Some behave intermediate character like Neem, *Shorea* spp. and *Coffea arabica* etc. Physical dormancy is as prevalent in dry tropical tree species as about 76% of dry tropical forest species produce dormant seeds as compared to the tropical rain forests where about 62% species produce non-dormant seeds. In dry forests, about 67% of species yield dormant seeds, whereas about 23% show possible physiological dormancy (Baskin and Baskin, 2001). Existing literatures (Kumar and Mishra, 2009; Moncaleano-Escandon et al., 2013, Mathur and Sharma, 2015) suggest that oil-bearing seeds have low viability period and hence less storage time. For proper storage, seeds must be properly dried and stored at a constant cool temperature and protected from fungal and insect attack until ready to be sown in field. Dry seed can be placed in airtight plastic bags and stored in numbered containers or tins. All extended storage should be in cool rooms at 2 - 4°C.

For most of the species of tropical dry forests, the dormancy is over by the time of next rains. This indicates that one should collect the seeds as and when they ripen during the year, store in cool and dry place and use for direct seeding at the onset of monsoon, which ensure moisture availability for the extended period. Seeds of a majority of species of dry tropical forests mature in summer and are dispersed at the beginning of the rainy season when sufficient moisture is available and environment is conducive for germination and seedling growth (Singh and Singh, 1992; van Schaik et al., 1993). However, the seeds of orthodox category (i.e., hard-coated seeds, such as those of native peas and acacias) require pre-treatment before sowing time (Vilela and Ravetta, 2001). Seed coat dormancy can be overcome by removing part of the seed coat (scarification) that help water uptake. For small quantity of seeds, pressing seeds against an abrasive surface or carefully cutting part of the seed coat with a knife, sandpaper or a file aids to remove dormancy. Other methods (Go et al., 2004; Khurana and Singh, 2001; Nasr et al., 2013) used for overcoming exogenous dormancy are:

- Soaking seeds in hot water up to a temperature of 90°C.
- Drying seeds in a heat oven.
- Soaking seeds in chemicals like hydrogen peroxide and concentrated sulfuric, hydrochloric or nitric acids, but with a great care using skilled workers.
- Use of smoke and smoke water.

In addition to treating seeds to break seed dormancy, seeds should also be treated with a repellent for seed-eating insects, birds, and mammals which will otherwise consume the entire seed crop. The most common repellent for birds is Thiram. Some of the species used under seed sowing are *Prosopis juliflora*, *Prosopis spicigera*, *Tecoma undulata*, *Cordia rothii*, *C. myxa, Zizyphus species, Salvadora persica, S. oleoides* etc. (Prakash and Pathak, 1957).

8.3 Site selections and preparation

Areas for direct sowing should have the conducive conditions so that the seeds could germinate and establish fast *in-situ* even in competition with the other existing vegetation. Direct seeding is often not successful on dry, upland sand or coarse sandy soils where the soil dries out too rapidly and moisture is not sufficient for the seeds to germinate. While poorly drained sites with a flooding period of more than 1-2 weeks leads seeding mortality, the small seedlings are trampled at the sites heavily affected by grazing. Likewise, there are chances of washing out of the seeds on sloped sites (Williston and Balmer, 1983). Though flat areas are relatively better for direct sowing, the chances of availability of such type of lands in forest area are really difficult. Edaphic factors also play important role in germination and seedling establishment as poor soil is a stress factor but the seedling establishment is sensitive to weed infestation as well. Other important factors are access to the site, easiness to do the soil preparation, sowing and weeding practices. Shaded sites are safe in general because the shade counteracts the water limitation in low rainfall periods and reduces seed and seedling desiccation (Lieberman and Li, 1992; Ray and Brown, 1995). Although many tree species need large canopy gaps to regenerate (Pinard et al., 1999; Dickinson et al., 2000), seed germination and early seedling establishment are constrained in open areas, even for light demanding species (Gerhardt, 1996; Woods and Elliot, 2004). A study in dry forests of Jamaica found that the proportion of seeds that germinated in partially shaded (37% full light) or heavily shaded (6% full light) plots was double than that in open plots with 86% full light (McLaren and

McDonald, 2003). In the same experiment, seedling survival was enhanced three to four times in the shaded plots.

In site preparation, the existing vegetation available that would hinder sowing or provide excessive competition to the seedling must be harvested. General options of site preparation are burning, mechanical scarification and/or spraying of herbicides in western countries (Jack et al., 1984). Sites covered by grass are clipped and the new sprouts are killed with a broadcast treatment of herbicide. However, under enrichment programme, the existing shrubs or trees are retained at the site as the retained plants provide functions consistent with the planned use. Retained trees and shrubs also provide den, nesting or roosting sites or mast production till the new planting is established. However, undesirable plants that will compete or provide excessive shade with the germinated seedlings should be removed or killed. Site preparation should be started in mid-summer with start of the rain. In case of high seed predation, seed predator numbers and/or habitat should be reduced. Prior to seeding, adequate protection from fire and livestock should be established. Most of the degraded areas or forest lands are lower in soil organic carbon and the nutrients. Availability of soil moisture is affected badly under low soil organic carbon, for which a soil amendment of organic matter could be beneficial in seedling emergence and establishment.

In highly degraded area, utilization of suitable niche like small bushes, areas of water or silt harvesting etc is more appropriate for seed sowing. Otherwise pits of the size: 0.20 m × 0.20 m × 0.20 m volume at a fixed spacing (i.e., 0.50 m × 0.50 m or 1 m × 1 m) may also be used (Fig. 12.2 right). Poor soil condition may not support nutrient for seedling growth, where application of farm yard manure and single super phosphate can alleviate water stress and facilitate seedling growth (Singh and Singh, 2011a). A better germination niche or microsite is a right place for seed sowing. These sites can have better soil seed bank in naturally intact forests because of seed trapping received through water, moist soils underneath natural shrubs, soil heap on the embankment of saucers around the planted seedlings, contour/staggered trenches or ditch fencing, the trench pit or trenches along the fencing of the restoration area (if soil is still sufficient in depth), freshly scratched and notched-up soil patches, soil bed near natural rock outcrops, rock crevices receiving soil and water, scars of borrowed boulders for fencing, soil or debris heap of the contour dykes and other rainwater harvesting structures (Afridi, 1951; Pandey and Prakash, 2014; Singh, 2012). Better soil moisture regime coupled with mineralization of the soil working in these microsites ensures seed germination and early establishment of the sapling. Sometimes performance of seeded seedlings is observed better as compared to the planted ones, though it is species specific, i.e. better in *Acacia senegal* and *Acacia catechu* but not in *Azadirachta indica* and *Zizyphus mauritiana* (Singh, 2011). Observations collected from experimental plots in late 1950s indicate that sowing on ridged berms results in 100% germination and establishment, where the seedlings grow fast in height as compared to the seedling in gradoni and bottoms of the trenches (Afridi, 1951). Seed broadcasting and planting of the seedlings (i.e., *Acacia tetragonophylla* F. Muell., *Atriplex bunburyana* F. Muell. and *Solanum orbiculatum* Poir.) experiment in Australia indicates an increased seedling emergence for broadcasted seeds under soil raking and/or ripping, but only after sufficient rainfall

(Commander et al., 2013). Under plantation, survival of *A. bunburyana* seedlings was 92% as compared to 13% for *A. tetragonophylla* at almost two years after planting and soil ripping partly alleviated soil impedance and resulted in increased seedling survival.

8.4 Time of sowing

Timing of seed sowing, particularly in arid and semi-arid regions has profound influence on seedling emergence (Carrick and Krüger, 2007; Turner *et al*., 2006). In Mediterranean southwest Western Australia, emergence of Banksia woodland seedlings from seed broadcast in May (autumn) was greater than seed broadcast in July (winter season) (Turner et al., 2006). Tree/shrub seed may be sown anytime from June to October when soil and site conditions are favourable in India. Sufficient soil moisture should be present in upper 20 -25 cm during sowing. Care must be taken to completely cover the seed and achieve good soil-seed contact (Kasera et al., 2002). If seed predation pressure is anticipated or surface soil moisture is limiting, deeper seeding depth is recommended particularly for larger seeds together with herbicide pretreatments. Seeds most often germinate in 2-4 weeks and begin growth before the onset of winter followed by hot dry summer.

8.5 Sowing rates

Direct seeding of native species has not been developed to the stage where field sowing rates can effectively be recommended. There are large differences in germination and establishment rates among tree or shrub species. Thus the amount of seeds required vary according to the species, method of sowing, degree of site preparation, and general ease of regeneration of the site. Burton et al. (2006) recommend that a desirable density is that which creates canopy on at least 50% of the soil cover. In this minimum density shall be related to maximum production, without observing an increment even with an increase of density and when it achieves a balance in demography, without a decrease or failure in the final stand. Further, with regard to the restoration of degraded dry areas in the tropical forest ecosystems, the success of the use of direct sowing is related to the degree of degradation as the possibility of success of establishing seedlings decreases with the increase in the degree of degradation. Sometimes sufficient availability of seeds is not there, whereas environment in terms of sufficient rainfall and soil moisture are at place and site has access to good weed control. It would be useful to collect the top soil from beneath tree canopies of tropical dry forests that have good seed availability in the soil at the end of the dry season and this transient seed bank (i.e., litter and soil) may be a promising strategy for dry forest restoration (Kettle et al., 2008). In general the aim of broadcast sowing is to establish at least 2500 seedlings per hectare or to get a soil cover by at least 50% in tropical dry areas, where about 4% establishment rates are considered for all species in general (i.e., 4 established seedlings per 100 seeds sown). Moreover, on fenced or fully protected sites this rate is assumed to be 8-10%. However, establishment rates also depend on the type of species as well as climatic conditions of the site. For example, establishment rates of *Azadirachta indica* and *Colophospermum mopane* have been observed to be 1.2% and 9.7%, respectively in arid region of Rajasthan India. In new planting situations with relatively severe degradation the recommended sowing rates are very high, i.e., 1,00,000 to 2,00,000 seeds per hectare to overcome early losses. Quantity of seeds required for broadcast sowing can be calculated as:

(i) Rate of stocking (number of plants per ha) = X

(ii) Germination of the seed of a species (%) = Y

(iii) Rate of establishment of the germinant (%) = Z

(iv) Quantity of seeds (nos.) required to achieve the stocking rate= X × (100/Y) × (100/Z)

For example, to get a stocking of 2500 plants per ha for a species at 4% establishment rate and with 90% germination, the quantity of seeds required as calculated with the formulae is 69,444, i.e. 2500 × 100/90 × 100/4 viable seeds/ha on a moderately favourable site.

8.6 Methods of sowing

There are a variety of methods for sowing seeds. The challenge is to match these methods to the areas having hilly terrains encountered in forests in general. Typically, the site characteristics of each seeding area will state the type of seeding method to be used like:

8.6.1 Broadcast Sowing

In this there is broadcasting of the seed evenly over the area and covering of the seeds with mineral soil (i.e., 20 - 50 mm). If necessary, rolling out the seed sown area to assure good soil-seed contact is beneficial (Kasera et al., 2002). Large tracts of land are often sown by broadcasting the seeds aerially by airplanes or helicopters (Joshi, 1986). This method is fastest and has the most accurate and complete coverage. Each species has a unique seed covering requirement. Seeds of most species must be buried in the soil or covered by mulch for effective germination. However, some species actually require some exposure to light in order to germinate and thus should not be covered very deeply. Existing literatures suggest that seed covering should be made so as to bury seeds at a depth twice (Munshower, 1994) to three times (Monsen and Stevens, 2004) the seed diameter. The tradeoff is that seedlings will have to expend more energy to emerge from the deeply buried seeds. Therefore, deeper the seeds are covered, the less likely they will dry out during germination, which will ultimately affect early seedling establishment. About 1 to 2 hectares of land can be sown in one day using this method. A small group of farmers can also share the cost of a helicopter or airplane if aerial seeding is preferred under restoration programme.

Hydroseeding are planned for the steep, north-facing slope where other equipment cannot reach. On the obliterated road, several ground based seeding methods could be used, including mixing seeds into the soil, or broadcasting on the surface and covering with soil or mulch for adequate germination. The south-facing slopes could be hand-seeded or hydroseeded involving the application of a watery mixture of seeds, fertilizers, mulches, adhesives and other additives depending upon situation and then covered by a soil cover or mulch to keep the seeds from drying out during germination (Lambrechtsen, 1986). Performance testing of seed sown kikar (*Prosopis juliflora*), babul (*Acacia nilotica*), shisham (*Dalbergia sissoo*) and papri (*Holoptelea integrifolia*) dispersed from a fixed wing aircraft indicates that kikar is the only species which is most successful followed by babul (Vedant, 1954). Sowing of *Prosopis juliflora*, *Acacia nilotica*, *Dalbergia sissoo*, *Holoptelea integrifolia*, *Acacia catechu* and Bamaboo in another seeding programme in Chambal area reveals *Prosopis juliflora* as the best performer, whereas in western Ghat of Maharashtra, 30 per cent germination of bamboo is reported (Joshi, 1986).

8.6.2 Strip Sowing

In strip sowing, seeds are broadcasted evenly over the prepared strips. The other activities like covering of the seeds and rolling out of the soil after seed sowing for better soil-seed contact are similar to broadcast sowing.

8.6.3 Spot Sowing

Sowing of 2 to 3 seeds per spot and 20-50 cm deep in the soil is commonly adopted in smaller area or the open forest patches, the berms or trenches of rainwater harvesting structures etc. The number of seeds per spot may be increased in case of low germination percentage. However, covering with soil and sealing of the sowing hole with adequate pressure gives better results. Seed can also be sown on hand-raked spots, approximately 60 cm in diameter and spaced about 2.5 m × 2.5 m, where six to eight seeds per spot are pressed 2 to 5 cm deep into the soil (Eden Foundation, 1991; Lohrey and Jones, 1983). In highly eroded area with undulating terrain manually digging of pits is the better method for seed sowing. Mixing of soils of the pits with farm yard manure added with single super phosphate will be beneficial in enhancing survival and growth of the germinated seedlings (Singh and Singh, 2011a). Application of a hollow crowbar approximately 1.5 m long will be more useful that convey the seeds to the selected location for utilizing the facilitative effects of existing trees/shrubs or clusters of thorny bushes that offer natural protection from grazing animals (Maestre et al., 2001; Castro et al., 1999). In this one end of the pipe-like steel shaft is pointed and the other end slightly flared. The hollow crowbar is used to dig a small pit even while one stands safely away from the thorny shrubs. The seeds are fed in from the flared end once the pit is dug (Patel, 2014).

8.6.4 Use of Machine

Sowing of seeds in 20-50 mm deep soil and covering the seeds with mineral soils are done using up packing wheels. In this hand-cranked seeders, with a metering device, could be most useful (Lohrey and Jones, 1983; Williston and Balmer, 1983). Petrol-driven mechanical blower which could be mounted on the back of a jeep can also be used to broadcast the seeds on the side of railway tracks, roads etc. The blower, fabricated in Rajkot, Gujarat, India at a cost of around Rs 12,000, could blow seeds to a distance of 15 m (Patel, 2014).

9. POST GERMINATION CARING

Light availability and soil moisture conditions are negatively correlated in dry areas (Belsky et al., 1993; Holmgren et al., 1997), where seed germination and seedling survival are relatively less in bare soil than in pasture, secondary or mature forest. However, contrary to this trend the findings of Sotomayor et al. (2014) indicate higher seed germination in open micro-habitats as compared to the understorey environments. Early seedling establishments are also limited by water availability leading to high mortality in dry tropical forests because of variable precipitation and frequent dry spells (Marod et al., 2002; McLaren and McDonald 2003). Reseeding is often required under such conditions necessitating the maintenance of seed stock. In harsh habitats, available plant cover successfully facilitates recruitment and growth of the seedlings (Duncan and Chapman, 2003). This should be utilized suitably. While seed germination is higher under plant canopy, seedling growth is reduced in these areas as compared to open areas during the rainy season or with supplemental water (Rincon and Huante, 1993; Gerhardt, 1996). Thus when germination and early establishment are favoured by shade, and established seedlings are favoured in open areas, the recommended management would be clipping undesired plants (i.e., weeding) around established seedlings and saplings. In Ghana, a study showed high tree-seedling density and diversity under pure stands of an aggressive pioneer shrub, and those seedlings had higher growth and survival rates after the shrubs were removed (Honu and Dang, 2002). Following precautions can be taken to protect and promote the growth of the seedling:

9.1 Livestock Exclusion

Domestic animals moving in the site might graze on seedlings, whereas germinating seedlings could be trampled. Providing protection to the restoration site by excluding cattle for a longer duration could help success the restoration work. By providing protection, plant injury or death could be controlled.

9.2 Weed control

Weed control is an important factor in tree and shrub seedling survival, especially for hardwood species. Though competition for light is also there but below-ground competition from grasses (Holl, 1999; Hooper et al., 2002), herbs, shrubs and lianas common to successional forests (Chen et al., 2008; Zahawi and Augspurger, 1999) negatively affect seedling performance. If these weeds are not controlled, tree seedlings will be out competed by the growing vegetation for moisture and sunlight. Elimination of competing vegetation is normally carried out for one to five years after sowing. Weed control can be accomplished through weeding and/or herbicide use. Mechanical or hand weeding should be kept at least 15 cm from the seedling and not deeper than 8 cm to avoid damage to the seedling as well as their roots. Additional methods may be applied to control weeds closer to the seedling.

9.3 Pest Management

Weeds, the hiding places for rodents or rabbits and repellants, should be controlled to reduce damage from wild animals. New seedlings should be monitored for potential wildlife, insect and disease problems and appropriate control measures should be taken if significant problems are found.

10. PERFORMANCE EVALUATION

Success of direct seeding depends on many variables for which careful inventories are required to evaluate the results. First inventory is essential at the end of the first growing season following the direct seeding. Depending on the results of this sampling, one might need a second inventory after the second or third growing season. For this the number of sample plots should be distributed evenly across the entire area. A circular plot with a radius of 113 cm (or a square plot of 200 cm × 200 cm size) using a measured string from a central point or making a permanent plot by iron rod or wooden frame will be more appropriate. Twenty-five is the minimum number of plots for any seeded area. Two to three plots can be appropriate in a hectare for large areas. During the inventorization there is need to count the number of seedlings in each plot and record the data separately for each plot. To get the number of seedlings per hectare area, following step can be followed:

- Find out average number of seedlings per plot by dividing the total number of counted seedlings by the total number of plots laid out in the area.
- Multiply the average number of seedlings per plot by 2,500 = average number of seedlings per hectare.

Likewise stocking percentage can be calculated as:

$$\frac{\text{Total number of plots with 1 or more seedlings}}{\text{Total number of plots}} \times 100 = \text{Stocking Percentage}$$

A successful seeding operation is one that results in 2,500 to 7,500 seedlings per hectare with more than 55 percent stocking rates. In case of lesser than 2,500 seedlings per hectare (or as prescribed), or 55 percent stocking, reseeding or planting will be necessary after verification in the second growing season. Areas with more than 2,500 seedlings per hectare require thinning operation. Further assessment of the site can be done at different stages like 3 months to assess germination rates and 12 months to assess establishment and survival rates. Assessment after 18 months is to assess any new germination particularly for hard seeded species.

10. CONCLUSION AND RECOMMENDATIONS

Varying environmental conditions and anthropogenic activities are affecting sufficient availability of woody seed banks in many dry tropical forests in general and degraded forests in particular. This limits natural regeneration and development of effective forest cover. Assisted natural regeneration, directs sowing, planting and a mix of these provide options to restore our degraded forests. Regeneration is in general influenced by site resources like soil and microclimate of the site, competition with existing vegetation, site disturbance, occurrences of established woody plants and their propagules, and seed dispersal by varying agents (Hardwick et al., 2004). Understanding about these diverse interactions and their functionality may stimulate better uses of available resources in broader perspectives as it is going to represent an alternative to recreate or restore degraded environments with characteristics more similar to the original natural environments. Direct sowing offers a feasible alternative to restore degraded forest ecosystems at low cost (Ferreira et al., 2009; Santos, 2010). For this there is a need to consider the degradation state of the site, suitable species with high adaptability, site characteristics like topography, soil fertility status and soil moisture condition, climatic conditions etc., and the existing vegetation. One can also consider the availability of local seed sources and sufficient quantities of viable seeds including the physical protection as it foster a more favourable micro-environment to the emergence of seedlings, and protection against agents that predate seeds and seedlings. Understanding the socio-economic conditions of the local communities in addition to the ecological and silvicultural aspects of the selected species and the need of the locals should also be involved in the process. For this purpose nitrogen fixing indigenous species with multipurpose value may be a better option. In this large-seeded and late-successional or climax species can be established in rangelands and successional forests (Bonilla-Moheno and Holl, 2009; Doust et al., 2006), but to maintain the growth one need to make the seedlings free of competitive effects of adjoining vegetation. Likewise most of the early-successional and small-seeded trees show higher establishment and growth rates when planted as seedlings (Engel and Parrotta, 2001). Alternatively, planting faster-growing early-successional species can serve to quickly ameliorate the environmental conditions, reducing the growing herbaceous vegetation and help to enhance establishment of later-successional or climax species (Holl et al., 2003; Lamb et al., 2005). It would be more effective to use direct seeding as a complimentary measure for more intensive restoration approach by planting fast-growing and multipurpose nitrogen fixing trees. This all, supported by dedication and responsibility, leads to a successful restoration programme for the benefit of society and nation.

13

PROTECTION AND POST PLANTING CARE OF FORESTS AND FOREST NURSERIES

In addition to providing water, mulch and fertilizers it is necessary to protect forests and forest plantations from weeds, pests and diseases also. A number of insects and diseases are known to damage both naturally regenerating forests and existing plantations. A report of Food and Agriculture Organization indicating damages caused by insect pests and diseases covers about 1 million ha and 8.4 million ha, respectively. Almost all parts of a tree are affected by these bioagents. Each tree species has a characteristic spectrum of associated insects comprising plant feeders, fungus eaters, detritivores, predators, parasitoids and sometime simply casual visitors. There are many foliar diseases like leaf blight and leaf spots affecting germination of seeds and causing rotting or wilting of germinated plantlets. Stem Canker, root rots, wilts and sooty moulds are some important diseases of forest plantation. The most effective way to deal with forest pests is integrated management. This includes prevention (proper tree, variety, site selection, natural regeneration, planting and thinning practices), observation (visual inspection or trapping systems) and suppression (mechanical, biological control or biopesticides and use of synthetic pesticides) measures in order to maintain pest populations and disease at a suitable level. This chapter describes varying types of pests and diseases in the tree species most common in tropical dry areas of India and suggests measures for effective, ecologically and economically efficient and socially acceptable.

1. INTRODUCTION

Biological diversity occurs in line with the amount of rainfall and soil conditions in a region. Availability of water, air and soil moisture are the main factors limiting natural distribution of vegetation along with the climate (rainfall, temperatures, wind) and soil quality (Malagnoux et al*.,* 2007). As one proceed along the moisture gradient from wet evergreen to dry deciduous tropical forests and along the temperature gradient from lower to higher latitudes, some species become more abundant, while others lead to monoculture. For example, teak (*Tectona grandis*) may constitute less than 10% to nearly 100% of the tree species present in the moist to dry deciduous forests in different parts of India. Likewise, sal (*Shorea robusta*) often occurs in high density stands in central and northern India. Many other dipterocarp species also occur in high densities in lowland evergreen forests of Southeast Asia. Monocultures tend to develop when competing species are eliminated mainly by climatic factors, though changes due to anthropogenic activities can not be ruled out. For example, the northern limit of natural teak in India is 25°N latitude, beyond which sal takes over, as teak seedlings, unlike sal, cannot survive frost (Nair, 2012).

In India, 3.226 million ha area is under forest plantations, that represents about 4.8 percent of the total forest area. The main plantation species are *Acacia* spp. *Eucalyptus* spp. and *Tectona grandis, Eucalyptus globulus*, *E. grandis* and *E. tereticornis* are most common Eucalypts, while acacias cover *A. auriculiformis*, *A. catechu*, *A. mearnsii*, *A. nilotica* and *A. tortilis*. Other commonly planted broadleaf species are *Albizia* spp., *Azadirachta indica*, *Casuarina equisetifolia*, *Dalbergia sissoo*, *Gmelina arborea*, *Populus* spp. *Prosopis* spp., *Shorea robusta* and *Terminalia* spp. The conifers under plantation like *Cedrus deodara* and *Pinus roxburghii* occupy a major area, whereas *Pinus patula* and *P. caribaea* have been planted to a limited extent (FAO, 2007). In Rajasthan, most of the vegetation consists of thorny shrubs, grasses and herbs particularly in western region, whereas tropical dry deciduous species occur in eastern and southern part. The forest area is tropical thorny forest. Khejri, Acacias, Rohida, Neem, Ardu, and Siris are the main tree species of the western region. Because of increased rainfall, forest density and diversity of habitats, the number of species in eastern and southern Rajasthan is relatively high (Singh, 2014a & b). Studies on forest protection have led to the knowledge of numerous disease pathogens and pests including nematodes attack on forest trees and formation of effective control measures for controlling them. Despite these achievements on forest protection, forest officials still feel reluctant to accept the value of investment on forest disease prevention or control because relatively less effect on timber production appeared to be obtained from this type of investment as observed like fertilization, control of competing vegetation and thinning. All these later conditions modify timber production and the change can be measured while measures aimed at controlling or preventing forest diseases and pests are not considered unless it become epidemic.

Insects are part of a forest ecosystem, where the activities of some groups of insects like decomposers and pollinators are beneficial to trees. However, the insects feeding on living trees have a negative impact on the growth and survival of individual trees. A number of insects and diseases are known to damage both naturally regenerating forests and plantations. According to an estimate about 1 million ha of forest is damaged by insect pests and 8.4 million ha by diseases (FAO, 2005). Insects feed on almost all parts of a tree. Phytophagous insects do not adversely affect the tree when the insect numbers are small. In general, a tree can dispense with some portion of its biomass without adverse effects on its growth. Though most species of insects cause only slight or occasional damage and their impact on the tree is negligible, but some species causes serious damage referred to as pests. Mention to some are leaf-feeding caterpillars *Hyblaea puera* and *Eutectona machaeralis* and wood-boring caterpillar *Xyleutes ceramicus* etc occurs on *T. grandis*. Besides, hepialid sapling stem borers and the scarabaeid seedling root feeders are pests of lesser importance. A wide number of pests and diseases have been observed and reported in tree nurseries and plantations on these species from Indian region (ftp://ftp.fao.org/docrep/fao/011/i0640e/i0640e13.pdf; Srivastava et al., 1989; Bakshi, 1977; Mathur and Singh, 1960). The incidence and severity of the most of them vary markedly in different regions.

Likewise, the plants are often exposed to persistent pathogenic attacks too, particularly those inciting root rot and wilt diseases, at primary stage of establishments. The root rot fungi which pose serious threats to forest nurseries include the species of *Fusarium*, *Phytophthora*, *Pythium*, *Rhizoctonia*, *Macrophomina*, and *Cylindrocladium* (Huang and Kuhlman 1990; Asiegbu et al., 1999; Haggag, 2002). These pathogens often invade terminal unsuberized roots of young seedlings and cause late damping off or root rot and wilt thereby killing the host. Damping-off disease in forest nurseries is one of the most economically important diseases causing heavy losses. Besides, inflicting significant economical losses, the disease may also disturb the whole forthcoming planting program. Forest plantations, especially monocultures of genetically identical plants species are very vulnerable to attack by insect pest and diseases in general (Wingfiled et al., 2001; Cock, 2003). Good silvicultural practices are important management tools for the most of the pests and diseases (Kumar, 1999; Luna, 2005).

2. TREE SPECIES AND THEIR PESTS/DISEASES

2.1 *Acacia nilotica* (Desi Babul)

Several fungal diseases and insect pests attack this tree. *Fomes badius* and *Ganoderma lucidum* are the most damaging fungi, causing spongy rot, affecting the heartwood of the stem and branches of old trees. Removal of infected trees and sporophores, and improved soil aeration provide some protection to plants or trees of this species. Powder-post beetles (*Sinoxylon* spp. and *Lyctus africanus*) attack the sapwood of felled timber (Fagg and James, 2005). Two distinctive rust fungi, i.e. *Ravenelia acaciae-arabicae* Mundk. & Thirum. and *R. evansii* Syd. & P. Syd. have been reported on *A. nilotica* subsp. *indica* in Tamil Nadu and Gujarat states of India (Shivas et al., 2013), though extent of its effects needs evaluation (Fig 13.1).

In India, the beetles *Celosterna scabrator* and *Psiloptera fastuosa* are the most destructive insects. *C. scabrator* is a root and stem borer, feeding on young bark. *P. fastuosa* defoliates and gnaws the bark of thin twigs. Larvae of *Ascotis* spp., *Cusiala* spp., *Hyposidra* spp, *Pteroma* spp and *Semiothesa* spp. defoliate the tree, whereas larvae of *Argyroploce illepida* bore into the pods. Grubs and adults of the weevil *Hypolixus truncatulus* damage seedlings and saplings. Seeds of *A. nilotica* are often predated by bruchid beetles that may destroy up to 70% of seeds. During storage damage is caused by a pest *Careydon serratus*.

2.2 *Prosopis cineraria* (Khejri)

Prosopis cineraria is the most important indigenous and keystone species of Rajasthan. Very little information is available about the insect-plant associations in *P. cineraria*. Some 153 insect and non-insect pests have been reported that damage *P. cineraria* throughout the world (Beeson, 1941; Mathur and Singh, 1960; Singh and Bhandari, 1986; Parihar, 1993; Parihar, 1994; Haldhar, 2012).

Figure 13.1 Rust of *Acacia nilotica* observed in Gujarat (left) Ganoderma root rot in *Acacia nilotica* (right).

Ahmed et al. (2004) reported 26 insect pests as potential threats of khejri in arid and semi-arid regions. Species of Chrysobothris and Sinoxylon bore into the dead wood, causing wood rot. Galls formation is caused by stimulation of plant cells due to interaction by the nematodes, fungus, bacteria, mites, insect etc and reduces the pod and seed production by converting ovary tissues in galls (Parihar, 1994; Sharma et al., 1995; Kumar and Ahmed, 2004; 2006; Bhansali, 2012). Research work on the mortality of Khejri in the western region of Rajasthan has been carried out. The most harmful pathogen and insect pest responsible for the mortality is *Ganoderma lucidum* a root rot fungi and *Acanthophorus serraticornis* a root borer (Fig 13.2).

Figure 13.2 Root borer (*Acanthophorus serraticornis*) at left and *Ganoderma lucidum* (right) of Khejri (*P. cineraria*).

2.3 *Prosopis juliflora* (Vilayati babool)

Many workers have reported different types of insect pest infestation on *P. juliflora* (Yousuf and Gaur, 1993; Dwivedi, 1993; Beeson, 1941; Roonwal and Bose, 1964; Ali, 1970). Among these *Taragama siva* (Lepidoptera: Lasiocampidae) and *Microtermes mycophagus* (Isoptera: Termitidae) are the major pests recorded from arid tracts of Rajasthan. Vir and Jindal, 2014 (http://www.fao.org/docrep/006/ad321e/ad321e0e.htm) have reported a storage pest infesting pod and seeds. This pest (*Caryedon serratus)* has been found to infest the pods and seeds during hot summer months. *Oxyrachis tarandus* Fabricius (Hemiptera: Membracidae) is important insect pest, though other hosts of this pest include *Acacia catechu*, *A. nilotica*, *Albizia chinensis*, *A. lebbek*, *Cassia fistula*, *Dalbergia latifolia*, *Prosopis juliflora*, *P. cineraria*, *Santalum album*, *Tamarindus indica*. Review of literatures (Bakshi et al., 1972; Bakshi, 1977; Bilgrami et al., 1979; 1981) show that very little work has been carried out on the diseases of *P. juliflora* in nurseries and plantations but Srivastava and Mishra, (2014) have reported some important diseases in nursery and plantation. These were root rot, collar rot, stem canker, leaf blight, twig blight and dieback.

2.4 *Azadirachta indica* (Neem)

Despite the fact that the fruits, seeds and leaves of Neem contain several compounds that repel or kill insects, inhibit the growth and development of fungi, and limit the infectivity of viruses, the plant itself is subject to a number of pests and diseases (Schmutterer, 1990; Tewari, 1992; Ciesla, 1993; Boa, 1995). More than eight order and 32 families and 68 species of insect pests have been recorded feeding and causing damage on neem (Browne, 1968; Parihar, 1978, 1981; Roonwal, 1978). Fire ants (*Solenopsis* spp.) have caused severe defoliation of 3-6 year-old Neem plants in Andhra Pradesh, India (Raghunath et al., 1982). Several species of moth and butterfly, e.g. *Ascotis selenaria* (*Lepidoptera: Geometridae*) defoliate Neem, especially in nurseries (Tewari, 1992). Caterpillars of the genus *Eurema* (*Lepidoptera: Pieridae*) have also been reported as leaf defoliators (Tewari, 1992). Two major insect pests are *Helopeteltis antonii* causing damage to inflorescence affecting fruit production and *Pulvinaria maxima* causing considerable damage to young plants. Species of termites viz. *Odontotermes obesus*, *O. redemanni* and *O. gurdaspurensis* are also potential insect pests (http://www.icfre.org/index.php?linkid=entlnk93os72&link=2). A check list of 20 species of insects, 2 species of mollusk and 3 species of mites, infesting Neem in 39 provenances has also been prepared and compiled (www.afri.res.in).

Many diseases of neem are caused by fungi that affect its leaves, stems or roots, and are major nursery problem. Damping off also affects neem. Other nursery diseases include *Rhizoctonia* leaf web blight (*Rhizoctonia solani*), characterized by grey-brown spots on neem foliage and fungal hyphae that join infected leaves together, and *Colletotrichum* leaf spot and blight caused by *Colletotrichium gloeosporide* (Ciesla, 1993). The fungus *Odium azadirachtae* causes powdery mildew of neem foliage. Several bacteria including *Pseudomonas viticola*, *P. azadirachtae* and *Xanthomonas azadirachtii* cause leaf spot diseases. The fungus

Corticium salmonicolor causes pink disease, which is characterized by a pink fungal mycelium that spreads over the tree, destroying the bark and outer layers of wood (Browne, 1968; Tewari, 1992). Branches are killed, which quickly causes the foliage to wilt and turn black. *Phomopsis azadirachtae* is the causal organism of die-back of neem. A bacterial disease of neem causing angular leaf spot, shot-hole and vein blight symptoms occurs in a severe form in parts of Rajasthan. The causal organism is a species of *Pseudomonas* (Srivastava, 1970). Five major diseases namely, shot hole (*Pseudomonas azadirachatae*), root rot (*Fusarium* spp.), leaf curl (sap sucking insects- mites), tip dying and sooty mould, *Alternaria* leaf spot and blight, and four minor diseases, i.e. *Ganoderma* root rot, die back and stem canker, powdery mildew and viral disease have been reported from various localities of Rajasthan and Gujarat (Srivastava, and Verma, 2008). Mortality has also been recorded due to charcoal root disease around Jodhpur caused by *Rhizoctonia bataticola* (Srivastava, and Verma, 2008).

2.5 *Acacia leucophloea* (Ronjh)

No serious infestation of diseases and insect pests so far have been recorded on this tree species, as Anuwongse and Cholprasert (1976) graded this tree resistant to decay fungus. It is also resistant to termite under field conditions. However, incidence of *Hapalophragmiopsis ponderosum* and the metabolic changes in plants due to fungal infections in terms of change in sugars, organic acids and polyphenol contents has been observed (Dharmadhikari and Jite, 1992; 1996). They also reported phytoalexin like substance after infection of *A. leucophloea* with *H. ponderosa. H. ponderosum* is a rust pathogen causing tumorous galls on infected plants of *A. leucophloea.* Studies have shown that the disease is systemic and seed-borne in nature (Mudhar and David, 1979). *H. ponderosa* infection induced development of large galls on the stem, leaves and fruits. Changes in the levels of total sugars and ascorbic acid have been investigated in healthy plants and in galls. Sucrose concentration is lower in the galls and fructose concentration is higher. The ascorbic acid content is lower in galls compared with healthy plants. Ascorbic acid oxidase activity is higher in the galls (Dharmadhikari and Jite, 1996). Seeds are generally attacked by *Bruchidius andrewesi* (Orwa et al*.,* 2009)

2.6 *Tecomella undulata* (Rohida)

Three species of fungi belonging to the family imperfecti (*Phoma* spp., *Fomes* spp. and *Botryodiplodia theobromae*) are primarily responsible for canker-rots in *T. undulata* in IGNP area at Mohangarh (http://fri.icfre.gov.in/UserFiles/File/archives/Ch-3.6.pdf). Sixty four insect species have been recorded in the form of pests. Of them, twenty four insect species have been observed for the first time to cause mild to severe damage to marwar teak in arid and semi arid areas. Seedlings and young plantations of *T. undulata* are frequently and severely attacked by a serious curculionid pest, *Patialus tecomella* throughout the tract of its distribution in arid and semi-arid areas (Ahmed et al., 2004).

2.7 *Boswellia serrata* (Salai Guggul)

It is known to be attacked by certain pathogens in avenues and forests like white spongy sap rot, spongy heart rot, mottled sap rot, spongy root and butt rot and white fibrous rot (Orwa et al., 2009). A number of insects have also been recorded on this species. The maximum damages is caused by two major insect pests, which are *Atteva fabriciella* and *Aractocerus reverses*. The former is the serious pest causing defoliation in young plantation of *B. serrata* and seed development is also affected due to damage of inflorescence (Sharma, 2015).

2.8 *Anogeissus* species

Two important species of this genus are *Anogeissus pendula* and *A. latifolia*. At present, *A. pendula* is extensively used as fuel wood, calorific value of sap-wood being 4837 kcal and hardwood 4739 kcal/kg. The leaves of this species are used as fodder and it is commonly browsed species indicated by a forest type '*Anogeissus pendula* 'scrub' due to excessive grazing. The bark yields a gum called gatti or Indian gum, but the main value of this tree lies in its afforestation purposes for afforesting of semi-rocky and rocky terrains of arid and semi-arid regions.

First report on leaf spot disease of *Anogeissus latifolia* due to *Pestalotiopsis versicolorfrom* Jubbulpore, India was reported by Agarwal and Ganguli (1959). Later, Bhatnagar et al. (2013) had reported two foliar pathogens *Nigrospora* spp. causing leaf spot and *Pestalotiopsis* spp. causing leaf blight and two root pathogen *G. lucidum* and *Macrphomina phaseolina* in *Anogeissus pendula* from Kota and Bundi districts of Rajasthan. The sapwood of *Anogeissus latifolia* is susceptible to Lyctus. *Sarcinella apocynacearum*, *S. combratcearum*, *Tripospermum caseariae* and *T. lougurensis* are ectoparasitic fungi associated with living leaves. Both dead and dying trees are attacked by the stem borers like *Olenecamptus anogeissi* and *Olenecamptus indianus*. Wood products susceptible to marine borer are attacked mainly by the teredinids- *Teredo furcifera*, *Lyrodus pedicellatus*, *Martesia striata*, *Teredo parksi*, *Bankia campanellata* and *Lyrodus bipartitus*. The fungus *Uncinula* spp. is reported on *A. latifolia*. Other fungi reportedly causing leaf spots are *Pestalotiopis versicolor*, *Marssonina poonensis* and *Monochaetia jabalpurensis* (Orwa et al., 2009).

2.9 *Albizia lebbek* (Siris)

In case of *A. lebbeck*, very heavy damage is caused by *Arytaina* psyllid in some nurseries (Sivaramakrishnan and Remadevi, 1996). Earlier in 1988, Hegde and Relwani had also reported a psyllid, probably of the genus *Heteropsylla* seriously affecting seedlings of *Albizia lebbeck* from Maharashtra and Karnataka. But, the most serious pests are bark-feeding larvae of longicorn beetles. These do not affect small stems and have little effect on large stems, but complete girdling can cause dieback in stems in the diameter range of 40-100 mm (http://www.fao.org/ag/AGP/AGPC/doc/publicat/gutt-shel/x5556e0a.htm).

2.10 *Acacia tortilis* (Israeli Babool)

In *A. tortilis* problems are caused by pod and seed pests and wood borers. Some of the pests of indigenous acacias have also been recorded on this species. Insect pests of standing trees are listed as the defoliators *Cryptothelea crameri* [*Eumeta crameri*] and a species of *Beralade*, the bark feeding caterpillar *Indarbela quadrinotata,* the sap sucker *Oxyrhachis tarandus* and the pod and seed pests *Bruchidius spadiceus* (a seed pest), *Caryedon gonagra* [*C. serratus*] (a pod pest) and *Callosobruchus chinensis* (a seed and pod pest). *Caryedon serratus*may causes 100% loss of the seed crop. Pests of felled timber are a species of *Acmaeodera,* the powder post beetles *Sinoxylon anale* and *S. crassum,* the dry wood longhorn beetle *Stromatium barbatum,* and *Lyctus africanus.* The powder post beetles are the most serious pests, attacking timber a few weeks after felling and reducing it to dust (Singh and Bhandari, 1987).

Figure 13.3 Mortality in *Acacia tortilis* plantation at GEER, Forest, Gandhinagar, Gujarat.

2.11 *Acacia senegal* (Kumat)

A. senegal, the gum Arabic producing tree, is of great economic importance (Eisa et al*.,* 2011). Seven species of the long-horned beetles were recorded on this species from Sudan. The recorded species were *Anthracocentrus arabicus, Crossotus subocellatus, Crossotus strgifrons, Doesus telephoroides, Titoceres Jaspideus Tithoes* sp. and *Gasponia gaurani* (Eisa et al., 2008). The buffalo treehopper (*Stictocephala bubalus*) destroys seed crops. Spiders (*Cyclops* sp.) can smother young growing apices. Larval stage of *Coleoptera* (bruchids), *Lepidoptera*, and *Hymenoptera* damage the seed. Locusts (*Acridium melanorhodon*) defoliate vast areas overnight. A wide range of fungi use to attack *A. senegal*. These are *Cladosporium herbarium*, *Fusarium* sp., *Ravenelia acaciae-senegalae* and *R. acaciocola.*

2.12 *Zizyphus* species (Ber)

Ber is a drought tolerant, poor man's fruit crop known for its nutritive value and is important particularly in Rajasthan. However, it is affected by many serious diseases like powdery mildew (Gupta, 1984), sooty mold, leaf spots (species of *Alternaria, Cercospora, Septoria, Cladosporium, Pestalotiopsis* etc.) and rust among the fungal and witches broom caused by MLOs (Jamadar et al., 2009). Zhang et al. (2011) had isolated three pathogens, i.e. *Alternaria alternate*, *Phoma destructiva* and *Fusicoccum* spp. from the fruit of Z*izyphus jujuba* causing fruit shrink disease. Zhou et al. (1998) has also studied the whitch-broom disease, regarded as a destructive disease for Chinese jujube (*Zizyphus jujuba* Mill). Six causal fungi (*Maxrophoma hawatsuhai* Hara, *Dothiorella gregaria* Sacc., *Coniaothyrium olivaceum* Bon, *Alternaria tenuis* Nees., *Phoma destructive* Plowr, *Fusicoccum* spp.) and two causal bacteria (*Erwinia jujubovora* and a bactrium) have been reported infecting Chinese jujube *(Zizyphus jujuba* Mill.) fruits singly or jointly (Zhang et al., 2008).

2.13 *Salvadora* species (Jaal)

S. persica, a facultative halophyte appears to be a potentially valuable oilseed crop for saline and alkali soils (Reddy et al., 2008). Very little information is present on the insect pest and diseases. *S. persica* trees with symptoms of witches'-broom, little leaf and severe leaf curling were observed in the Biodiversity Park, North Delhi (India) during February 2010. The study reports a new host of phytoplasma in India and worldwide (Kumar et al., 2012b). Galls were noticed on stem and leaves of coppice of *S. persica* in the vicinity of Shambat Research Station, and National Botanic Garden in Khartoum North, Sudan (15°31'N & 32°35'E) during the month of October 2010 (Moawia et al., 2012). Bhatnagar et al. (2014) has studied life cycle of *Colotis amata* Fabricius (Lepidoptera: Pieridae), a leaf eating pest of *Salvadora persica* which causes severe damage in plantation. Four species of insects have also been recorded on *S. oleoides.* In this maximum loss is caused by two major insect pests *Colotis fausta* and *Amitermes belli.*

2.14 *Ailanthus* species (Ardu)

Ailanthus species are mainly considered resistant to both fungal and insect attacks but Skarmoutsos and Skarmoutsou (1998) reported *Verticillium* wilt on *A. glandulosa* in Greece. *Navisporus floccosus* causing heart rot was recorded in living trees of *Alianthus excelsa* for the first time by Nagadesi and Arya (2014). *N. floccosus* causes decay mostly heartwood of living tree. It colonized in the central portion of tree and begins decaying of wood which ultimately lead to death of *A. excelsa* tree. About twenty seven species of insect pests have been observed associated with this species. However, most dominant insect-pests are *Atteva fabriciella* and *Eligma narcissus* causing maximum damage to the plantation (Plate 13.1). The second and third instar of *Atteva fabriciella* larvae make holes in the leaves and often bore inside the young twigs and feed on the panicles of the flowers also (Sharma, 2015).

2.15 *Bauhinia* species (Kachnaar)

There are three most common species viz. *B. variegata*, *B. racemosa* and *B. purpurea*. The heartwood of *B. purpurea* is dark-brown, strong, hard and easy to polish and work. But it is not a durable timber and is readily attacked by wood borers, white ants and decaying fungus. It is used mainly for heavy packing cases, agricultural implements, posts, scantlings, rafters and inferior construction, besides it is used for fuel. The leaves give a fodder of medium quality and flowers are cooked as vegetable and pickles. The bark is used as a cheap tan, dye and in indigenous medicine. The tree has ornamental value because of its gorgeous flowers. Decline of *B. variegata* caused by *Phellinus noxius* in Taiwan has been reported for the first time (Chang, 1995).

2.16 *Eucalyptus* species

Insect problems in Eucalypts differ between intensively-managed eucalypt plantations and those occurring in naturally regenerated forests (Ohmart, 1990). The risks from insect pests in eucalyptus plantations has aroused from reduced genetic diversity and the use of species outside their natural range (Elliott et al., 1990). The two main ways insects cause economic damage to eucalypt forests is either by defoliation or log degradation. About a dozen genera have been regularly reported as causing significant damage to Eucalypts (Moore, 1961). Psyllids sporadically cause high levels of defoliation. Presence of Bell Miner (*Manorina melanophrys*) colonies along with psyllids shows a synergistic detrimental effect on tree health (Loyn et al., 1983). Other insects are: Blue gum chalcid (BGC) (*Leptocybe invasa*), a small gall-forming wasp; eucalyptus snout beetle (*Gonipterus scutellatus*) that attacks eucalyptus by the adult feeding on the edge of the leaf, while the larvae feeds on the entire epidermis of the leaf; and winter bronzing bug (*Thaumastocoris peregrines*), a sap-sucking insect that causes the tree foliage to turn reddish-brown. Termites are also important pest and associated with damage to eucalyptus in the field plantations. Some termite species kill healthy trees and, therefore cause greater losses, which includes attacking the bole, ring barking and death of seedlings. A number of chemicals are used to protect trees against attack by termites such as Gladiator, Confidor, Imaxi etc.

The diseases (Mwangi, 2014) common to Eucalypts are: Canker, leaf spots and powdery mildews. Canker is caused by *Botyrosphaeria* and is the most common disease of Eucalyptus mainly associated with stress. The disease causes formation of stem cankers and production of gum that result in stunted growth. The most affected species are *E. grandis* and *E. camaldulensis*. Leaf spot is caused by *Mycosphaerella* and mostly observed in seedlings and older leaves of trees. The symptoms of the disease are mainly blackish appearance on the underside of the leaves and purplish or brown spots on the upper side. Management of this disease is by use of fungicides or planting disease tolerant material. Powdery mildew is a nursery disease that reduces growth of seedlings but sometimes kills seedlings too. The symptoms are whitish coating and curling of young leaves. Management of this disease is done by regular spraying with fungicides.

2.17 *Tectona grandis* (Teak)

Teak (*Tectona grandis* L.f.) is an economically important plant known as Sagun and Sagwan. It belongs to family Verbenaceae. It is a large deciduous tree which is light demander and sensitive to frost, drought, coppices and pollards vigorously (Troup, 1921). About 174 species of insects are associated with teak (Mathur, 1960). Many of these insects are minor or occasional pests and very few are recognized as major pests. Among the various insect-pest infesting teak plants, 136 are defoliators belonging to order: Lepidoptera, Coleoptera and Orthoptera. Out of these the most important are the Lepidopterans, teak defoliator, *Hyblaea puera* Cramer (Lepidoptera: Hyblaeidae) and teak skeletonizer, *Eutectona maturalis* Walker (Lepidoptera: Pyraustidae) causing defoliation, skletonizering and browning of teak leaves, adversely affecting growth (Mathur and Singh, 1960). Three species of insects, viz., Cicadellid (*Tettigoniella ferruginea* F.), teak defoliator (*Hyblaea puera* C.), teak skeltonizer (*E. macheralils*) have been found causing severe damage to teak. These insects also have been reported as major pests of this plant at several places (Ghude et al., 1993; Appanch et al*.,* 2000; Loganathan et al., 2002). *Hyblaea puera* is a moth and commonly known as teak defoliator, and the caterpillar of this species feeds on teak or other species of the region. *Eutectona machaeralis* is commonly known as teak skeletonizer or teak leaf skeletonizer. The larvae of this species feed only on green leaf tissue matter among the networks of veins, leaving the skeleton of veins intact. *Asphondylia tectonae* is a gall insect that is one of few insects recorded as pests of teak in naturally regenerating forests of India.

T. grandis is also affected by root or butt rot. Out of the many causal organisms for this disease, the most widely studied is the *Rigidoporus lignosus* (klotzch) Imazeki. The spore of *R. lignosus* infects the stumps left behind when a forest is cleared. This pathogen use to associate with the roots of only teak. The most economical method is biological control by involving the growth of leguminous cover crops like *Pueraria phaseoloides*, *Flemingia congesta* etc. in the forest plantation (http://www.naerls.gov.ng/extmat/bulletins/Major%20Diseases.pdf.)

2.18 *Gmelina arborea*

The defoliator *Calopepla leayana* appears to be most important insect pest of *Gmelina arborea* in plantations within the natural range of the tree (Wingfield and Robison, 2004). It is perhaps the most widely reported and studied defoliator of *G. arborea* in Asia. Young larvae feed mainly on the undersurface of Gamhar (*Gmelina arborea*) leaves, leaving only the mid-ribs and main veins intact. The adult beetle feeds on the leaf, cutting large circular holes, and also eats young buds and shoots. Heavy infestation leads to drying up of shoots of young trees and the trees remain leafless for about 4 months of the growing season leading to ultimate death. *C. leayana* was reported for the first time on *G. areborea* in Meghalya, India in 1995, indicating its expansion to the northeast of India (Wingfield and Robison, 2004). It is considered a serious pest of Gamhar plantations in Assam (FAO, 2003).

2.19 *Dalbergia sissoo*

Dalbergia sissoo Roxb. (Fabaceae) is one of the most important commercially valuable timber species of India. It is best known for its highly valued timber. However, it is also associated with about 125 species of insect fauna. Among these, 10 species are known to have attained economic status as potential pests of nursery and plantations of *D. sissoo*. Most common and destructive insects pests are

Plecoptera reflexa Guenee (Lepidoptera: Noctuidae) and *Apoderus sissoo* Marshal (Coleoptera: Curculionidae). Among diseases, root rot caused by *Fusarium solani* f. *dalbergiae* is a serious disease in almost all forest nurseries located in different parts of India. It causes up to 60-80 percent losses particularly in heavy and wet soils (Kaushik and Singh, 1996). A dieback disease causing decline began in the late 1990s and is still continuing. The condition is most prevalent in plantations of this species although in some areas, naturally regenerating forests are also affected. The problem is regional in nature and stands of this species have been affected in Bangladesh, India, Nepal and Pakistan. According to FAO (2005) about 8 400 km^2 area with *D. sissoo* covering Gangetic plains including UP and Bihar are affected by this diseases. Unfortunately, the cause of the dieback is not yet known though soil nutrients, climatic factors, water logging of soils and root fungi are considered factors favouring this disease (Sah et al., 2002; FAO, 2005).

Besides this *Lymantria mathura* is a serious defoliator found in Asian countries and is polyphagous that feeds on a variety of deciduous trees including Fagaceae (oaks and beeches), Salicaceae (willows), Rosaceae (fruit trees), Betulaceae (birches), Juglandaceae (hickories and walnuts), Oleaceae (ashes) and a number of tropical families of trees. Recorded hosts in India for this insect are *Antocephalus cadamba*, *Mangifera indica*, *Quercus incana*, *Q. serrata*, *Shorea robusta*, *Syzygium cuminii*, *Terminalia arunja* and *T. myriocarpa*. In India outbreaks are infrequent but extensive when they do occur. No significant tree mortality occurs after defoliation of the sal tree (*Shorea robusta*) but tree vigour generally reduced and susceptibility to attack from other insect species increase. However, successive defoliations on *Shorea robusta* in Assam and north India have been known to kill trees (Appanah and Turnbull, 1998).

3. SYMPTOMS BASED MANAGEMENT OF TREE DISEASES

3.1 Nursery diseases

Main symptoms on nursery diseases are pre emergence damping off, post emergence damping off, collar rot, root rots and many foliar diseases. Saplings/seedlings are very susceptible to the diseases in nursery. The pathogens may be carried through seeds and get established in the nurseries. The soil borne propagules of the pathogen also attack the young seedlings.

Damping off: Pre-emergence damping-off is caused by fungi that rot seedlings before they emerge while Post-emergence damping-off is caused by fungi that infect and kill stem tissues at the ground line after seedling emergence, resulting in a seedling collapse (Plate 13.2). *Pythium*, *Rhizoctonia*, *Phytophthora* and *Fusarium* are fungi that commonly cause damping-off (Riffle and Smith, 1997). Other fungi responsible for occasional damping off are *Cylindrocladium* spp, *Botrytis cinerea* and *Sphaeropsis sapinea* (Fisher, 1941), *M. phaseolina* (Boyce, 1961)*, Alternaria alternata, Cladosporium cladosporoides, Penicillium expansum* (Huang and Kuhlman, 1990) and *Phoma* spp (Russell, 1990).

Root rots: *Phytophthora cinnamomi* causes root rots in some coniferous and broadleaf nursery stocks (Crandall et al., 1945). Disease is visible in form of wilting and drying of the seedlings.

Charcoal Root rot: Charcoal root rot is caused by *M. phaseolina* attacking *A. nilotica* and *P. juliflora* seedlings (Srivastava et al., 1990).

Wilt: It is mostly caused by *Furasium* spp. but sometimes *Verticillium* spp. (Escudero and Blanco, 2011) and *Rhizoctonia bataticola* (Singh et al., 1977) has also been found associated with it. *Fusarium* wilt has been reported on *Dalbergia sissoo, Eucalyptus, Cassia siamea, A. tortilis, P. juliflora* and *A. indica* from arid and semi arid areas of Rajasthan and Gujarat. The losses are up to 20-25% (Srivastava and Verma, 2008). The common symptoms are withering, drying and dying of the seedling.

Collar rot: Collar rots occur at the soil line where the plant emerges. The tissue may turn brown to black in the localized area around the soil line. The discoloration may migrate upward and downward around the outside of the tissue from the point of infection. Eventually, when the pathogen has almost completely encircle of the stem, the plant begins to show wilting and dieback symptoms. Causal organisms of disease are *Rhizoctonia solani, Phytophthora* spp., *Lasidiploidia thoebromae* etc. The disease mainly occurs in hot and humid conditions. This disease has been recorded on *A. nilotica, T. undulata, P. juliflora* and *A. lebbek* from arid regions of Rajasthan (Srivastava and Verma, 2008).

Dieback: It is caused by wide range of organism including *Colletotrichum gloeosporioides, Fusarium* spp., *Rhizoctonia solani*, *Phytophthora cinnamomi* and *Botryosphaeria* spp. Drying of branches start from the tip and proceed to base hence called as dieback.

Foliar diseases: Foliar diseases are generally characterized by leaf spots, leaf blight, leaf curling, powdery mildew, rusts etc. General symptom is circular or irregular patches of yellow, purple, brown and ash color or burn like symptom or curling and crinkling of leaves. The common pathogen causing foliar diseases are *Alternaria* spp., *Cercospora* spp., *Phytophthora* spp., *Xanthomonas* spp. etc. Foliar diseases result in defoliation of plants. An established plant can tolerate almost complete defoliation if it happens late in the season or irregular in the year. Small or newly planted seedlings that become defoliated are more at risk of suffering damage until they become established.

3.2 Management of nursery diseases

- Soil solarization of the nursery beds (Stapleton and Devay, 1986; Stapleton, 2000).
- Disinfestations of potting media/nursery soil should be properly fumigated with 4% formaldehyde before use in the nursery.
- Amendment of soil with neem cakes as biocontrol agents like *Trichoderma, Azotobacter, Azospirillum,* etc.
- Excess soil moisture should be avoided since the fungus like *Pythium* and *Phytophthora* thrive on free moisture available to them.

- Cleanliness and hygiene are very important inside the mist chambers, poly tunnels and shade house. Infected tissues should not be taken inside these structures. The nursery and its surroundings should be kept neat and clean.
- Application of biofertilizers e.g. Arbuscular Mycorrhizae (AM fungi), Ectomycorrhizal fungi, *Rhizobium, Azospirillum, Phosphobacterium* etc. and biocontrol agents (*Trichoderma viride, T. harzianum, Pseudomonas fluorescence* etc) reduce/inhibit the growth of soil borne fungi. Bioagents are also applied making suspension in sterilized water at the rate of 10 g (10^8 cfu/ml) of formulation per litre /kg of FYM while VAM is applied at the rate of 50 gm of inoculums per seedling/saplings.
- Chemical seed coating with thiram captan, metalaxyl (1gm fungicide per 500 gm of seeds) or with carbendazim 50WP or Topsin-M WP (2g/Kg) for seed borne pathogens and soil drenching with 0.2% of above fungicide or 0.2% Bavistin for soil borne pathogens will be beneficial (Song et al., 2004).
- For foliar disease, spray inoculation is done on the leaf surface using many chemicals depending upon the pathogens associated with it. Carbendazim spraying (0.1%) for *Cercospora* leaf spot (Rathore, 2015) mancozeb (0.3%) or Rovarol for *Alternaria* spp. appears to be beneficial (Janardhanan, 2002).
- Powdery mildew disease can be effectively managed by alternate sprays of triadimefon at 0.1% followed by wettable sulphur at 0.3% at an interval of 12-15 days.
- Rust disease is managed by spraying mancozeb at 0.2% or wettable sulphur at 0.2%.

3.3 Nursery insect pests

Nursery pests are cutworms (*Agrotis ipsilon*), cockchafers or white grubs (mainly *Leucopholis, Holotrichia* and *Anomala* spp.), termites and ants, crickets and mole crickets (mainly *Brachytrupes portentosus, Gryllotalpa africana* and *Tradactylla* spp.), defoliators (leaf eaters like *Catopsilla* spp. and *Eurema* spp., the leaf rollers like *Parotis marginata,* and the leaf miners) and sap suckers (Baksha, 1990). It is important to be mentioned here that 75 to 80% defoliations can reduce the growth of plants by 20% (Bassman et al., 1982).

3.4 Management of insect pests

- The edges of the nursery beds, surroundings, transplant beds etc., should be kept clean from the weed. It prevents the egg laying of the moths affecting the seedling growth.
- Collection of the larvae, while digging and then destroying them also reduce the population of cutworm and helps to improve the quality of seedlings.

- Irrigation or flooding of nurseries allows the cutworms to come out from their tunnels and these can be collected and destroyed mechanically.
- The mother beds should be dusted with a mixture of quick lime and ash. This checks attack of cutworm larvae.
- Dusting of quinolphos @ 1.5%, i.e. 25 kg/ha is effective against the cutworms
- Ploughing and digging of soil during winter facilitate in collection and destruction of white grubs.
- Mixture of carbaryl @ 5% and malathion dusts @ 5% (each @ 30 to 40 kg/ha) in nursery beds during the month of July kill the freshly hatched grubs.
- Red ants collected from field and released on to nursery beds is another option for destroying the termites.
- Drenching of mother beds or propagation chambers or polybags with a solution of chlorpyrifos TC 20 @ 2 ml/lit will control the termites effectively.

4. DISEASES OF PLANTATION AND FOREST STANDS

4.1 Types of diseases

Stem Canker: Stem canker is one of the important diseases of the tree and posses threat to the quality timber production**.** Many insects and fungi are reported to cause stem canker in different host trees. The most common fungi are *Fusarium solani*, *F. oxysporum* and *F. decemcellulare* (Lombard et al., 2008) and *Acremonium strictum* and *F. roseum* (Hassan and Hassan, 2008). Among the insects twig beetle, *Pityophthorus juglandis* (Luna et al., 2014), *Xanthomonas* sp. (Taylor et al., 2001), *Neonectria fuckeliana* (Dick et al., 2011) and *Lasiodiplodia theobrome* (Mohali et al., 2005; Punithalingam, 1976) are most common. Vajna (1986) described branch canker caused by *Botryodiplodia* spp. on *Quercus prinus* in the USA. *Botryodiplodia theobromae* (Botryosphaeriaceae) isolates is also associated with die-back and bark canker of pear trees in Punjab, India (Shah et al., 2010), stem canker of *Jatropha curcas* in Malaysia (Sulaiman et al., 2012) and of Almond in California (Chen and Morgan, 2013). In the arid region of India, insect pests and disease studies reveal that the tree deformity pertaining to hollowness might initiate the formation of cankers in the main trunks of the trees (Plate 13.3). It is further stated that the infection occurs in the form of splitting of bark on the bole, which spreads in upward and downward direction (Ahmed, 2007)

Wilts: Different species are associated with this disease but most common species are *Fusarium oxysporum* (Chavan and Dake, 2001; Russell, 1975) and *Verticillium* spp. (Levin et al*.,* 2003; Tjamos at al., 1991). *Fusarium oxysporum* has been recorded from different host species viz. *D. sisso, Eucalyptus* spp., *Cassia siamea, A. tortilis, P. juliflora* and *A. indica* causing loss of about 20-25% in various tree species (Srivastava and Verma, 2008).

Root rots: It is caused by pathogens like *M. phaseolina* causing Charcoal root rot (Srivastava and Mishra, 1998) and *Ganoderma* spp. causing white rot, etc. Both the diseases have been reported from tree species such as *A. nilotica*, *A. leucophloea*, *A. indica* and *Dalbergia sissoo* (Bakshi, 1976)

Sooty moulds: Sooty moulds are ascomycetes that grow on plant exudates and honey dew secreted by insects such as aphids, whiteflies etc. Severely infected leaves shows premature defoliation in various tree species (Srivastava and Verma, 2008). Some common genera causing sooty molds are *Cladosporium*, *Aureobasidium*, *Antennariella*, *Limacinula*, *Scorias* and *Capnodium* (en.wikipedia.org/wiki/Sooty_mold, 2014).

4.2 Management of diseases in plantation

- Field sanitation, i.e. removal and burning of infected plant debris.
- Application of Rogor 30EC (0.05%) + Blitox (0.2%) for sooty moulds.
- Soil drenching with mancozeb or carbendazim @ 0.2% for soil borne fungal pathogens which causes wiltings and rottings.
- Application of suspension of bioagents like *Trichoderma viride, Trichoderma harzianum, Pseudomonas flourescence* etc. @ 8-10g of formulations/litre water.

4.3 Plantation and forest insect pests

Forest tree species are vulnerable to the insect pests at all stages such as seeds on standing trees, in storage, seedlings in nursery, plantations, natural forests and timbers.

Major groups of plantation pests and their hosts are given in the table below:

S.No.	Name of the Pest	Affected Species	Type
1.	*Hyblaea puera* and *Eutectona machaeralis*	*Tectona grandis*	Defoliators
2.	*Calopepla leayana*	*Gmelina arborea*	Defoliators
3.	*Dihamnus cervinus*	*Tectona grandis* *Gmelina arborea*	canker grub
4.	*Hoplocerambyx spinicornis*	*Shorea robusta*	heartwood borer
5.	*Tonica niviferana*	*Bombax malabaricum*	shoot borer
6.	*Hypsipyla robusta*	*Swietenia macrophylla* *Cedrela toona* *Chickrassia tabularis*	shoot borer

The wood and timber pests found during drying and seasoning include borers attacking green logs (e.g. *Platypus, Crossotarsus, Xyleborus* and *Webbia* spp.), sap and heartwood borers like buprestids *Chrysocroa* spp., *Catoxantha* spp. and *Belionata* spp. and cerambycids like *Hoplocerambyx spinicornis* and *Glenea* spp. infest logs with moisture content <50%. Dry wood borers like powder post beetles such as *Sinoxylon, Dinoderus, Lyctus* and *Heterobostrychus* spp. attack drier wood and well seasoned timber (Baksha, 1990). Two species of termite *Microcerotermes beesoni* and *Odontotermes* spp. infect fully grown stands. Under insect pest management in Australian radiata pine plantations, Yousuf et al. (2014) recorded bark beetle *Ips grandicollis* in South and Western Australia, and the wood wasp *Sirex noctilio* in Tasmania and Victoria that cause deaths in generally unthrifty stands. Scarab beetle adult is defoliator where as the larvae is root feeder (Kulkarni et al*.,* 2007).

4.4 Management of insect pest in plantation forest

- Sap feeders can be effectively controlled by spraying one of the ‘systemic insecticides' like methyl demeton, dimethoate 30 EC, formothion 25 EC, phosphamidon 85 EC @ 1 ml/lit. or acephate 75 SP @ 1g/lit in water solution.
- Mites can be controlled by applying a suitable acaricide like dicofol 18 EC @ 1.5 ml/lit.
- Early detection and timely insecticidal treatment are essential to manage the sap feeders since these pests multiply very rapidly and cause extensive damage to the plantation.
- Spraying of Phosalone 35 EC @ 2ml/lit. is effective in killing most of the young and adults grasshoppers.
- Phorate 10% granular @ 20 g/m^2 and chlorpyriphos 20% emulsifiable concentrate @ 5.0 mL/m^2 is effective for many types of insect pests under field conditions.
- Application of *Bacillus thuringiensis*, B.t. @ 1g/litre of water can be applied for highly effective that induces cent percent larval mortality in teak defoliator and skeletonizer in nursery and plantations.

5. CONCLUSION AND FUTURE THRUST

Because of large area management of diseases and insect pests in forestry crops is not only difficult but expansive also. However, the disease or insect pests can be managed by integrating cultural, chemical as well as biological practices. There are many insect pests either native or invasive, which infest tree species leading to outbreaks in plantation areas. Insect pests like *Hyblaea puera*, *Indarbela quadrinotata,* and *Leptocybe invasa* cause a serious problem in teak, Casuarina and Eucalypts plantation, respectively. Insect pest management techniques mostly aim at maintenance of pest populations at moderate levels that have greater chance of success than conventional methods of pest control. Observations on simple behavioural can sometimes used to great advantage in the development of such methods. The measures to control pests and diseases generally followed and suggestive measures are provided below:

- Most pest management strategies include chemical, biological and silvicultural techniques and are aimed at protecting planted forests. A combination of silvicultural and biological control methods of defoliators of *Tectona grandis* and some other species have also been developed.

- Preventative control through tree improvement programs, stand hygiene, timely selective thinning, and routine plantation surveillance involving field forest staff throughout the year are beneficial in controlling pests and diseases outbreak.
- There should be more emphasis to selection of quality seeds, i.e free from seed born diseases.
- Systematic surveys of forest insect and disease damage are not done on regular basis. Except in few cases information on pest occurrence are obtained via informal observations by foresters and forest workers. Thus ground or aerial pest monitoring surveys and application of biological and occasional chemical curative control would help control pests and diseases.
- Further research on all aspects of pest management helps to control pest attacks by effective application of physical, biological and chemical curative resources.
- Enhancement of plant characteristics which contribute to resistance like surface texture, leaf nutrient content, concentration and identity of chemical toxins including volatiles in plant tissues would be beneficial in increasing host plant resistance.
- Identification of provenances / land races tolerant/ resistant to natural incidence of key pests and their use in plantation would help increase plantation yield.
- Exploration of natural variation in allelochemical, their identification and widespread deployment of the chemo types mixtures of clones/ provenances of tree species used in plantation would help in ameliorating the damage caused by insect pests.

Plate 13.1 Atteva fabriciella attack on *Ailanthus excelsa* plantations.

Plate 13.2 Post emergence Damping off (left) and wilt disease (right).

Plate 13.3 Symptom of stem canker (left), hole in stem (centre) and Sooty mould (right). Source: www.yates.com.au.

14

PLANT GROWTH AND BIOMASS PRODUCTION OF DRY FORESTS

Growth in a plant is the time-dependent change in dimensions (i.e. height, diameter, crown etc.) influencing productivity of natural communities. Besides age and size, every environmental factor deviating from an optimum value affects growth and biomass production. There are substantial variations in physiographic and climatic parameters and so are the ecosystem distribution, plant growth and species composition. The changes in forest composition, growth and biomass bring changes in different carbon pools like standing forest biomass, soil and litter and coarse woody debris in an ecosystem. Growth and productivity of an ecosystem/tree depend on site quality (soil conditions, nutrient availability, aspects etc.), rainfall and water availability, intensity of light, air temperature, atmospheric gases like oxygen and carbon dioxide, species composition etc. Among the soil and environmental variables, elevation favourably influences growth and biomass unless other factors are not limiting. Plant growth variables like height, diameter, crown spread, basal area, wood density and biomass etc. are inter-related. It means one growth variable can be assessed using the other measurable variable/s through suitably selected model. This would help in decision making for planning sustainable management and utilization of forest resources for human well-being. Many models have been developed that either use diameter alone, or use a combination of height and other measurable variables to predict tree volume or biomass, but most of them are species or region-specific. Selecting the regional or local models appears relatively better in terms of accuracy while accounting biomass or carbon budgeting. This chapter describes growth and biomass related factors for enhanced production and various equations and models to interrelate growth variables among themselves or their use in predicting tree/stand volume and biomass in view of sustainable forest management and climate change mitigation.

1. INTRODUCTION

Age-dependent changes in plant size together with changes in species composition in a forest modify plant growth conditions. These time-dependent modifications always occur in natural communities and have significant impact on plant growth and survival. Apart from age and size effects, every environmental factor deviating from an optimum value affects growth and biomass production (Chen et al., 2015). Atmospheric oxygen (O_2) and carbon dioxide (CO_2) influence the physiology of plants. While O_2 is essential in respiration for the production of energy that is utilized in various growth and development processes, CO_2 is a raw material in photosynthetic process of the plants. This is the function by which forests sequester atmospheric carbon by uptake of CO_2 in photosynthesis, and transfer and store carbon in the forest ecosystem (Poudel, 2014). The carbon sequestration of the forests is determined by the growth of trees or other vegetation. In addition to climatic factors, site conditions also influence forest growth and development of forest cover (Worrell and Malcolm, 1990). Future forest growth may also be favourably influenced by increasing temperature and longer growing seasons at higher latitudes, as more sunlight will be used for photosynthesis that will enhance biomass production (Bergh et al., 2003; Rosenzweig et al., 2008; Raupach and Canadell, 2010). While growth shows elongation and thickening of roots, stems and branches increasing over a given period of time, the yield is the total amount available for harvest at a given time. Yield is also the summation of the annual increments. Temperature, light, water, oxygen supply, nutrient supply, etc along with internal factors like genetic control etc., affect plant growth and yield.

Increasing biomass is the primary factor in the building up of the carbon pools and is derived from the reaction between CO_2 in air, water and sunlight, via a process called photosynthesis, to produce carbohydrates - building blocks of biomass. In general, photosynthesis converts less than 1% of the available sunlight to stored chemical energy. The solar energy driving photosynthesis is stored in the chemical bonds of the structural components of biomass. Overall reaction of oxygen generating photosynthesis is:

$$6\,CO_2 + 6\,H_2O \rightarrow 6\,O_2 + C_6H_{12}O_6$$

In the process of extracting the energy stored in the biomass in the form of chemical bonds, the organic product after combining with oxygen either chemically or biologically oxidizes to produce CO_2 and water. Thus, it is a cyclic process as the CO_2 produced is then available to produce new biomass (Gifford, 2003).The photosynthetic process consists of two phases: a series of light-dependent reactions that are temperature-independent (light reaction) and a series of temperature-dependent reactions that are light independent (dark reaction). The rate of the light reaction can be increased by increasing light intensity (within certain limits) but not by increasing temperature. In the dark reaction, the rate can be increased by increasing temperature (within certain limits) but not by increasing light intensity (Lodish et al., 2000). Another differentiator amongst plant species is the type of photosynthetic pathway the plants utilize. Most plants make use of C_3 photosynthesis route, in which the C_3 determines the mass of carbon contained in the plant material. A different photosynthesis pathway is represented by C_4 plants, which accumulate a significantly greater dry mass of carbon as compared to that observed in C_3 plants by way of increased potential for energy conversion (Cescatti and Niinemets, 2004). Acacias, poplar, willow, wheat and most other cereal crops are examples of C_3 species, whereas perennial grass, miscanthus, sweet sorghum, maize and artichoke use the C_4 pathway of photosynthesis. Light and nutrients usually interact in natural ecosystems. Plants are often more strongly nutrient-limited under higher than lower light availabilities. Light impacts on ecosystem distribution and plant growth and species composition are expected to be substantial in dry areas, where changes and variations in climatic parameters such as temperature and precipitation may be significant. Elevated temperature and CO_2 concentration that have been observed worldwide can modify the rate of critical natural processes as predicted by bio-geochemical models (Mcmahon et al., 2010). The changes in forest composition, growth and biomass can bring changes in different carbon pools such as standing forest biomass carbon and soil/litter carbon in the ecosystem and carbon emission reduction due to the use of wood products in place of other carbon-intensive products of industries. Thus, in any assessment of forest/plantation growth and prediction, there is a need of considering climatic factors especially in areas where climatic change is likely to have greater influence on forest growth and cover (Bonan et al., 1990; Tyler et al., 1995; Raich et al., 1997; Yang et al., 2003).

In turn, tree biomass also influences biogeochemical cycles, climate, and biodiversity not only at local levels but a global scale also. Thus understanding the environmental control of tree biomass requires consideration of the drivers of individual tree growth over the lifespan of a tree (Weiskittel et al., 2011; Bowman et al., 2013). This can be obtained by studying tree growth in permanent sample plots (to measure repeatedly over life span) and tree ring analyses (i.e., retrospective studies). While site index to climatic variables assume that the sensitivity of a species to climate remains stable across the geographic range, a provenance trial assume that populations are adapted to their local climatic conditions and tend to respond differently to climate (Anyomi et al., 2012). In view of spatial and temporal complexity of forest productivity and climate-relationships there is need for regional studies on forest growth dynamics of current and future populations. Further, to tracking and predicting of the effects of environmental change on tree biomass require models based on data static inventory and permanent sample plots are required. In forestry, the term model generally refers to a table, formula, or computer software package that describes how the forest structure is going to change (Weiskittel et al., 2011).

2. GROWTH AND BIOMASS

Field observations indicate a trend of increased biomass and growth in tropical (Chave et al., 2008; Lewis et al., 2009; Philips et al., 2008) and temperate (Spiecker, 1999; Hember et al., 2012) forests. Growth is defined as the increase in dimensions (height and diameter for example) of an individual tree through time. The easily measured dimensions like height and diameter are strongly correlated with wood volume and biomass. Basal area (i.e., cross-sectional area of stems expressed per unit ground surface area) is also calculated from diameter and is used in ecological or physiological studies (Slik et al., 2010; Markesteijn et al., 2011; Premavani et al., 2014). The rate of change of a dimension per unit time can be expressed in either absolute or in relative terms. For example, relative growth rate (change in a dimension per sampling interval relative to initial size) is commonly used in short-lived plants, but is less useful for tree growth because of rapid decline in relative growth rate with increasing tree size due to building up of non-photosynthetic material like stems, branches and roots (Tomlinson et al., 2014).Tree growth varies according to tree species and growing conditions (Herault et al., 2011). Following germination height increases rapidly in general for some time, then increment peaks and the added height each year becomes less and less (Assmann, 1970), whereas the increases in stem diameter is gradual over a tree's lifespan (Hann and Larsen, 1991). However, increments in stem basal area and volume of the tree follows a similar pattern but the maximum basal area increment occurs at some time after the maximum height increment (Nock et al., 2011). The increase in basal area in a tall tree will add more volume to the stem compared to a short tree; hence, the increment in stem volume (or mass) peaks very late (Eastaugh et al., nil) and deviates slightly from the fact that rate of tree carbon accumulation increases continuously with tree size (Stephenson et al., 2014).

Biomass is an important indicator of ecological and management processes in the forests and vegetation (McKendry, 2002). Biomass production in a plant engrosses different physiological processes. The process take place in a plant with interception of light and involves CO_2, temperature, and nitrogen (Chapin et al., 2002). This process produces carbon-containing organic matter and then transfers them into different components of the plant and into the soil (Chapin et al., 2002). The increasing tree biomass with age contributes to increase in the carbon sequestration rate and subsequent increase in biomass and carbon stock (Rizvi et al., 2014). However, biomass is a plant attribute that is time consuming and difficult to measure or estimate, but easy to interpret. Plants that dominate a site, in terms of biomass, are a reflection of the plants that are controlling the resources like nutrient, water and solar radiations. Thus, biomass is often measured to assess the ecological status of a site and is time-dependent. Effects of forest age on biomass increase can be exemplified by increase in biomass of *Butea* forest in western India ranging from 183.7 to 298.3 tons ha^{-1} for trees, from 4.9 to 6.3 tons ha^{-1} for shrubs, and from 1.7 to 2.1 tons ha^{-1} for herbs in 5-year to 15-year-old forest stands (Kumar et al., 2011).

Site as well as the climatic factors influence the growth and productivity of forests or plantation and the surrounding vegetation (Iqbal et al., 2010; Henmann and Hugh, 2010). The site factors include topography, soil texture and soil moisture; the climatic factors are rainfall and water, light, temperature, relative humidity, air, and wind. They are the nonliving components of the **environment** which, along with the biotic or living factors, determine the extent resulting in expression of the **genetic factor** in the plant (McKeand et al., 2003; Potts et al., 2008). Temperature, forest age, forest cover, soil thickness (nutrient level), precipitation and aspect are well related to forest growth, i.e. stem volume (Cardoso et al., 2012). Precipitation generally shows a positive effect on growth and biomass which is indicated by increased above-ground tree and shrub biomasses with annual normal rainfall in Rajasthan; however, data pattern showed a cyclic relationship with lowest biomass in regions of about 400 mm rainfall (possibly due to degradation) and relatively greater biomass in below 400 mm rainfall zone due to plantation (Fig 14.1). The simultaneous increase in temperature as a result of global warming may reduce forest growing stock because of increased evapo-transpiration and soil water deficit (Goel, 2004).

Seasonal and historical tree growths are very much controlled by the environmental factors like precipitation, soil moisture, solar radiation, temperature and depth to water table during each growing season. For example, radial growth increment is related to these environmental variables in a floodplain area. In such areas, the growth ceases early during dry and later during wet years. In the wettest year, growth shows a negative correlation with water table depth but during the driest year, the growth is positively correlated to precipitation (Robertson, 1992).

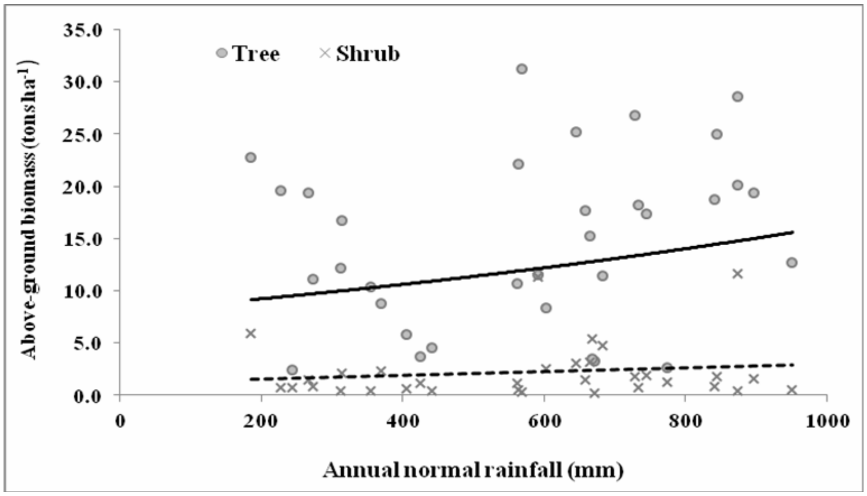


Figure 14.1 An increasing trend in above-ground forests trees and shrubs biomasses with annual normal rainfall across Rajasthan.

The fixed effects (elevation, slope and soil water-holding capacity) are most important in shaping the age–diameter relationships as lower elevations, steeper slopes, north-facing aspects, higher water-holding capacities and moist summers result in larger maximum diameters (Rohner et al., 2013). A number of factors that regulate processes like vegetative meristem activities, cell elongation, photosynthetic efficiency, and secondary wall biosynthesis, all of which are crucial for plant biomass production have also been identified in recent molecular and genetic studies that could potentially be applied to improve the yield of biomass of some species like Miscanthus, switch grass (*Panicum virgatum*) and hybrid Poplar (Demura and Ye, 2010). Aspect also influences forest growth as indicated by lowest forest growth on south-west- and south-facing slopes, and highest growth on north-facing slopes in the Taihang Mountain region of northern China (Yang et al., 2006). Greater tree diversity and soil carbon stock have also been observed however in the southeast aspect and shrub diversity; and their population on southwest aspect in Aravalli Range of Rajasthan, India (Singh and Singh, 2013).

2.1 Plant density

Tree growth and biomass differ with spacing of plants (Gupta et al., 1998; Singh et al., 2007). Planting density modifies productivity and water use in both pure stand or in a combination with crops/grasses. Biomass production per tree is generally low at high tree densities as compared to medium or low density plantations. Rate of transpiration per tree has also been observed to be lowest at high tree densities indicating high water use efficiency in the densely planted stands of *E. grandis* (Eastham et al., 1990). Despite of greater cumulative losses of trees, close spacing retains more live trees per unit area than a wider spacing, but these trees are smaller in growth as well as in biomass production. In contrary the wider spaced plants are greater in growth and biomass (Miller et al., 2004; Singh et al., 2007). Possible explanations for such differences are: (i) more intense competition between tree at closer spacing, and (ii) relatively greater soil resource availability at greater spacing than at closer spacing. In contrast, *Conocarpus erectus* tree seedlings planted at 0.7, 1.4 and 2.1m spacing though produced 4.57, 11.93 and 20.80 kg tree^{-1} biomass after three years, the close spacing yielded highest biomass per hectare (i.e., 40.8, 26.1 and 26.3 tons ha^{-1} for stem, branches and foliage, respectively). This indicates the effects of high density plantation on biomass production. However, high density forest stands may enhance nutrient demands from the soil and subsequently affect belowground productivity by differential aboveground biomass allocation and tissue nitrogen concentration (Eastham et al., 1990).

2.2 Soil water availability

Soil water availability plays the most significant role amongst many factors which run counter to the natural establishment, growth and development of plants (Chaturvedi et al., 2012a). Varying water availability greatly influences physiological processes (Fig 14.1& 14.2), which manifest in the structural traits of plants and alter the timings of many vital processes (Saraswathi and Paliwal, 2011; Singh et al., 2013b).

Supplemental irrigation improves growth and biomass production in most of the tree species, and fertilizer application shows synergistic effects to watering (Singh and Singh, 2011b). While supplemental watering enhances plant growth, the enhanced water availability through rainwater harvesting increases growth and ecosystem productivity by way of improving soil nutrient mobilization and uptake (Gupta, 1995; Singh, 2009b, 2012). Deep trenches favour tree growth though efficient utilization of enhanced soil resources is species specific (Singh et al., 2013);on the other hand an inefficient utilization of available resources may lead to invasion of other species for complete use of the enhanced resources in spite of strong resistance from the native vegetation (Maron and Marler, 2007; Daleo et al., 2009). Generation of gap also leads to invasion because of enhanced resource availability. Thus both physical disturbance and increased availability of scarce resources contribute to a community's susceptibility to invasion and suggest a linear relationship between the size of logging gaps and the magnitude of exotic species invasion (Blair et al., 2010). Soil water gradient in dry region also influences tree phenology and their associations, which has to deal with seasonal drought - a characteristic feature of tropical region (Baker et al., 2008; Nanda et al., 2013).

Tree diameter growth is more sensitive to seasonal and inter-annual environmental variations (Dobbertin, 2005). Tree growth increases with precipitation and relative soil water content, though growth responses to precipitation and temperature are species–specific (Hanson et al., 2001; Nath et al., 2006; Bräuning et al., 2010). A pan tropical study indicates that secondary growth is higher during the wet season (Wagner et al., 2014), but tropical forests maintain or even increase their productivity during the dry season (Hutyra et al., 2007; Baker et al., 2008; Bonal et al., 2008). This is because of varying uses of carbohydrates accumulated in dry seasons by evergreen species (Wurth et al., 2005) and support respiration costs in deciduous species when they are leafless particularly at the onset of the dry season (Poorter and Kitazima, 2007; Janzen and Wilson, 1974). It is not only the dry region where seasonal growth is a common feature, but tropical trees species of extremely wet environments also exhibit this phenomenon (Pélissier and Pascal, 2000; Clark et al., 2010). The increase in aridity also leads to transitions of tropical dry forests to savanna woodlands called ‘desertification’ (Dirzo et al., 2011). Likewise, dry forests are also under danger by way of conversion into farmlands and grasslands (Janzen, 1988). In spite of these adversities, tropical dry forests are dominated by many drought-tolerant species with varied strategies to tolerate and mitigate the effects of water scarcity and climate change (Phillips et al., 2009; Markesteijn et al., 2011).

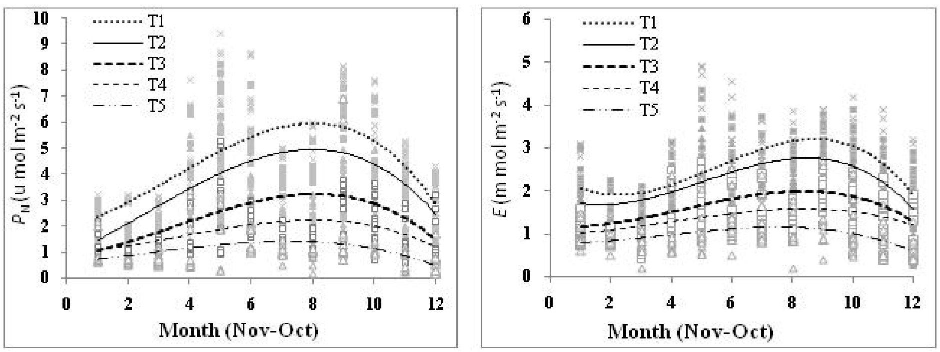


Figure 14.2 Effects of varying levels of irrigation (36.2 mm in T_1, 26.5 mm in T_2, 20.2 mm in T_3, 18.1 mm in T_4 and live saving irrigation in T_5 in 1-m deep loamy sand soil in non-weighing lysimeters) on temporal variations in rate of photosynthesis (P_N, left) and transpiration (E, right) across the species (*A. nilotica*, *D. sissoo* and *E. camaldulensis*).

Though dry regions always face scarcity of water, effects of soil water stress vary with species. For example, a greater reduction in growth is observed in *Albizia lebbeck*, whereas it is less in *Prosopis cineraria* and this has been attributed to the water holding capacities of these species (Dhupper, 2012). The deleterious effects of water stress can be envisaged at any stage of plant growth and development, although the net effect is determined by the stress intensity and growth phase of the plant (Thakur and Rai, 1984). An increase in transpiration rate (*Tecomella undulata*) and early foliation (*Capparis decidua*) have also been reported under severe water stress (Lahiri and Kharbanda, 1966). While increased water availability through precipitation or supplemental irrigation enhances tree growth (Fig 14.3) and biomass in dry region, the global warming-driven drought stress (including annual seasonal water stress) may put forests of dry region at climatic risks (Bullock et al., 1995).

Severe water stress reduces net primary production of both natural and plantation forests (Phillips et al., 2009; Zhao and Running, 2010; Singh and Singh, 2006) and reduction is more in above-ground biomass, which is most sensitive to the water deficit (Brando et al., 2008; Singh and Singh, 2009). Tolerance of growth of trees/shrubs to decreased irrigation level is species-specific. When plants of *Acacia nilotica*, *Dalbergia sissoo* and *E. camaldulensis* were irrigated at varying levels, more sensitivity and tolerance to water stress were observed in *D. sissoo* and *A. nilotica,* respectively (Table 14.1). Providing supplemental irrigation above 50% of soil field capacity was suggested to be better for plant growth and biomass production (Singh and Singh, 2006, 2009; Singh and Rathod, 2010; Singh, 2011a).

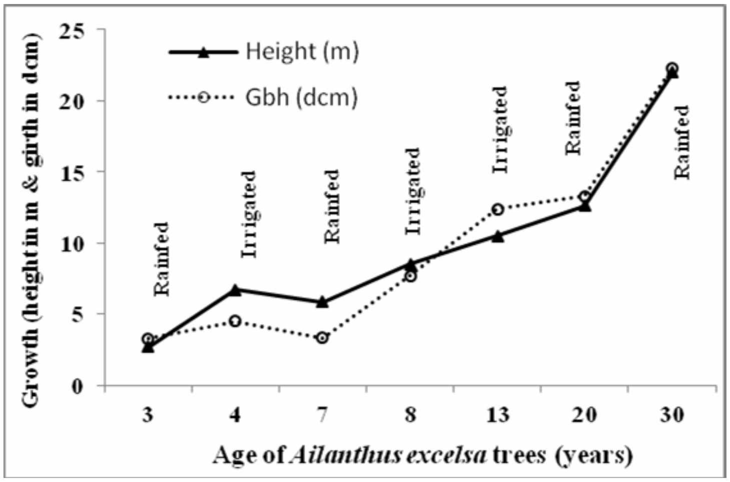


Figure 14.3 Changing height and girth at breast height (Gbh) of *Ailanthus excelsa* under irrigation and rainfed conditions near Jaipur area of Rajasthan. Irrigated ones perform better than the rainfed trees. (Data source: ICFRE, Ardu, FRI, Dehradun).

Table 14.1 Height growth (cm) of seedlings/trees as influenced by different levels of supplemental irrigation.

Level*	***E. camaldulensis***					***A. nilotica***					***D. sissoo***				
Age (month)	**3**	**12**	**24**	**36**	**48**	**3**	**12**	**24**	**36**	**48**	**3**	**12**	**24**	**36**	**48**
T_1	43	248	393	730	815	41	215	300	370	410	50	290	490	520	570
T_2	45	223	350	530	580	48	162	269	345	390	50	260	380	375	415
T_3	46	233	323	545	565	42	143	230	335	350	49	239	350	375	395
T_4	44	247	310	475	520	41	163	221	295	310	50	213	289	295	335
T_5	40	180	235	345	400	46	163	220	275	290	50	185	235	230	-

* Irrigation levels as in Fig 14.2.

2.3 Light intensity

The intensity of light varies with the time of the day, season, geographic location, distance from the equator, and weather conditions (Soni et al., 2012; Akpootu and Aruna, 2013). It gradually increases from sunrise and attains a peak between 12:00 and 14:00 hr after which the values fall to a minimum in the late afternoon and evening toward sunset. Light intensity is high during summer, moderate in spring and fall, and low during winter season (Singh and Singh, 2003), though a long-term decrease in bright sunshine duration (0.0 to 0.5 h per decade) has also been observed with strong spatial variations in India (Soni et al., 2012). Leaves on a plant differ in the amount of light that they receive. The amount of light falling on a leaf decreases as sunlight passes downward through the canopy. Leaves on the upper part of the canopy shade and reflect light away from the lower leaves. For example, relative light intensity above the cacao (*Theohroma cacao*) canopy ranged between 30 and 100% of full daylight, whereas at ground level it was 4-10% (Miyaji et al., 1997). Trees with somewhat vertical leaves allow more light downward and tolerate high population density than the trees with drooping leaves (Chapman and Carter, 1976). Plantation in row with proper spacing can also minimize interplant shading. Plants differ in optimum requirements of light, thus, both deficient and excessive light intensities are injurious to the plants (Gonçalves et al., 2005; Safeer et al., 2013).

An increase in the intensity of light results in an increase in the rate of photosynthesis across relatively low ranges of light intensity, and then the rates decelerate until they reach an asymptotic maximum (Singh and Singh, 2003; Fan et al., 2013). Photosynthetic rate (P_N) has been observed to vary diurnally with the highest value in morning hours (particularly 10-11 hrs). It decreases during peak hours of 12-14, increases again during 15 hrs and decreases to lowest at sunset (Singh and Singh, 2003). Because of varying orientations and shading of many leaves, most plant canopies do not reach light saturation at full sunlight; that is, they would be able to respond to light levels well beyond full solar irradiance (Hoasain and Kamaludin, 2004). In a study, Phonguodume et al. (2012) observed variation in adaptations towards light conditions among *Afzelia xylocarpa*, *Anisoptera costata*, *Dalbergia cochinchinensis*, *Dipterocarpus alatus* and *Hopea odorata* seedlings. Here *A. costata* and *D. cochinchinensis* showed higher collar diameter growth under higher light intensity, whereas *A. xylocarpa* showed better height growth at lower light intensity. *A. xylocarpa* and *D. alatus* accumulated higher total biomass under medium light intensity. *Hopea odorata* showed increasing biomass with increasing light intensity but *A. costata* accumulated more biomass at lower light intensity. A global scale model of light-use efficiency and the theoretical maximum efficiency with which plant canopies convert solar radiation to biomass indicates two times higher net primary production than the productivity of most currently managed or natural ecosystems (Delucea et al., 2014).

Increments in biomass, its partitioning among different parts, and architectural arrangement of plant canopy in space are influenced by light (Küppers, 1989). Thinner canopy in tropical deciduous forest or canopy removal leads to light penetration and more under growth including tree seedling density and invasion of exotics (Chandrashekaran and Swamy, 2002; Lima and Moura, 2008; Sharma and Raghubanshi, 2010; Singh and Shukla, 2013). The relative seedling density of *Terminalia alata* increases with increase in gap areas, while that of *Shorea robusta* decreases with increases in tree fall basal area, thereby lowering the plot-level dominance. However, the relative seedling densities of *Eugenia operculata* and *Syzygium cumini* are negatively and positively correlated, respectively, with tree fall basal area (Sapkota and Oden, 2009). In deciduous forests, seasonal changes in the light and temperature are enough to trigger the trees to drop their leaves (Johnson, 2009). However, light environment in degraded secondary forests may be diverse because light condition changes by forest structure such as gap formation and time span as a result of disturbance (Barik et al., 1992; Davis et al., 2000).

2.4 Air temperature

Temperature is vital to all metabolic processes influencing uptake, release, and storage of carbon and nitrogen as well. In absence of resource limitation, rising temperatures coinciding with adequate precipitation increases tree metabolic processes that in turn lead to higher biomass accumulation (Luo, 2007; Anderson et al., 2006). Because of low intra-annual variability of temperature in the tropics as compared to the temperate areas, studies relating long-term growth responses to temperature in tropical forests are limited (Clark and Clark, 2010; Dong et al., 2012). Responses of diameter growth to higher temperatures across forest types can be both positive (Delpierre et al., 2009; Dunn et al., 2007) and negative (Clark et al., 2003; Freeley et al., 2007). The decreases in diameter appear to be due to the effects of water limitation on photosynthesis. Rising temperatures impact the carbon storage negatively because of strong link between temperature and rate of carbohydrate consumption (Amthor, 2000). Photorespiration rates rises with temperature in C_3 plants like Acacias (Santosh Kumari, 2010) that reduce quantum yield, which drops with decreasing partial CO_2, but are insensitive to CO_2 changes in case of C_4 plants like *Euphorbia* spp., *Calligonum* spp. and *Haloxylon* spp. (Pearcy and Toughton, 1975; Ehleringer et al., 1997; Sage et al., 2011). Photorespiration however, plays an essential role in nitrate assimilation in C_3 plants (Rachmilevitch et al., 2004).

With increase in atmospheric temperature (Houghton et al., 2001) and the possible average increase in precipitation of about 3.4 per cent globally per 1°C rise in temperature (Allen and Ingram, 2002), there is chance of increase in forest growth. But net growth will depend upon a balance between hydrological cycles as rise in temperature will also increase the vapour pressure deficit and water loss through transpiration. For example, an increase in temperature by 20% (maximum 8°C) was reported to increase the total evapotranspiration demand by 14.8% in western Rajasthan, India (Goel, 2004). Such losses may be controlled by stomatal closure in isohydric species like *Capsicum annuum*, *Prunus dulcis*, *Sorghum bicolor* etc., or may be affected due to decreased margin of safety under hydraulic failure in anisohydric species like *Malus domestica*, *Populus* spp., *Vigna unguiculata* etc. (Jones and Tardieu, 1998; Jones, 2004; Maseda and Fernández, 2006). Global warming and N_2 deposition also regulate plant community composition and biomass production in temperate meadow steppe ecosystem (Zhang et al., 2015). Though warming shows little effect on aboveground biomass in the years with higher precipitation, it reduces aboveground biomass in dry years significantly via its effect on the water availability. Increased temperature could also lead to increased soil biological activities implying increased mineralization and nitrogen availability in forest soil (Strömgren and Linder, 2002; Rasmussen et al., 2006). Rise in temperature appears a common driver in forest tree mortality as indicated by climate-induced tree mortality not only in semi-arid regions but in mesic forests also (van Mantgem et al., 2009; Adams et al., 2009).

Increasing latitudes also determine the intra-annual variability of thermal conditions (Eamus, 1999). Obviously, species that grow near the equator do not respond to temperature, probably because of the low inter-monthly variability of temperature (i.e., < 3ºC). For example, *Juniperus procera* located at 9º N in Ethiopian dry forests (Sass-Klaassen et al., 2008) and *Zanthoxylum rhoifolium* located at 4º N in Colombian forests show no responsiveness of radial growth to temperature variability. In contrast, six out of the seven studied species in the Bolivian forests located at 16º S with an inter-monthly variability of temperature of about 5ºC, showed negative growth responses to temperature particularly during the wet season. Similar patterns have also been observed in *Centrolobium microchaete* and *Machaerium scleroxylon*stands (López and Villalba, 2011; Paredes-Villanueva et al., 2013) and *Mimosa acantholoba* occurring in Mexican dry forests at 16º N (Brienen et al., 2010). This suggests that rising temperatures and increased evapo-transpiration negatively affect tree growth of dry forests (Clark et al., 2010).

2.5 Atmospheric CO_2 concentration

Anthropogenic activities have increased, and will continue to increase the concentration of the atmospheric CO_2. From values of about 280 µmol mol^{-1} between the end of the last glaciation and about 1750, atmospheric CO_2 has increased to above 400 µmol mol^{-1} today, and the value in 2050 will be about 550 µmol mol^{-1} (Raven and Karley, 2006). Elevated CO_2 level can increase tree growth through carbon fertilization (Pataki et al., 2006), however, it may be species specific and nutrient and water limitation can mitigate growth (Oren et al., 2001). Increase in atmospheric CO_2 levels can also cause higher temperatures and longer growing seasons (Barford et al., 2001; Cao and Woodward, 1998; Schimel, 2007). Experimental evidences show that under optimal growing conditions, plant growth is enhanced by elevated CO_2 (i.e., fertilization effect). The magnitude of this effect is, however, highly dependent on water and nutrient availability (N or P) and under conditions of limiting nutrients, enhanced growth at elevated CO_2 may not occur at all. Species like Acacias or Prosopis that dominate in dry areas and are prone to nutrient and/or water limitation (despite of efficient water user) may have considerable uncertainty on CO_2 fertilization effects. Elevated CO_2 enhances water use efficiency in isohydric plant species by reducing stomatal conductance and hence mitigate some of the potential negative impacts of warming (Farquhar 1997; Wullschleger et al. 2002). Most acacias are more robust to modest warming, but bio-climates of 59% of acacia species would disappear with a 1°C increase and the rest suffer a decline in distribution of more than 75%. Many species are predicted to track moving climate zones across the landscape because of soil constraints or shrink to a smaller range within their current distribution (Chapman and Milne, 1998).Thus, drought avoiding species may move closer to carbon starvation, while drought-tolerant species may come closer to hydraulic failure under climatic warming (McDowell et al., 2008).

Increased CO_2 may mitigate some of the impacts of climate change by reducing water stress. The impacts on particular ecosystems include increased forest growth, alterations in competitive regimes between C_3 and C_4 grasses, increased encroachment of woody shrubs in dry areas, continued incursion of mangrove communities into freshwater wetlands, increasing frequency of coral bleaching, and establishment of woody species at increasingly higher elevations in the alpine zone (Hughes, 2003).

Plantations play an effective role in balancing atmospheric CO_2 levels by capturing and storing the carbon in biomass and soil. Because of wide variability among tree species towards varying resources, species with greater survival and growth appears to be more effective in this endeavor. For example, *Alnus subcordata* and *Acer velutinum* are better in biomass production and carbon storage compared to *Cupressus sempervirens* in Iranian lowlands (Haghdoost et al., 2012).

2.6 Nutrient fertilization

Fertilizer application improves plant growth (leaves, branch, stem and roots) and biomass production considerably (Kishor, 1987; Ogbonnaya, 1994; Singh and Singh, 2011b). Nitrogen (N) availability together with light modifies plant growth and competitive potential along the light gradients in forest understory, whereas combinations of N and P enhance plant growth significantly. Nitrogen addition increases both above and below-ground production, suggesting that N is one of the most important limiting factors determining plant productivity (Zhang et al., 2015). Phosphorous fertilization is also possible in the tropics, where P and N are not limited. While P application shows synergic effects with soil water availability, it ameliorates the conditions of soil water stress also and hence helps establish the plantation (Singh and Singh, 2011b). However, relatively low correlation have been observed between growth and development parameters (height, diameter and dry biomasses) of *Moringa oleifera* and *Adansonia digitata* and different fertilizers compared to watering regimes indicating the importance of water in drylands (Larvanou et al., 2014). In a study, application of 18 g N and 3 g P_2O_5 per tree increased tree height by 35 to 85% and collar circumference by 11 to 56%, during first three years of establishment of *Ailanthus excelsa* (Gupta, 1994b). Plant growth is generally more strongly limited by nutrients in high (than in low) light condition even at a common nutrient supply (Poorter and Nagel, 2000), amplifying the interactive effects of light and nutrients on plant growth. Increased nitrogen supply invariably leads to a larger leaf area ratio (Küppers et al., 1988; Thompson et al., 1988; Bowler and Press, 1996; Wang et al., 1998), but this increasement depends on light availability (McDonald et al., 1992) and appears to be species-specific (Walters and Reich, 1997). This indicates that species effects superimposed by light and N limitations can importantly modify species competitive performance in forest environments. Forest fertilization causes residual long-term effects on stand nitrogen dynamics and increases soil N mineralization rates, amounts of mobile soil NH_4-N and NO_3-N and tree height as well (From et al., 2015).

2.7 Community composition

Closed canopy forests generally produce higher above ground tree biomass than the open forests. Similarly forests with miscellaneous species shows higher above ground tree biomass than the production under forest dominated by less number of species, i.e. sal forest (Pande and Patra, 2010). Studies conducted in the forests of Rajasthan, India indicate an increasing trend in Shanon-Weiner tree diversity index with annual normal rainfall (Fig 14.4 left); both diversity and species richness show weak but significant positive relation (power relationship) with tree aboveground biomass (Fig 14.4 right). In another study, the diversity components and tree density show positive relation with total tree basal area, which is positively related to productivity (Sagar, 2006). Thus, basal area, tree density and species diversity are important characteristic of the dry forests, where recurring disturbances do not permit concentration of biomass or stems in only a few strong competitors. Functional groups also have profound influence on plant productivity (Hutchings and de Kroon, 1994; Penuelas et al., 2004) and show varying responses to warming (Fay et al., 2011). Because of species specific recovery from disturbances, the differential species growth rates could potentially influence biomass-accumulation rates also (Marín-Spiotta et al., 2007; Pare and Bergeron, 1995). Furthermore, the effects of expected increase in temperature on terrestrial plant ecosystem stability will be a decrease in species richness and diversity (Rull and Vegas-Vilarrúbia, 2006; Fonty et al, 2009; Yang et al., 2011). However, some study negates the effect of warming on plant diversity (Zavaleta et al., 2003).

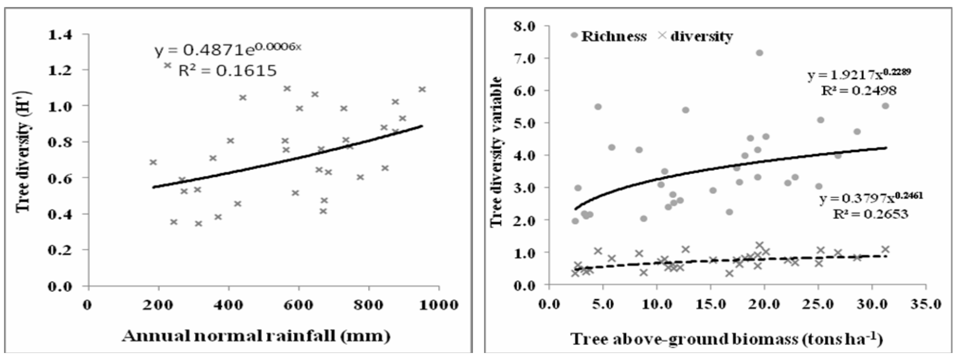


Figure 14.4 Relationship between tree diversity variables with rainfall and tree above-ground biomass production across Rajasthan forests, India.

3. GROWTH MODELLING AND BIOMASS PREDICTIONS

Standing forests volume, biomass and carbon stock are the measures that are normally considered within the framework of sustainable forest management and for carbon accounting (Brown, 1997; Brandies et al., 2006). Accurate estimation of tree volume and biomass is essential to predict expected yields for commercial and subsistence harvesting and is important for carbon stock assessment concerning climate change mitigation (Chave et al., 2005; Weiskittel et al., 2011). It is also beneficial for national development planning as well as for scientific studies of ecosystem productivity, carbon budgets, etc. (Zheng et al., 2004; Zianis and Muukkonen, 2004; Hall et al., 2006; Pekham et al., 2012). Forest biomass is applied to estimate carbon stocks and carbon fluxes when measured frequently, thus providing means for estimating the amount of CO_2 released into or removed from the atmosphere. Active management of forests offers more opportunities than management towards old-growth forests with maximized carbon stocks in the standing biomass. On the other hand, forest biomass can be used intensively in order to provide timber for the substitution of other materials and forest biomass for energy generation (Jandl et al., 2013). Growth and yield models illustrate forest dynamics (i.e., the growth, mortality, reproduction, and associated changes in the stand) over time and thus have been widely used in forest management because of their ability to update inventories, predict future yield, and to explore management alternatives and silvicultural option, thus providing information for future planning (Vanclay, 1994).

3.1 Methods of forests assessment

Application of appropriate methods and transparent and consistent reporting of forest growing stock are needed in both, scientific literature and the GHG inventory measures (Somogyi et al., 2006). Different approaches, based on field measurements, remote sensing and GIS are applied for estimation of forest growing stock (Lu, 2006). The traditional techniques based on field measurements are the most accurate but have also proven to be very costly and time consuming (de Gier, 2003). Remote sensing (RS) techniques are used in many cases but this approach has met with little success for multi-age, multi-species forests and only with limited success in forest with few species and age classes representing a broad range of biomass distributions (Schroeder et al., 1997). Even where RS data is useful for estimating forest growing stock, ground data is still necessary to develop the biomass predictive model (i.e. calibration) and its validation (Zianis et al., 2005) because remote sensing does not measure biomass, but rather it measures some other forest characteristics (e.g. spectral reflectance from the canopy). Though there is considerable interest in estimating the biomass of forests for both practical forestry issues and scientific purposes, the quantification of biomass or carbon pools of a forest suffers from a number of methodological problems. The generally used parameter is the average tree volume (Volume_{av}) calculated from diameter at breast height (DBH) and tree height (H) as:

$$Volume_{av} = \pi \times (\mathrm{DBH} / 200)^2 \times \mathrm{H} \times 0.5$$

Height is calculated using the equation obtained from Brown et al. (1989) like:

$$\mathrm{H} = \exp^{(1.0710 + 0.5677 \times \log(DBH))}$$

Biomass is then calculated from the volume as:

$$\mathrm{Biomass}_{average} = \mathrm{Volume}_{av} \times 0.62 \times 10^3$$

Here, 0.62×10^3 is the average wood specific gravity (Mg m^{-3}) provided by the Intergovernmental Panel on Climate Change (IPCC 2006) and 0.5 is the average form coefficient for conic trees (CIRAD and MAE, 2004).

3.2. Volume and yield tables

Volume table is tabular presentation of volume of a given species for single, double or multiple variables like dbh, dbh and height or dbh, height and some measure of form or taper of the tree. The choice of variables depends on the extent of their intended application, simplicity and promptness (money and time). Single variable shows better estimation of tree volume in restricted area only and is of limited use. For larger area volume table, it is better to incorporate two variables. Volume table with three variables however, appears more accurate and is applicable at national level or useful in research (Chaturvedi et al., 2012b). Among the variables, DBH is the most important, then height followed by the form of a tree (including wood specific gravity). Tabular statement which summarizes all essential data relating to the development of a fully-stocked (per unit area basis) and regularly thinned even-aged crop at periodic intervals covering the greater part of its useful life is generally called yield table. The development of yield tables requires different expressions representing relationships among stand variables. The variables used in general are age (years), number of stems per hectare, mean dbh (cm) and height (m), basal area (m^2 ha^{-1}), total and individual commercial volume in m^3 ha^{-1} and m^3 per stem (Montero et al., 2001). Yield models can be used in site index classification of the inventory units, the estimation of periodic increment in inventories for forest management, in the estimation of volumes with a fair degree of accuracy when inventories are not possible, and production forecasting for regional scale planning (Bermezo et al., 2004).

Forest growth and yield is usually connected with site classification and the mathematical functions are used for modeling the relationship between stand height and age to determine site classes (Skovsgaard and Vanclay, 2008). Growth and yield prediction models are abstract or simplified representations of some aspect of reality used primarily to estimate the future growth and yield of forest stands (Peng, 2000; Bermejo et al., 2004). However, accurate prediction of intermediate and final harvests in the construction of yield tables depends on the accuracy of individual-tree volume equation (Tewari and Singh, 2006a). A method for relating some non-easy to measure tree characteristics from easily collected data like diameter at breast height (DBH), total height, or tree age is 'allometry' that provides relatively accurate estimates. Models for volume, biomass or nutrient content within the trees belong to the same class as methodologies for sampling trees and fitting and using the equations are similar (Picard et al., 2012). Tree heights, diameter at breast height (DBH, 1.37 m stem height) and bark of tree trunk are recorded from plots (0.1 ha) either repeatedly at a regular interval for collecting yield table data for a particular silvicultural program (permanent plots), or measured only once to obtain age based information about a relevant parameter to use in constructing a yield table/gain assuming normal or representative silvicultural practice (Temporary plots), or re-measured once to obtain an average rate of change in response to a given set of initial conditions (interval plots) laid out after a reconnaissance survey of planted or natural forest area. Hypsometer, Criteria 400, Relescop, Telerelascop, Sunto-clinometer and dendrometer are used to measure tree height, whereas DBH is measured by caliper or measuring tape at 1.37 m of trunk height above the ground surface. The 'Bark of tree trunk' is gauged for measuring thickness of the bark of the trees. Linear and non-linear equations are used to model the relationship between total volume and dbh or dbh and total height, though incorporation of crown variables has also been reported to improve volume prediction models (Özçelik et al., 2014). Wherever, only stem DBH is used in estimating tree volume it is called single entry, whereas use of both height and DBH in estimating volume is called double entry volume.

A stand growth model represents an abstract of the natural dynamics of a forest stand, and depicts growth, mortality and other changes in the composition and structure of the stand. It can also be mathematically described as the growth and yield of trees and stands. Some models are developed to predict the yield, which is the final accumulated growth at the end of a certain period of time, i.e. total volume growth in cubic meters per hectare. Others models predict growth - total increase in dimensions of one or more individuals in a forest over a given period of time (i.e., total volume growth in cubic meters per hectare and per year). Traditionally growth and yield models are classified into different major groups. The models which require stand summary information like volume per hectare and stand average diameter are called 'Whole Stand Models' (Vanclay, 1994). The models that use basal area, number of trees and basal area in specified diameter class, site index etc are 'Size-class distribution models'. The above models which require sum of individual tree information (e.g., tree heights, diameters and crown lengths) to produce estimates of yield are called 'Individual Tree Models' (Gonzalez-Benecke et al., 2014). These models are further subdivided according to how the stand density is modeled. For instance, variable density whole stand models can assess the effects of yield on variation in stand density (e.g., crown cover, basal area). Of the individual tree models, only distance-dependent models maintain a spatial record of the point density around individual trees (Ek and Monserud, 1974; Botkin, 1993). Growth and yield models have also been categorized into empirical, process (mechanistic), or hybrid classes depending on the structure and description process of their simulation system. However, use of a model depends on proper selection and preparation of the input data and proper interpretation of the model output. Care must be taken to understand the implications and limitations of using various quantitative measures as surrogates for management objectives. The main uses of growth and yield predictions are:

- To estimate increment and update forest inventories.
- To compare silviculture treatments by simulating treatments and predicting outcomes.
- To facilitate stand and forest level decision making.
- To provide input for forest management planning including timber supply analysis, allowable annual cut determinations and policy making.
- To assess the impact of timber losses due to pests, diseases and fire.
- To allow extrapolations for missing or inadequate data.
- To explore and teach tree and stand dynamics.

3.2.1 Types of Volume Table

There are three types of volume table. When the growth data are collected from all growing location of the species and utilized to construct a volume table or equation, the resulting table is called ‘General Volume Table’. If growth data are collected from different growing locations of a region, the resultant volume table/equation is called ‘Regional Volume Table’. Growth data collected from different growing location locally and utilized in construction of volume table/equation resulting in a ‘Local Volume Table’. Different terms used in interpreting the growth and volume table are mean annual increment (MAI), current annual increment (CAI), circumference or girth and breast height (GBH), diameter (D), basal area (BA), volume (V) and stand yield. These growth variables are calculated as:

1. MAI (%) $= \dfrac{\text{Total volume}}{\text{age (years)}} \times 100$

2. CAI (%) = $\dfrac{\text{Current volume} - \text{Last volume}}{\text{Last volume}} \times 100$

3. GBH (cm) = $2\pi r$

4. Diameter ($2r$ or D) = Girth / π

5. BA (cm^2) = $\dfrac{\pi\,(\text{DBH})^2}{4}$

6. Basal areas (cm^2/ha) = $\dfrac{\pi\,(\text{DBH})^2}{4}$ * no. of stem per ha

7. Volume (m^3) = $\dfrac{\pi\,(\text{DBH})^2 \times \text{H}}{4}$

8. Stand Yield (m^3/ha) = $\dfrac{\pi\,(\text{DBH})^2 \times \text{H}}{4} \times$ no. of stem or tree per ha

3.2.2 Measurement of Tree for Volume

Though least, whenever available, the use of volume table can lead to 30% or more errors in volume estimates regardless of the sophistication of the sampling system used. There are different approaches by which volumes are determined. These are:

- Use of formulas in which stem is represented by a solid of revolution.
- Measuring displaced water by putting a piece of wood in fixed water volume.
- By integrating and generalizing formulas.
- Use of graphical methods.
- By height accumulation.

Normally, the volume of a sample tree in the forest is estimated and then it is extrapolated to obtain an estimate for all the trees in the entire stand rather than measuring volume of all the trees in a stand one by one. In this, the length of a felled tree is measured and stump height is added to get tree total height (H). For computation of total volume (V), stem and branch wood up to a minimum diameter of 5 cm is considered. The volume is then calculated by dividing the stem and branches into logs of about 3 m length (L), measuring the mid-diameters (D) and applying Huber's formula ($V = \pi D^2 L/4$) to estimate individual log volumes accurately. To estimate under bark volume, the bark thickness at each point is measured with a bark gauge on one side of stem/log, multiplied by 2 and then subtracted from the dbh (over bark) to arrive at the value of dbh inside the bark. Tree volumes are calculated by adding the volume of individual logs starting at the base to the top of the tree (i.e., cumulative values). Bruce's formula $V = (0.25B + 0.75S) \times L$, where V is volume, B is cross sectional area of the butt end, S is cross sectional area of small end of log and L is log length, performed better for all sizes of logs compared to other models as far as composite effect of accuracy and precision is concerned (Tewari and Singh, 2005).

3.2.3 Volume Equations and Yield Table

Volume equations play a crucial role in forest management and construction of these equations for tree species is an important step in this direction (Annexure I). Volume equations developed for *Eucalyptus camaldulensis*, *Dalbergia sissoo* and *Tecomella undulata* are based on data collected from IGNP area of Rajasthan (Tewari et al., 2001a & b; Tewari, 2007) and used either both height and DBH (double entry) or DBH alone (single entry). Because of difficulty in measuring height accurately in a closed stand (as treetops are hidden by the canopy layer), development of growth and yield models based on diameter is generally preferred as it is measured easily and more accurately (Ter-Mikaelian and Khozurkhin; 1997; Tewari and Kishan Kumar,1998; Wirth et al., 2004). Diameter is a convenient variable for predicting the growth of trees in the plantation as well as in forests. The volume table (Table 14.2) for *Eucalyptus camaldulensis* was prepared using following equation:

$$V=0.02397+2.31E\text{-}05D^2H$$

Table 14.2 Stemwood volume (m^3) table of *Eucalyptus camaldulensis* tree in IGNP area Rajasthan.

Diameter (cm)	Height (m)						
	5	10	15	20	25	30	35
5	0.02686	0.02975	0.03263	0.03552	0.03841	0.04130	0.04418
10	0.03552	0.04707	0.05862	0.70170	0.08172	0.09327	0.10482
15	0.04996	0.07595	0.10193	0.12792	0.15391	0.17990	0.20588
20	0.07017	0.11637	0.16257	0.20877	0.25497	0.30117	0.34737
25	0.09616	0.16835	0.24053	0.31272	0.38491	0.45710	0.52928
30	0.12792	0.23187	0.33582	0.43977	0.54372	0.64767	0.75162
35	0.16546	0.30695	0.44843	0.58992	0.73141	0.87290	1.01438
40	0.20877	0.39357	0.57837	0.76317	0.94797	1.13277	1.31757

Source: Tewari and Kishan Kumar (1998).

Being closely correlated with stem volume, diameter is an essential quantity for economic and silvicultural decision making. Volume yield of *D. sissoo* plantation ranged between 2.10 and 19.90 m^3/ha/year, though it depends upon age, density and site quality. At a spacing of 2m × 3m, the plantation of age 8 years produce an MAI value of 2.23 m^3 on poorer site and 16.04 m^3 on relatively better site (Tewari and Kishan Kumar, 2001). Volume yields of *E. camaldulensis* ranged from 1.82 to 24.82 m^3/ha/year across age, density and site quality, where a plantation at spacing of 2m × 3m produced an MAI of 4.76 m^3 on poorer site and 11.35 m^3 at better site at 7 years age. The volume of *Tecomella undulata* trees ranged from 0.00315 m^3 to 0.17935 m^3 per tree at the age 15 and 19 years, respectively (Tewari and Singh, 2009) following the volume equation:

$$V = 0.000066\ D^{2.100121}\ H^{0.553696}$$

$$R^2 = 0.924,\ RMSE = 0.00772$$

In case of difficulty in measuring height, volume of *T. undulata* can be calculated following the equation:

$$V = 0.000088\ D^{2.381398}$$

$$R^2 = 0.918,\ RMSE = 0.00803$$

The models widely used to estimate total stand volume (Husch et al., 2003; van Laar and Akça, 2007; Weiskittel et al., 2011) use independent variables like dominant height (H) and basal area (BA). To estimate total stand volume of teak for Karnataka State, the following equation has been found best which explains more than 97% of the total volume variability with a root mean square error of 13.34 m^3 ha^{-1} (Tewari et al., 2014).

$$V=0.4628H^{0.8063}\ BA^{1.1547}$$

Following equations estimated the total stand volume of teak for Gujarat state that ranged between 17.65 and 342.63 m^3 ha^{-1}at ages ranging from 14 to 43 years (Chawhaan and Singh, 2015).

$$V\ (ob) = -0.007532+0.0000386848106*D^2H$$

$$V\ (ub) = -0.014092+0.0000285536204*D^2H$$

Likewise, yield tables are prepared relating various growth parameters like basal area, top height, mean annual increment etc. with tree age (Table 14.3).

Table. 14.3 Provisional yield tables of *E. camaldulensis* for IGNP area, Rajasthan.

Age (years)	Stems/ha (No.)	Vol/ha (m^3)	BA/ha (cm^2)	Top ht (m)	Crop dia (cm)	Crop ht (m)	MAI (m^3)
4.0	1789	52.01	119515	13.61	9.22	10.96	13.003
5.5	1724	85.01	166090	15.61	10.07	12.01	15.456
6.5	1692	102.50	185035	16.52	11.80	12.82	15.769
6.5	1583	103.47	192374	16.06	12.44	12.05	15.918
7.5	2027	97.53	164811	18.84	10.17	12.16	13.004
8.0	1583	135.40	226620	17.53	13.50	13.31	16.925
8.5	1894	150.25	251614	18.41	13.00	12.67	17.676
8.5	1583	140.28	230503	17.75	13.61	13.57	16.504
9.0	2044	112.53	182236	17.80	10.65	12.95	12.503
9.0	2027	110.81	182157	19.16	10.69	12.51	12.312
9.5	2027	114.97	193503	19.35	10.02	12.91	12.102
9.5	1544	154.46	240493	18.60	14.08	14.36	16.259
10.0	2400	201.52	310755	20.02	12.84	13.85	20.152
10.0	1875	177.20	282685	19.09	13.85	13.41	17.72
10.5	2044	148.50	217411	20.59	11.62	14.08	14.143
10.5	2009	136.95	218448	20.04	11.76	13.60	13.043

Age (years)	Stems/ha (No.)	Vol/ha (m^3)	BA/ha (cm^2)	Top ht (m)	Crop dia (cm)	Crop ht (m)	MAI (m^3)
10.5	1875	185.36	290164	19.38	14.03	13.63	17.653
11.0	2374	214.14	317143	20.68	13.04	14.50	19.467
11.0	2000	149.70	228994	19.59	12.07	15.05	13.609
11.5	2349	223.81	326550	20.94	13.30	14.78	19.462
11.5	1836	209.97	312685	20.93	14.72	13.95	18.258
12.0	1884	164.00	227440	21.86	12.40	15.07	13.667
12.5	2223	243.30	337036	21.73	13.89	15.80	19.464
12.5	2000	182.09	255911	21.99	12.76	16.37	14.567
12.5	994	233.49	322533	21.61	20.31	15.69	18.679
13.0	1843	183.36	240045	22.99	12.87	16.05	14.105
14.0	1842	180.96	247776	22.54	13.08	16.98	12.926
14.0	957	261.09	341140	22.34	21.30	16.62	18.649
15.0	1842	184.63	249310	22.88	13.12	17.24	12.309
17.0	481	271.08	263951	26.06	26.42	23.40	15.946
18.0	481	320.21	302988	26.96	28.31	24.34	17.789
19.0	481	323.71	304821	27.00	28.40	24.51	17.037

Source: Tewari and Kishan Kumar (1998).

3.2.4 Tree Growth-Age Relations

Height growth is driven by annual sums of stand age following different functions including Chapman-Richards in case of *Azadirachta indica* (Tewari and Kishan Kumar, 2002). Soil available nutrients, moisture and density modulate climate influence and tree growth (Table 14.4). Such growths are species as well as site specific. For example, among *Eucalyptus camaldulensis, Dalbergia sissoo, Acacia nilotica, Zizyphus mauritiana*, *Tecomella undulata* and *Prosopis cineraria,* the first one attained maximum height and collar girth, whereas the last one attained the least growth (Upadhyaya, 1996). Average height and DBH growth of *Dalbergia sissoo* have been recorded as 1.68 m and 1.6 cm per year on a better site, whereas it varies from 76-100 cm and 0.8-1.0 cm, respectively on poorer sites at in IGNP plantations of 8 to 12 years of age (Tewari and Kishan Kumar, 1998). The respective growth parameter for *Eucalyptus camaldulensis* is 1.72 m and 1.8 cm per year on better sites, and 76-100 cm and 0.6-1.0 cm at poorer sites. In a study Anyomi et al. (2012) observed that aspen productivity is better explained with a model that assumes that specific populations have a different response function to climate and are adapted to their local climatic conditions. Height response with age have been modeled for eucalyptus and Weibull Model ($r = 0.9998$, $S = 0.0419$) is found best fitting that predicted eucalyptus plant heights as 3.35, 5.92, 9.39, 12.68, 15.07, 16.47, 17.12, 17.37, 17.45 and 17.47 m in December over a period of 10 years (Singh et al., 2010). This may be useful in estimating height of eucalyptus trees at different age in a bio-drainage belt.

Table 14.4 Tree age, density and growth variables of different tree species in north-western India.

Species	Age (yrs)	Density (trees ha^{-1})	Height (m)	DBH (cm)	Reference
E. hybrid	1 to 23	336 - 3562	5.84 – 27.6	3.51 - 30.57	Tewari and Singh (2007)
A. nilotica	4 to 23	208 - 3910	4.4 - 17.3	3.21-24.51	Tewari and Singh (2007)
T. undulata	14 to 21	450 - 2188	4.43 - 8.64	6.12 -12.32	Tewari and Singh (2009)
A. indica	4 to 28	380-3043	4.7-12.8	4.70-18.83	Tewari and Kishan Kumar (2002)
A. tortilis	18	627	4.6-12.4	11-30	Jain et al. (1996)
E. camaldulensis	3 to 31	454 - 3257	6.81 - 25.65	4.74 - 35.88	Tewari and Kishan Kumar (1998)
D. sissoo	7 to 33	342 - 2632	6.97 - 18.49	5.76 - 29.84	Tewari and Kishan Kumar (1998)
P. cineraria	21 to 24	436-1267	3.61 – 13.28	3.15 – 36.60	Kumar(2014)
A. excels	6 to 25	813.1370	4.60 – 16.12	4.61 – 40.10	Kumar (2014)
T. grandis	14 to 43	306 - 2496	7.27 - 24.28	9.18 - 34.32	Chawhaan and Singh (2015)

3.2.5 Height -diameter Growth Models

Though ratio of height: diameter on tree stability is rarely considered for broadleaves species, it is an important measure of stand stability in conifers, where a decrease in this ratio was observed with age and an increase with stand density. The height to diameter ratios of dominant trees is always lower than that of mean trees (Vospernik et al., 2010). The generalized diameter-height equations (Schnute, 1981; Ratkowsky, 1990; Temesgen and Gadow, 2004) differ with ordinary diameter-height equations (Wykoff et al., 1982; Yang et al., 1978) being including quadratic mean diameter, stand basal area or stem/ha as extra independent variable. In this way, the equation can be applied on the plantation available on different sites with varying stocking. On the basis of the allometric growth theory, Gadow and Hui (1993) has developed a generalized height regression for the stands of *Cunninghamia lanceolata* in southern China:

$$h_i = 1.3 + \alpha_1 \, H_0 \, \beta_1 \, d_i \, \alpha_2 \, H_0 \, \beta_2$$

Where, h_i = height of tree (m), d_i=breast height diameter over bark of tree (cm), H_0=dominant stand height (m), α_1, α_2, β_1, β_2 = parameters to be estimated and 1.3 is a constant used to avoid the prediction of a height less than 1.3 m when d_i is very small. The coefficient values for the generalized height model developed for *Tecomella undulata* plantation in IGNP area of Rajasthan are α_1= 0.41183, α_2= 0.57050, β_1= 0.43565 and β_2 = 0.06388 with R^2 and RMSE values of 0.92 and 0.33483, respectively (Tewari, 2008). However, there are reports suggesting to incorporate additional parameter (i.e., age, dominant height, dominant diameter, crown area and soil fertility etc) together with diameter as the ability of DBH in determining height has been observed to be not strong enough based on the model's goodness of fit and the model's ability for predictive purposes for *Gmelina areborea* (Ige et al., 2013) and *Populus tremula* (Misir, 2010).

3.2.6 Basal Area Growth Models

Invariant algebraic difference form of non-linear growth functions is applied in forestry while analyzing basal area growth. Schumacher (1939) propose an age dependent basal area model, whereas Souter (1986) present a modified version of Schumacher model. These models can be used to predict basal area growth as a function of stand variables such as initial basal area, age or dominant height and stem number ha^{-1} and are crucial for evaluating different silvicultural treatment options. Schumacher (1939) basal area model is:

$$\ln(\mathrm{BA}_2) = (\alpha + \ln \mathrm{BA}_1 - \alpha) * \left(\frac{\mathrm{A}_1}{\mathrm{A}_2}\right)$$

Souter's (1986) model which was based on Schumacker model is:

$$\ln(\mathrm{BA}_2) = \left(\frac{\mathrm{A}_1}{\mathrm{A}_2}\right) * \ln \mathrm{BA}_1 + \alpha * \left(1 - \frac{\mathrm{A}_1}{\mathrm{A}_2}\right) + \beta * \left(\ln \mathrm{N}_2 - \left(\frac{\mathrm{A}_1}{\mathrm{A}_2}\right) * \ln \mathrm{N}_1\right)$$

Where, BA_1 and BA_2 are basal areas at ages A_1 and A_2, N_1 and N_2 are number of stem per unit area at the above-mentioned ages and α and β are regression constants.

However, for estimating basal area in the stand at every stage, Schumacher and Souter's models are useful out of the 7 models tested for the climatic condition of Gujarat, where the performance of the models are found useful in evaluating basal area of *Azadirachta indica* (Table 14.5). If natural mortality or appreciable change in stem number ha^{-1} over a period of time is there, the equations can be considered more useful (Tewari and Gadow, 2005).The model proposed by Hui and Gadow (1993) perform best for predicting basal area development in *T. undulata* plantations in Rajasthan, India (Tewari, 2010).

Table 14.5 Estimated parameters and summary statistics obtained for basal area models.

Model	α	B	R^2	MSE
Schumacher	3.1680	-	0.956	0.36357
Souter	3.2987	-0.0185	0.956	0.38129

3.2.7 Potential Stand Density

Predicting the potential stand density in term of the surviving trees per ha is an important element of growth modeling. Populations of trees growing at higher densities are subject to density-dependent mortality called self-thinning (Westoby, 1984). The relationship between the quadratic mean diameter (Dg), dominant height (H) and number of stems per unit area (N) are related to each other with the equation of Goulding (1972):

$$Dg = \frac{1}{\alpha_0 \, H^{\alpha 1} \, N + \beta_o \, H^{\beta 1}}$$

Where α_0, α_1, β_0, β_1 are different parameters varied with types of species. For example, the estimated parameter for *Azadirachta indica*, *Acacia nilotica, Eucalyptus hybrid* and *E. camaldulensis* (Tewari, 2004; Tewari and Singh, 2007) vary widely as presented in Table 14.6. The equations proposed to predict future basal area and stem number are also related and coefficients have been obtained by modeling (Tewari, 2007).The quadratic mean diameter at maximum basal area can be calculated as:

$$D_{gG\ max} = \frac{1}{2\,\beta_o \, H^{\beta 1}}$$

Though the equation by Sterba (1987) represents the limiting line of maximum basal area, one can apply it to find out the number of stem ha^{-1} at maximum basal area:

$$N_{G\ max} = \frac{\beta_0}{\alpha_0} (2\,\beta_0)^{\frac{\alpha 1}{\beta 1} - 1} \; D_{gG\ max}$$

Table 14.6 Parameter estimates for different species growing under plantation in north-western India (Source: Tewari, 2004, 2007; Tewari and Singh, 2007).

Species	Coefficients			
	α_0	α_1	β_0	β_1
A. indica	8x10^{-6}	0.533	0.6524	-1.0948
A. nilotica	0.000016	0.395519	1.163729	-1.260270
E. hybrid	0.000013	0.216513	2.616281	-1.341080
E. camaldulensis	8 x 10^{-6}	0.3534	9.2688	-1.8550

3.3 Assessment of forest biomass

Forest biomass constitutes the largest terrestrial carbon sink and accounts for approximately 90% of all living terrestrial biomass (Zhao and Zhou, 2005; Tan et al., 2007) and has rightly been recognized for its role in carbon sequestration (UNFCC, 1992 in its Kyoto Protocol). The amount of carbon sequestered by a forest can be inferred from the biomass accumulation since approximately 50% of forest dry biomass is carbon (Cairns et al., 2003; de Gier, 2003). Considering the influence of natural succession, anthropogenic actions like deforestation, harvesting, plantation, silviculture, and natural disturbance by pests, fire in forests and corresponding climate change (Brown, 1997; IPCC, 2006; Schroeder et al., 1997), biomass assessment is important to understand the change in forest structure.

Estimation of biomass of forests is a usual practice to quantify fuel and wood stock and allocate harvestable amount (Dias et al., 2007). Conventionally the changes in living biomass are assessed by first estimating the change in the volume of stem wood and then converting this volume to whole tree biomass using biomass expansion factors (BEFs) like aboveground biomass (tons /ha) = wood volume × wood density × expansion factor (Brown and Lugo, 1992). This conversion is often non-trivial because the proportion of stem wood increases with tree size at the expense of branches, foliage, stump and roots. Hence, the use of biomass expansion factors may lead to biased estimates because BEFs vary with tree size (age, etc.) and tree populations change over time (Petersson et al., 2012). Alternatively, forest managers also prefer the so called "forest taxation" method – a method in which the basal area of each stand or each cohort within a stand is solely estimated by relascope-sampling (Hartig, 1804; Bitterlich, 1952; Kuusela 1966). Though this method is associated with comparably high uncertainties at stand scale (Kurth et al., 1994), it allows the forest owners and managers to get reliable estimates for small forestry units at low costs compared to the usual sample-based inventory approach and is applied in many European countries (Wutzler et al., 2011).

Majority of biomass assessments are done for above ground biomass (AGB) of tree as it generally accounts for the greatest fraction of total living biomass in a forest. AGB includes all living biomass above the soil, while below ground biomass includes all biomass of live roots excluding fine roots of less than 2 mm diameter (IPCC, 2006). Dry biomass is preferred for the purpose of carbon estimation that contains roughly 50% carbon (Brown, 1997; IPCC, 2003; Paladinić et al., 2009). It varies, however, marginally from 43 to 52% depending upon type of species and degradation stage in case of woody debris (Singh, 2014b). Thus, selection of appropriate biomass estimation method and use of reliable forest inventory data are two key factors (Zhao and Zhou, 2005). Though time consuming, a sufficient number of field measurements are a prerequisite for developing AGB estimation models and for evaluating the AGB estimation results. GIS-based methods require ancillary data on land-cover, site quality and forest age to establish an indirect relationship for biomass estimation in an area (Lu, 2006; Vashum and Jaikumar, 2012).

3.3.1 Biomass Equations

Developing a biomass equation requires harvesting and measurement of sample trees for their biomass. While this method is accurate for a particular location, it is prohibitively time-consuming, expensive, destructive and impractical for region or country level analysis. In this different components of tree biomass are partitioning of the tree on the basis of end use and market requirement for different products and economic feasibility of tree species being assessed. These components can be categorised as:

- Branches of < 1 cm diameter (small branches, twig and leaf).
- Branches of 1 cm to <5 cm diameter (small branch for fuel wood).
- Branches of 5 cm to < 20 cm diameter (branch and stem for small timber and fuel wood).
- Braches or stem of 20 cm and above (timber use).

The most direct way to quantify the above ground and below ground biomasses in even aged or un-even aged trees is to harvest all trees in known area, dry them and weigh the biomass (Magnussen and Reed, 2004). Further, sub-sampling method of biomass assessment is designed to substitute the time consuming field measurement techniques or biased methods. But be sure about the accuracy by which the estimate of tree biomass by sub-sampling method has been done, appropriateness about models like polynomial, power and combined variable forms used for the estimation of above-ground biomass at a landscape scale (Deo, 2008). Likewise consideration should also be paid to the accuracy and problems in tree variables measurements, reliability in estimating carbon sequestration obtained from growth ring measurement and best related vegetation index or spectral bands to estimate above-ground biomass used.

In response to the growing interest in estimating carbon stocks in forests, available allometric equations have been compiled for sub-Saharan Africa (Henry et al., 2011), where tree, sprout and stand volume and biomass equations were reviewed and 850 equations and 125 related references were incorporated into an open-access database on the Carboafrica website (http://www.carboafrica.net). Tree diameter (dbh) and total height are mostly used in these models for a wide variety of species (Rai and Proctor, 1986; Brown et al., 1989; Tewari and Kishan Kumar, 1998; Chave et al., 2001; Ketterings et al., 2001; Lodhiyal and Lodhiyal, 2003; Jenkins et al., 2004; Zianis et al., 2005; Mani and Parthasarathy, 2007; Devi and Yadava, 2009; Singh et al., 2011) (Annexure 14.1). Tree diameter or basal areas are used to predict the below-ground biomass of many species (Navar, 2015; Singh, 2014b), though it is also calculated by use of above-ground biomass (Cairn et al., 1997). In case forests under study miss measurements of stand age or site index parameters root to shoot ratio approach for estimating below-ground biomass and productivity can also be taken into consideration or used as correction factor (Navar, 2015). However, biomass equations show a substantial variation in stand-level AGB estimates (Araujo et al., 1999; Baker et al., 2004; Chambers et al., 2001), because of high correlation between AGB and dbh or trunk diameter (Brown, 1997; Brown et al., 1989; Brown and Lugo, 1992; Clark et al., 2001; Cairns et al., 2003; Kale et al., 2004; Ketterings et al., 2001; Lodhiyal and Lodhiyal, 2003; Saldarriaga et al., 1988; Overman et al., 1994; Verwijst and Telenius, 1999; Singh, 2014b).

Using more variables in an equation requires measurement of sufficient number of trees to cover the full range of the variables used in the equation. Equations that use few possible variables are more useful and reduce number of trees to be felled. Further, incorporating more variables in the equation does not necessarily improve the accuracy of the estimate (De Gier, 1989; Schroeder et al., 1997; Wang, 2006). However, there are reports favouring incorporation of both tree height and density in the model to improve accuracy (Chaturvedi et al., 2012b; Feldpausch et al., 2012).

Various biomass equations have also been developed for tree species of Indian origin and can easily be applied for estimating biomass (Annexure 14.2). For example, Kumar et al. (2011) have quantified the biomass content and net primary productivity in different aged *Butea monosperma* in Butea forest ecosystems of Western India, Rajasthan. Similarly, tree biomass equations have been developed for a number of hardwood forest species viz. *Azadirachta indica*, *Prosopis juliflora*, *Prosopis velutina*, *Hardwickia binata, Colophospermum mopane, Calligonum polygonoides*, mixed tree species, mixed shrubs and mixed under shrubs species either at local level or across a region (Kishan Kumar and Tewari, 1999; Singh and Singh, 2011; 2015; McClaran et al., 2013; Singh, 2014b).

This indicates the existence of a large number of biomass models in literature (Jenkins et al., 2004; Henry et al., 2011); but it is really difficult to choose the appropriate model for a particular set of data. The good Practice Guidance (IPCC, 2003) and the guidelines for National Greenhouse Gas Inventories (IPCC, 2006) prefer the selection and use of species specific or similar species allometric equations in the priority order of local to national to global scale. Thus biomass estimates from local site specific equations are considered more accurate in forestry applications (Annexure 14.2). Belowground biomass can also be calculated by multiplying the above ground biomass (AGB) by 0.43, 0.51 and 0.47 factors as the root: shoot ratio of trees, shrubs and under shrubs, respectively for Rajasthan (Hangarge et al., 2012; Singh, 2014b).

$$RB = AGB \times 0.43 \text{ or } 0.51 \text{ or } 0.47$$

Where, RB is root dry biomass, AGB is above-ground biomass and the numerical are the root: shoot ratios for trees, shrubs and under shrubs, respectively. The total biomass is the sum of the above and below ground biomass (Sheikh et al., 2011).

3.1.2 Calculation of Carbon

In many applications, the carbon content of vegetation has been reported a simple fraction of the biomass, say C = 0.457 of dry biomass (FAO, 2007). However, carbon content in biomass varies from 45 to 50% of oven dry biomass (Schlesinger, 1991). Average carbon content across the species and plant parts of Rajasthan India, has been observed as 0.4477 of oven dry biomass. Carbon contents in litters and coarse woody debris on the forest floor/dead standing trees has been observed as 0.4245 and 0.4553 of the respective dry biomass. Thus carbon stock per unit area can easily be calculated by multiplying the dry biomass(s) of tree (or as applicable) with the carbon fraction (i.e., 0.4477 for tree, 0.4245 for litter and 0.4553 for woody debris) mentioned above.

4. CONCLUSION AND RECOMMENDATIONS

Growth shows elongation and thickening of roots, stems and branches increasing over a given period of time influencing productivity of natural communities. Atmospheric temperature, precipitation (water availability), light, oxygen and nutrient supply along with internal factors like genetic control etc., affect plant growth and yield. However, elevation, slope and soil water-holding capacity are also important in shaping the age–diameter relationships.

Two important atmospheric gases oxygen and carbon dioxide affect the physiology of plants by taking part in respiration and photosynthetic process, respectively influencing net primary productivity and carbon sequestration.

Any changes in soils and environmental variables have a bearing on community growth and production. These must be redirected favourably through effective resource conservation and management. Forest growth may also be favourably influenced by increasing CO_2, temperature and lengthening growing seasons at higher latitudes in future as a consequent of climate changes. However, such favourable situation will happen only when other factors (soil water, nutrients) improve accordingly.

Soil water is the most significant amongst many factors which run counter to the natural establishment, growth and development of plants and variations in it greatly influences physiological processes manifesting the structural traits of plants and alter the timings of many vital processes. Harvesting rainwater and its use in supplemental irrigation can improve plantation/forest growth and production. Fertilizer application further enhances the effects of increased water availability.

Though varying in space and time, plant growth variables like height, diameter, crown spread, basal area, wood density and biomass etc. are interrelated and can be assessed by correctly selected models.

Field measurements, remote sensing and GIS are different approaches applied for estimation of forest growing stock, but each one has its own limitations. Though more accurate, field measurements prove to be very costly and time consuming, emphasis should also be given to improve accuracy of other techniques in growing stock assessment.

Volume table, yield table, biomass and carbon stock are different ways of presentation of forest growing stock estimated by using variables either dbh alone or a combination of dbh, height and some other measures.

Many models have been developed that use diameter alone to predict tree volume or biomass and are useful at local or regional level, but to cover a larger area and its utilization in scientific purposes, inclusion of other variables like height, wood specific gravity, crown volume etc. will be beneficial as they improve the accuracy of the models.

Though selecting the regional or local models will be relatively better in terms of accuracy while accounting biomass or carbon budgeting, more works are still awaited for the woody species of arid and semi-arid regions in order to support a broad spectrum of users and a comprehensive reporting under national communication and sustainable management.

Annexure 14.1. Volume tables/equations of different tree species in dry areas of India.

Species	Volume table/equation	Reference	Remark
A. tortilis	TWob = -0.02179 + 0.00003451*D^2H + 0.0001990*DH TWub = -0.01808 + 0.00002876*D^2H + 0.0001385*DH TWob = -0.09415 + 0.0253594*D TWub = -0.09248 + 0.0230838*D	Jain et al. (1996)	Volume tables and equation based measurement of 40 felled trees. The diameter and height ranged from 11 - 30 cm and 6- 14 m, respectively.
E. camaldulensis	TWob = -0.00308 + 0.0000333*D^2H TWub = -0.00450 + 0.0000266*D^2H TMob = -0.11040 + 0.0000265*D^2H TMub = -0.09895 + 0.0000219*D^2H √(TWob) = -0.11887 + 0.031077*D √(TWub) = -0.11447 + 0.027996*D √(TMob) = -0.31565 + 0.031733*D √(TMub) = -0.30012 + 0.028997*D	Tewari et al. (2001a), Tewari and Kishan Kumar (1998)	Volume equation based on 91 trees from IGNP area, Rajasthan. DBH, height and age ranged from 5.0- 51.9 cm, 6.6- 26.6 m and 3.0- 28.5 years respectively
D. sissoo	TWob = -0.00260 + 0.0000365*D^2H TWub = -0.00298 + 0.0000280*D^2H TMob = -0.10150 + 0.0000347*D^2H TMub = -0.07859 + 0.0000270*D^2H √(TWob) = -0.09266 + 0.027732*D √(TWub) = -0.08607 + 0.024449*D TMob = -0.18743 + 0.000694*D^2 TMub = -0.14738 + 0.000543*D^2	Tewari et al. (2001b) Tewari and Kishan Kumar (1998)	Volume equation based on 71 felled trees from IGNP area, Rajasthan. Tree data were 8.2-19.8 m height, 5.8-35.9 cm DBH and 4.2-30.4 years age.
T. undulata	V = 0.000088 $D^{2.381398}$ V = 0.000066 $D^{2.100121}H^{0.553696}$	Tewari (2007), Tewari and Singh (2009)	Volume and site index equations based on data from IGNP area, Rajasthan. The felled trees were 5-9.0 m tall, 4.25-22.90 cm in DBH and 15-19 years age.
A. indica	TWob = 0.07033 - 0.013865*D + 0.00098532*D^2 TWub = 0.05973 - 0.011755*D +	Jain et al. (1998)	Volume equation based on data from semi-arid region of

Species	Volume table/equation	Reference	Remark
	$0.00079016*D^2$		Gujarat. DBH, height and age ranged from 4.71-21.37 cm, 4.66-12.75 m and 4 to 28 years, respectively.
E. hybrid	$Vob = 0.000076*D^{2.761477}$ $Vub = 0.000036*D^{2.919192}$ $Vob = 0.000014*D^{2.141947}H^{1.168588}$ $Vub = 0.000004*D^{2.143407}H^{1.509019}$	Tewari and Singh, (2006a, 2007)	Volume equation based on data from central Gujarat. DBH, height and age ranged from 4.7-33.1 cm, 6.6-27.6 m and 1 to 19 years, respectively.
A. nilotica	$Vob = 0.000071*D^{2.735778}$ $Vub = 0.000044*D^{2.810563}$ $Vob = 0.000018*D^{2.363677}H^{0.938962}$ $Vub = 0.000010*D^{2.421580}H^{0.989619}$	Tewari and Singh, (2006b, 2007)	Volume equation based on data from central Gujarat. DBH, height and age ranged from 4.5-31.9 cm, 4.4-17.3 m and 4-21 years, respectively.
P. cineraria	$Vob = 0.10497+0.00544D+ 0.00117 D^2+0.000183D^2H$ $Vub = 0.08839-0.00686D +0.0016 D^2+0.000249D^2H$ Merchantable $Vob = 0.02565-0.00393 D+0.000266D^2+0.000038D^2H$ Merchantable $Vub = 0.008831-0.00175D+0.000238D^2+0.00002D^2H$	Kumar (2014)	Volume equation based on data from IGNP plantation. DBH, height and age ranged from 3.2-36.6 cm, 4.4-15.5 m and 7-25 years, respectively.
A. excelsa	Log total $Vob = 3.71155+1.61865\log D+ 0.84136 D^2H$ Total $Vub = 0.03868+0.0069D+ 0.00014D^2+0.0000286D^2H$ Merchantable $Vob = 0.03452+ 0.006587D+0.00016D^2+0.000027D^2H$ Merchantable $Vub = 0.00159 + 0.000007D+0.000124D^2+0.00002D^2H$	Kumar (2014)	Volume equation based on data from IGNP area and Pali division. DBH, height and age ranged from 4.6-40.1 cm,4.6-16.3 m

Species	Volume table/equation	Reference	Remark
			and 7-18 years, respectively.
T. grandis	Volume over bark = $0.000159 * D^{2.419024}$ Volume under bark = $0.0001110 * D^{2.453857}$ Volume over bark = $0.00003009 * D^{2.027827} * H^{1.045771}$ Volume under bark = $0.000025511 * D^{2.0305862} * H^{1.012115147}$	Chawahaan and Singh (2015)	Total wood and timber wood volume equations based on data collected from Gujarat. DBH, height and age ranged from 7.3-30.8 cm, 8.2-22 m and 14-43 years, respectively. V is the teak volume (m^3/ tree, up to5 cm diameter over bark), D (cm) and H the total height (m).
A. ferruginea	$\sqrt{V} = -0.00142 + 2.61911 * D - 0.54703 * \sqrt{D}$	FSI(2003)	Western Plains regions of India
Anogeissus pendula	$V/D^2 = 0.00085/D^2 - 0.35165/D + 4.77386 – 0.90585 * D$		
Boswellia serrata	$\sqrt{V} = 0.11629 + 2.4254 * D$		
Butea monosperma (old)	$\sqrt{V} = - 0.24276 + 2.95525 * D$		
Capparis decidua	$V = 0.081467 – 1.06366 * D + 6.452918 * D^2$		
Lanneacoromandelica	$V = -0.00146 – 0.39953 * D + 5.33895 * D^2$		
Wrightia tinctoria	$V = 0.028917 – 7.777047 * D^2$		

Here V/ TW is the total wood volume over-bark (Vob/TWob) and under bark (Vub/TWub) in m^3, TMob merchantable wood volume is greater than 5 cm diameter of stem, D is the dbh in cm and H is the total tree height in meter.

Annexure 14.2. Biomass equations for predicting biomass of different tree species of dry areas.

Species	Biomass equation	Reference	Remark
Azadirachta indica	Total green wood biomass = $-20.689 + 0.047 * D^2 H$ Total green above biomass = $1.409 + 1.382 * D^2 - 1.219 * DH$ Total dry wood biomass = $8.690 + 0.036 * D^2 H + 0.036 * H^2$	Kishan Kumar and Tewari, (1999)	Biomass equations based on data from north Gujarat. DBH, height and age ranged from 4.71-21.37 cm, 4.66-12.75 m and 4-28 years, respectively.

Species	Biomass equation	Reference	Remark
	Total dry above biomass = 13.410 + 0.049*D^2H		
Prosopis juliflora	Above ground biomass ($\sqrt{W}$) = 0.004534+0.500151*D Root biomass W = 1.850979+0.08440*D^2 Total biomass W = 0.405377$D^{1.943568}$ Economic biomass (stem greater than 2 cm dia) W = 0.090651$D^{1.132956}$	Singh and Singh (2011c)	Biomass equations based on data collected from seven district of Rajasthan DBH and height ranged from 3.10-23.90 cm and 3.10-9.60 m, respectively.
Hardwickia binata	ln Total biomass = 1.002332 + 0.235342* D + 35.946* (ln(D) $^{-97.27}$) ln Above biomass = 2.211933+ 0.156459* D -6.345196* (ln(D) $^{-2.98442}$) log Below biomass = 0.088328 + 0.670075* (log D $^{3.10177}$)	Singh and Singh (2015)	Biomass equations based on 17 years old plantation at Jodhpur. DBH and height ranged from 4.45-17.5 cm and 3.25-9.10 m, respectively.
Colophospermum mopane	log Total biomass = 0.777145+ 0.782653* (log D $^{2.451}$) log Above biomass = 0.642967+ 0.820837* (log D $^{2.488}$) log Below biomass = 0.144146+ 0.703225* (log D $^{1.913}$)	Singh and Singh (2015)	Biomass equations based on 17 years old plantation at Jodhpur. DBH and height ranged from 2.9-17.5 cm and 3 - 6.2 m, respectively.
Calligonum polygonoides	Stem biomass = 1.02524 + 16.7264* (log D $^{6.289669}$) Above biomass = 1.220309 + 20.691679304* (log D $^{5.436036}$) Below biomass = 1.241631 + 10.219185* (log D $^{3.869759}$) Total biomass = 2.484028 + 30.373021* (log D$^{**4.756885452}$)	Singh (2014b)	Biomass equations based on data collected from 8 arid districts of Rajasthan. DBH and height ranged from 1.1-8.25 cm and 0.35 – 3.15 m, respectively.
Butea monosperma	Stem biomass (10 year age) = -0.2284 + 1.5442 D Stem biomass (15 year age) = -3.2148 + 2.3544D Branch biomass (10 year age) = - 1.8955 + 0.5983 D Branch biomass (15 year age) = -2.4985+ 0.7256D Root biomass (10 year age) = - 2.3561+ 0.3197 D Root biomass (15 year age) = - 2.0457+ 0.4021 D	Kumar et al. (2011)	Biomass equations based on data collected from Udaipur forests. Age ranged from 5-15 years.

Species	Biomass equation	Reference	Remark
Mixed tree species across Rajasthan state	Total biomass = 0.265851100 $D^{2.0499383}$ Above biomass = 0.181494261 $D^{2.058650773}$ Root biomass = 0.084773863 $D^{2.028825779}$	Singh (2014b)	Biomass equations based on 291 trees of 44 species across the Rajasthan. Dbh of trees ranged from 3.18 to 52.50 cm.
Mixed shrub species across Rajasthan state	Total biomass = 2.643968 - 1.674535 D + 0.3374487 D^2 Above biomass= 1.422873 - 0.909824 D + 0.199237 D^2 Root biomass = 1.221440 - 0.764804 D -0.138231 D^2	Singh (2014b)	Biomass equations based on 271 plants of 17 shrub species across the Rajasthan. Collar diameter of shrub ranged from 1.60 to 13.30 cm.
Mixed under shrub species across Rajasthan state	Total biomass = 0.133068859 $D^{1.864749130}$ Above biomass= 0.101733611 $D^{1.779509643}$ Root biomass = 0.031496821 $D^{2.078442433}$	Singh (2014b)	Biomass equations for mixed under shrub species across the Rajasthan. Collar diameter ranged from 0.90 to 6.20 cm.
Mixed species of tropical dry forests	Biomass (kg/tree) $=\exp^{\{-1.996+3.32*\ln(D)\}}$ Biomass (kg/tree) = 10^$^{\{-0.535+\log10(BA)\}}$	Brown (1997)	DBH ranges from 5-40 cm and 3-30 cm in respective equation
Mixed tropical Species	Root dry biomass = exp [-1.0587+0.8836*ln (Above ground dry biomass)]	Cairn et al. (1997)	Root biomass equation for species of pan tropical region
Paraserianthes falcataria	AGB(kg/tree) $=0.049*D^{2.591}$	Banaticla et al. (nil)	D ranged from 4.1-36 cm for 21 trees
Gmelina arborea	AGB(kg/tree) $=0.151*D^{2.217}$		D ranged from 8.0-31.4 cm for 7 trees
Swietenia macrophylla	AGB(kg/tree) $=0.022*D^{2.920}$		D ranged from 6.7-26.5 cm for 5 trees
L. leucocephala	AGB(kg/tree) $=0.206*D^{2.350}$		D ranged from 4-31.8 cm for 111 trees
Dipterocarpaceae	AGB(kg/tree) $=0.342*D^{2.073}$		D ranged from 7.3-34.0 for 7 trees
All species/site tropical region of Philpines	AGB(kg/tree) $=0.342*D^{2.073}$		D ranged from 4.0-36.1 for 141 trees.
Bamboo spp.	$LnABG=2.487 + 0.414* \ln\rho D^2H$	Chaturvedi et al. (2012b)	ρ is specific gravity (0.47 g cm^3), D is diameter of culm in cm at collar and H is height of the culm

Species	Biomass equation	Reference	Remark
Jatropha carcus Linn. (Planted)	Ln (SY) = -9.38977+ 26.31237/CW where SY=Seed yield (gm), CW=Crown width (m)	Tewari and Mishra (2009)	Collar diameter from 8.29-10.40 cm while height and crown width from 2.08-2.21m and 1.97 - 2.11m, respectively. Plant age 2-4 year.
Jatropha carcus Linn. (Wild)	Ln (SY) = -6.55226+1 9.09991/CW where SY=Seed yield (gm), CW=Crown width (m)	Tewari and Mishra (2009)	Crown diameter from 3.1-3.3 m, while height and collar girth ranged from 3.5-4 m and 2.8-3.0 m.

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PEOPLE PARTICIPATION AND FOREST MANAGEMENT

Protective role of most of the forest policies in India alienated the people from the forests for hundreds of years. This increased the hardships of vulnerable social groups because of denying them access to the forests and forest products. A sustainable forest management addresses forest degradation and deforestation while increasing direct benefits to people and the environment. Forest management has undergone many changes since last two centuries ranging from totally government control to community forest management and conventional methods of forest management to alternative silviculture to maximize community participation and improve people livelihood. The management practices of planting or natural regeneration through coppice or natural/seed sown, combined with weed control and stand improvement to control species composition, tree size and quality etc. are conventional methods of forest management. However, increased scientific awareness, incentive and better understanding about the impact of conventional forest management practices on biodiversity and habitat quality, soils, water and nutrient cycling, landscape visual quality, and natural capital and ecosystem services motivated the development of silvicultural approaches. Combined strategies of assisted natural regeneration and plantation development have been observed beneficial and cost effective especially in areas where mosaics of different degradation states and other land uses are found. Being a country problem forest protection and conservation must be undertaken with perfect coordination between forest department and other line departments, where people's participation is of vital importance and we must get them involved in this task. However, functioning of most of the forest management committees is critical towards reducing poverty and participations are limited to wage labours. This chapter highlights the people perception, participation and management of forest resources with a view to improve overall forest cover and ecological services they provide considering the future climatic changes.

1. INTRODUCTION

Over two million years of the evolution of mankind, forests had been seen as mysterious or even fearful places. The forests were considered impediment to people as they hindered agriculture, and harboured many dangerous wildlife. However, forests were useful to people by providing food, firewood and timber. The priorities of forest use differ, however, depending on per capita income and forest cover in the region. Exceptionally high rate of timber removals, grazing and shifting cultivation and conversion of natural forests into agriculture land including rubber, oil palm, cacao, or sugar cane plantations and other developmental activities have caused deforestation and forest degradation coupled with uninterrupted degradation of environmental quality. Extent of degradation and increasingly high demands of forest resources are now placing stress to manage this resource in benefits of mankind (Banerjee and Chowdhury, 2013; Davidar et al., 2010).

Forests are considered to have the ability to cope with extremes of environmental stresses like low rainfall (drought), low soil water availability, increased temperature, level of pollutants etc. Resilience of dry forests towards varying stresses depends on a variety of factors like severity and duration of the stress, vegetation type, the type and magnitude of injury, growth rates and competition between the species, and variations in environmental conditions (Galiano et al., 2010; Vicente-Serrano et al., 2012). The impacts of these stresses are usually in the form of decreased vegetation activity (Vicente-Serrano, 2007) and plant growth (Pasho et al., 2011). The plant mortality or long-term injury to these forests are relatively less because of strong resistance to water stress in plants of these communities as they show varying mechanisms to adapt water shortage and cope with the varying environmental conditions (Heumann et al., 2007; Chaves et al., 2003; Maherali et al., 2004). Mechanisms allowing plant species to respond to water availability vary among the different bioclimatic regions like arid, semi-arid, subhumid (dry and wet) and humid regions. While plants of arid region rapidly adapt to changing water availability, the plant response to drought in semiarid and sub-humid regions is at long time scale. In humid region the response to severe water stress is at short time-scales, though physiological mechanisms in this region is a poor adaptability to water shortage. Severe water stress may lead tree mortality and vegetation loss triggering desertification particularly in arid environments, where recurrent droughts may produce a progressive loss of resilience that affects negatively the ability of plant to recover to initial state. In such a scenario forests will be less capable of storing carbon than the climate models are predicting (Anderegg et al., 2015).

The carbon accumulation in biomass is higher when a tree is in its fast growing stage, but when tree reaches to its maturity (>80 years in boreal forests or >100 years for *Tectona grandis* or *Prosopis cineraria* in dry areas) it becomes almost carbon neutral and eventually become a carbon source if it dies and decays (Gower et al., 2001; Nabuurs et al., 2003). In such cases more appropriate strategies are to use biomass for construction materials and bioenergy production, to reduce carbon emission by replacing carbon-intensive materials and fossil fuels (Gustavsson et al., 1995; Schlamadinger et al., 1997). The burning of biomass grown in a managed forest is part of a cyclical flow with the assumption that carbon emitted during combustion will be absorbed by re-growth in a planted forest. Using wood products from a managed forest in place of non-wood construction materials can reduce net CO_2 emission, as less energy is required to manufacture wood materials as compared to the non-wood materials. Substitution of carbon-intensive materials keeps away from emission process during the manufacture of non-wood products, such as cement and steel. The use of wood products would also delay an emission of biogenic carbon by allowing wood to stay without decay for a longer time. The biomass by-products from the product-chains can also be used for bioenergy similar to wood from construction work at the end of its useful life (Gustavsson et al., 2006; Sathre et al., 2010).

Reduced growth rates and enhanced mortality in tree seedlings due to prolonged dry seasons and soil water stress generate problems in managing tropical dry forests. Management of dry forests for both timber and non-timber products are largely confined to their extraction. Coppice systems are important in the regeneration of dry forests but very little attention is paid to silviculture. Though reduced-impact logging operations are being increasingly applied in tropical forests, but post-harvest silvicultural treatments have not been integrated in their management. Moreover, management in any form is often complex in areas where dry forests have been fragmented and harvested for subsistence products, such as firewood, and are affected by the damaging effects of livestock grazing and wildfire (Fredericksen, 2011). Further, tropical forests are still being harvested unsustainably irrespective of whether protected areas are controlled by the communities, if not illegally, through logging, hunting, or collection of non-timber forest products. This is partly because of the reason that the legal frameworks are often non-conducive, inadequate, underfunded and most importantly poorly enforced. Though under staff may also be a reason but corruption is generally widespread at all levels in natural resource management (Kolstad and Soreide, 2009).

India has traditionally been characterized as a low forest cover-low deforestation country exposed to significant direct-human induced deforestation and degradation (Ravindranath et al., 2012). Considering the huge population depending on forest for subsistence livelihood, the strategies for controlling forest degradation are reducing the dependence by creating alternative livelihood opportunities for the forest dependent communities; providing alternative technologies to reduce the gap in demand and supply of forest products; and making the community adopt sustainable harvesting practices. This in general provides opportunities for the village community to utilize the traditional knowledge in sustainable forest management adopting community participation and/ or Joint Forest Management (JFM). While forestry promises a vast potential to achieve the indigenous rural development through the integrated management of natural resources, the participatory forestry promotes the economic, social and environmental growth, increases agricultural and silvicultural productivity, and enhances the prospects of people livelihoods (Pandey, 2007). By reforming CDM, REDD, NAMA or other new market mechanism for engaging donors in the development of baselines for climate mitigation programs linking carbon finance and alternative livelihood improvement activities with well defined criterion of equity may reduce pressure on forests, enhance forest cover and would benefit community through conservation of forest ecosystem (Gebara, 2013; Balooni and Lund, 2014; Purdon and Lokina, 2014).

2. DEGRADING FORESTS

2.1 Forest history of India

Historically India has been well-known for its forest wealth even during the time of invasion of Alexander the Great. Extensive tracts of this country were wooded till

18th century. The statements like "The forests covered nearly half the area of Northern India. In the Deccan as well as the coastal region, there were extensive forests" (Chopra et al., 1990), and "the tract east of Aravallis was, however, covered with forests even till late into the 18th century, as can be seen from James Todd's travel accounts of Rajasthan in the 19th century" (100^{th} years of Indian Forestry). It tells about the luxurious status of forests in India before the British. In the early days of the establishment of British rules, the accessible forests suffered a lot due to large scale felling of valuable timber trees. It is only when questions began to arise whether the timber requirements of the Navy and the Empire would continue to be available without disruption.

Importance of scientific forest management was realized for meeting the requirements of their industries both in India and in England. Large-scale survey of Indian forests was carried out and reserve forest areas were demarcated and Forest Act 1864 was enacted. Indian Forest Service was established under the Government Forest Act as an agency to initiate more systematic and efficient planning of forests management and first such reservation in the country was made in the Central Provinces in 1865 (Poffenberger and Singh, 1996). The Forest Act 1864 gave the colonial power to the authority to declare any land as forest land. The Act was strengthened further in 1878 with the classification of forests in to protected, reserved and village forests. The reserved forests were exclusively for use of the Forest Department (FD), and the surrounding villagers had no rights other than the ones explicitly permitted by the government (Gadgil and Guha, 1992). The protected forests were also managed by the Forest Department, but the people had certain rights in them, like gathering of fruits and other forest produce, and cutting wood allowed specifically for the household use (Khare et al., 2000). Villagers also had freedom to graze their livestock and hunt wild game for domestic purposes.

The national forest policy 1894 further restricted the rights of the forest dwellers by putting restrictions on the right for collection of fuel, fodder and other means of livelihood, whereas the Land Acquisition Act 1894 maintained that any land could be acquired by the government for use of public purpose with no or minimal compensation. The rights of forest dwellers were not acknowledged even in the 1927 Act, which continued to maintain that the forest dwellers had no right over the forests. Forest Policy of 1952 maintained the conservation and protection of forests with emphasis to control the exploitation of minor forest produce, whereas the Forest Conservation Act 1980 puts all forest land under the control of the central government and the old Acts from the colonial rule continued to play their part in the name of public good and development. To alleviate the increasingly emerging conflicts between multiple actors over the forest use rights, Government of India brought up the concept of participatory forest management through its National Forest Policy 1988 (GoI, 1988). The Joint Forest Management (JFM) guidelines defined the involvement of the local communities in forest management outside protected areas (GoI, 1990), specifying the sharing between local user groups and governmental agencies about the responsibilities, benefits, control, and decision making over the forests under management (Berkes, 2008; Bhattacharya et al., 2010). However, the power given to the communities involved in JFM is limited, participation inadequate, the common property rights ill defined, and the FD retains substantial control (Behera and Engel, 2006; Bhattacharya et al., 2010). The Scheduled Tribes and Other Traditional Forest Dwellers (Recognition of Forest Rights) Act established in 2006 (GoI, 2007) asserts traditional rights over forest resources and forest lands to the tribal populations and other traditional forest dwellers and gives substantial power to the local government, called "gram sabha" or village panchayat/assembly (Sathyapalan, 2010). The Act bestows traditional community rights to ownership and access to collect and use minor forest produce, products of water bodies, and rights to grazing. Besides, it also gives rights over disputed land, recognizes ownership of land by forest dwellers, and among others, grants right of settlement.

With start of 20th century, the areas under reserved and protected forests were 20 million ha and 2.4 m ha, respectively (Stebbing, 1926), which increased to 31 million ha and 10 m ha in 1947. Since then the net area under the control of Forest Department has increased to 43 million ha and 22 million ha in respective category with additional 13 million ha as unclassed forest (FSI, 2013). The processes responsible for the increase in forest area during 1950 to 1980 were the abolition of the princely states and landlordism and acquiring private forests. In the first category all uncultivated lands under the control of landlords became vested to state government, and most of the areas were transferred to the Forest Department in the form of protected forests, whereas the rest area was vested in the village panchayats under supervision of the Revenue Department. In second category private forests were acquired by the state governments in the two decades following Independence. In view of expected forests nationalization a massive felling of trees took place during 1950's and 60's that led to exceptionally high degradation in forest cover. Indeed the policies influenced forest management and conservation. Another example is decline in Tibetan forests, which occupied about 25.2 million hectares area in 1959, but it declined to 13.57 million hectares in 1985 alone in name of development under Chinese occupation (http://www.friendsoftibet.org/main/ eco.html).

2.2 Forest history of Rajasthan

The history of rangeland management in Rajasthan goes back to Mahabharata period, when cattle raring were there in 'Braj' and 'Viratnagar' to ensure milk supply to the then King's families. Demarcation of lands for each village was carried out after Indian Forest Act, 1927. Tree felling supposed to be less before 1934 and people could still extract dry wood and small timber for domestic needs in Rajasthan. World War II resulted in enhanced timber felling. The demarcation and settlement of reserved forests was completed by 1940 but a majority of protected forests could not be set out until the princely states merged into Rajasthan. By this time most of the state forests has been felled leaving scars of forests in name of scrub lands. Under the Rajasthan Biswedari Abolition Act of 1959 large areas came under the control of the government were transferred to FD. However, before the Act came into force, most Jagirdars had sold their forests and the areas were clear-felled. The Rajasthan Forest Act was enacted in 1953, under which the forest areas were demarcated and settled and regulations made for their management. The forests which could not be classified like the Jagirdari forests were put under unclassed forests and since been classified as protected forests. Likewise, management and control of the community pastures was transferred to panchayats, but ownership lay with government. With passing time and increasing grazing pressures the forests and pasture lands were degraded, whereas panchayats were unable to establish effective systems of grazing management.

Rajasthan has a long history of community forest management also that is in the form of traditional practices like Kakad Bani (community forests between two villages), Oran (sacred patch of forests) or Dev Van (God's groves), Kesar Chhanta (Saffron Sprinkling), Radi (minor forests maintain by state for the use of the villagers), etc. The legendary devotion of Vishnoi and other communities towards flora and fauna are well documented. The Aravalli Sacred Grove Conservation Programme was also launched by the Udaipur Forest Division in 1992 involving the protection of groves, planting of indigenous species, soil and water conservation, and participatory approaches to restoration of these sacred groves. Government of Rajasthan issued the first JFM resolution on 15th March 1991 and became one of the pioneer states to initiate JFM. It was legally formalized with the JFM resolution by formation of village level Forest Protection Committees. Since then many JFM resolutions have been issued facilitating increased community participation and forest management.

2.3 Forest vs. People

Most of the Indian forest policies alienated the people from the forests during pre-independence that exacerbated the rates of deforestation. Post-independence forest policies contributed to an expansion in agricultural production strictly to met the raw materials demand of industries and tightened control of forest lands through restricted access to forests and forest products. Such protective role of forest policies increased the hardships of vulnerable social groups by denying them access to forests. Conversely, several years after abolition of landlordism and transfer of forest land gave an impression among the people that planted trees on private lands would belong to Government including the land on which such plantation has taken place. All these factors led forest degradation as indicated by National Forest commission report 2006 that about 41% of Indian forests have been degraded or understock and about 70% forests have no natural regeneration and 55% forests are prone to fire (Aggarwal et al., 2009; Bahuguna et al., 2004; MoEF, 2006). However, since last four decades forest cover in India has almost stabilized with 40.23 million hectare area under dense forest (i.e., canopy cover >40%) and 29.57 million hectare under open forests (10-40% canopy cover). In addition, 4.14 million hectare land is under scrub land with canopy cover <10% (FSI, 2013). However, subtracting plantations as tree plantations have expanded in India at an estimated rate of roughly 15,400 sq km per year (since the early 1990s), from total forest cover, it shows that native forests in India have declined by 1.5%–2.7% per year (Puyravaud et al., 2010). It is also indicated by current rate of gross deforestation (for 2009–11) at -0.43% due to ongoing human-induced land-use changes for various economic purposes as compared with the global average of –0.6% (Reddy et al., 2013).

Unregulated and unsustainable use of forest produce coupled with high rates of deforestation in the past (for example, millions of *Cedrus deodara* sleepers were extracted from the Yamuna Valley forests in the Himalayan region railway, after exhausting of *Tectona grandis* and *Shorea obusta* forests in peninsular India during 1869 to 1885, http://enviroscope.iges.or.jp/modules/envirolib/upload/1508/attach/1ws-9-pankaji.pdf) were because of erosion of customary resource management regimes and the materialist approaches of the states. Failure to recognize community control of forests led to a collapse in institutional norms that were instrumental in protecting and managing the forest resources for local uses. A shift in property rights from local to the state gradually weakened the rights of tribal people to use and extract forest resources (Chopra and Sharma, 2008), while managing forests as communal property was crucial in the economic subsistence of individuals, families and community and was the basis for managing forests as communal resources.

Research findings indicate that decision makers tend to favour the *status quo* over other alternatives (Samuelson and Zeckhauser, 1988), particularly in the cases where payoffs are not certain (Kahneman and Tversky, 1979). Besides, diversion for forestland for industrial and developmental activities, shifting cultivation, over grazing, encroachments and forest fires have also led to a decline in the ecological conditions, functions and values of forest ecosystems, whereas unsustainable biomass removal and illegal logging practices are resulting in increasing forest degradation. While forest management looking for to maintain current forest conditions by favourable decision making process so that the resultant forests could adapt to the changing climatic conditions, sustainable forest management require a firm willingness to experiment, learn, and adapt management strategies to the changing conditions (Blate et al., 2009; Millar et al., 2007; Seastadt et al., 2008).

3. PEOPLE'S PARTICIPATION

3.1 Forest management regimes

Forests are a type of common pool resource, where it is difficult to physically exclude potential users from them. Under competitive consumption of forest resource lead to an increased consumption by some those results in less availability for the others (Ostrom et al., 1994). It means managing forests effectively is not only difficult but they can degrade easily also when in excessive use. Increasing greater attention is being given to systems of 'shared management', involving both the forest department and local communities. Although extent of powers transferred, local enforcement, forest types and sizes, and coverage of decentralized management varied among the countries (Balooni and Inoue, 2007; Agrawal et al., 2008), but there is substantial evidences that forests under decentralized management are undeniably conserved, across the continents, countries, and forest types and sizes (Nagendra, 2007; Somanathan et al., 2009; Bowler et al., 2012). Under collective management, the community-based forest management organizations belong to (i) ones that have emerged out of local initiatives, primarily as a response to the hardships arising from scarcity of forest products; (ii) second type is those promoted by the state FDs and can be very much categorized as Joint Forest Management (JFM); and (iii) the third type is community bodies that were originally sponsored by local government or NGO programmes to carry out a more general rural development mandate, and which became involved in forest management as one of their activities (Sarin, 1996).

3.1.1 Direct State Management

This is the conventional form of forest management in India and is still in practice. Most reserved forests and virtually all forest wildlife sanctuaries are still (at least nominally) managed in this way.

3.1.2 Community Forest Management

Community forest management can be described as a system where a community has developed institutions, norms, rules, fines and fees to sustain forest resources and appears to be more community centric approach. It is also now promoted as a means by which payment for ecosystem services schemes can be implemented (Rasolofoson et al., 2015). This system characteristically involve one or more communities (social group, village) protecting and using a specific forest area (IUCN, 1996). Community based forest management is not legally recognized in India, i.e. it has no legal basis. It spread widely in India during the 1970s and 1980s because growing scarcity of forest products primarily due to the activities of the contractors, and growing population pressures on the resource also. Most prevalent regions connected with community forest management are Orissa (more than half of the cases), south Rajasthan, parts of Gujarat and parts of Andhra Pradesh (Negi, 2000; Conroy et al., 2002; Nayak and Berkes, 2008).

3.1.3 Joint Forest Management

The widespread process of deforestation and degradation of forests in recent decades ultimately led the government to recognize that forests could only be protected and managed effectively if local communities are involved in the process. Decreasing forest cover, lack of interest of the State in depleted forests, reduced revenue from the forests, weakening of forest department by both financially and administratively, and increasing instances of community protection and control of forests lead towards community involvement in forest conservation and management (Nayak, 2002). After Indian Forest Policy 1988 establishment of joint forest management (JFM) - a form of co-management between the state and communities, took place. Guidelines for strengthening JFM were issued through a GoI circular in 2000 and 22 states passed the resolutions accordingly. JFM can be safely defined as "sharing of products, responsibilities, control, and decision making authority over forest lands, between forest departments and local user groups, based on a formal agreement". The primary purpose of JFM is to give users a stake in the forest benefits and a role in planning and management for the sustainable improvement of forests. A second goal is to support an equitable distribution of forest products (Hill and Shields, 1998). Key characteristics of JFM are:

- JFM encourages the development of partnerships between local people and Forest Departments to manage forest lands jointly.
- It provides state-approved access for the local communities to the nearby forest areas.
- It encourages local people to protect forest lands, prevent them from free grazing and to assist in preventing illegal activities by the outsiders.
- It assures local people sharing of a certain proportion of the intermediate and final harvests from the forest lands protected by them.

JFM has received a lot of attention since last two and half decades from both researchers and development practitioners, and has become the principal alternative to direct state management. About 14.52 million families (50% of this are SC and ST families) in 1.18 lakh Joint Forest Management Committees (JFMCs) are managing about 22.94 million ha forest area, i.e. about 25% of total forest area in all states of India (Table 15.1). Though there was an overall increase in the number of JFMCs in 2010, the area covered under forests has decreased as compared to that in 2006.

Table 15.1 Number of JFM committees and forest area under JFM in different states of India.

States	JFM Committees	Area under JFM (ha)	Number of families involved			
			GN	SC	ST	Total
A & N Islands	4	262	360	-	-	360
Andhra Pradesh	7,718	15,19,000	4,92,000	3,95,000	5,51,000	14,38,000
Arunachal Pradesh	1,013	1,00,377	-	-	33,048	33,048
Assam	1,184	52,499	1,48,074	27,392	1,19,368	2,94,834
Bihar	682	4,62,333	91,606	80,586	39,482	2,11,674
Chhattisgarh	7,887	33,19,000	3,13,000	1,90,000	6,14,000	11,17,000
Goa	26	10,000	-	-	336	336
Gujarat	3,067	4,14,151	1,47,302	29,068	2,40,662	4,17,032
Haryana	2,487	41,188	53,026	13,010	-	66,036
Himachal Pradesh	1,023	2,05,056	1,90,000	65,000	8,024	2,63,024
Jammu & Kashmir	4,173	38,736	2,36,388	64,469	1,28,939	4,29,796
Jharkhand	9,926	17,21,700	2,36,388	64,469	1,28,939	4,29,796
Karnataka	3,848	8,08,020	1,85,290	55,480	32,035	2,72,805
Kerala	576	2,07,404	47,407	9,708	21,386	78,501
Madhya Pradesh	15,228	66,87,390	6,45,000	2,55,000	8,00,000	17,00,000
Maharashtra	12,665	24,03,344	18,20,640	3,58,097	5,29,860	27,08,597
Manipur	665	1,66,767	7,884	132	16,086	24,102
Meghalaya	285	17,245	-	-	39,210	39,210
Mizoram	613	55,990	-	57	80,628	80,685
Nagaland	951	42,929	-	-	1,59,587	1,59,587
Orissa	12,494	11,48,676	7,26,102	2,71,139	6,45,741	16,42,982
Punjab	1,224	1,78,333	70,696	21,140	14	91,850
Rajasthan	5,316	8,58,614	2,38,015	73,802	2,59,234	5,71,051
Sikkim	219	88,518	29,000	-	17,000	46,000
Tamil Nadu	3,487	7,56,446	3,54,002	98,298	29,969	4,82,269
Tripura	920	2,41,138	19,561	14,643	45,241	79,445
Uttar Pradesh	3,426	1,83,393	4,50,251	2,41,689	14,110	7,06,050
Uttarakhand	12,738	5,64,221	5,01,000	1,10,000	18,000	6,29,000
West Bengal	4,368	6,46,084	2,25,309	1,59,425	1,20,415	5,05,149
Total	**1,18,213**	**2,29,38,814**	**72,28,301**	**25,97,604**	**46,92,314**	**1,45,18,219**

Source: National Workshop on JFM, Dehradun, 27-28 June 2011. Proceedings. Dehradun, Forest Research Institute.

There has been downward correction in number of JFMCs and forest area covered in the states of Andhra Pradesh, Himachal Pradesh, Mizoram and Punjab because many of the registered JFMCs appears to be non-functional. In Jammu & Kashmir, JFMCs of Integrated Watershed Development and Eco-restoration of Degraded Catchment have become non-functional because of closure of such projects, though some addition in JFMCs and in forest area took place in some other programmes like Social Forestry program. Nevertheless JFM approach is now graduated to JFM+ by involving livelihood issues in addition to protection, conservation, and management. This is in accordance to 12th Financial Year (FY) Plan Steering Committee "JFM also needs to be evolved into a higher platform "JFM Plus" where the livelihood promotion of the communities, especially women Self Help Groups (SHGs) formed for such activities, gets increased importance in the conservation and development of forests" and the last 20 years experiences through many forestry projects, JFM approach is now graduated to JFM+ by involving livelihood issues in addition to protection, conservation, and management. However, to achieve this, JFMCs are required to be adequately and strategically revitalized and empowered. In Rajasthan, there are 5316 JFM committees managing about 0.86 million hectare area, i.e. 26.3% of the total forest area in Rajasthan. Some studies indicated an increase in species diversity, stem density and species richness in plantations and natural forests protected and managed by JFM. But there is potential to cover more villages to enhance forest cover, productivity and people livelihood (Aggarwal et al., 2006; Arya and Yadav, 2014).

3.2 How community is engaged

Devolution of management of natural resources has widely been recognized as the most viable option for ecological and economic sustainability of the natural resources and enforced through the Rio Declaration of 1992 (Conroy et al., 2002). This has resulted in participatory management approach attracting a great deal of attention because of systematic failure of central governments to reverse the loss of forests (Odera, 2004). People's participation aims for basic forest products, socio-economic development, and overall improvement of forest resources and has been at the centre of the resource conservation and rural development efforts in the developing countries (Yogesh, 2011). Though there is widespread dissatisfaction and limited level of people participation at different levels of forest management in terms of either labour or finances or both, but favourable perception of the community forestry programmes have also been observed when owned and managed by the community itself (Kobbail, 2012). The level of participation varies from a nominal membership to a dynamic process in which the deprived have voice and influence in decision-making processes of forest management (Narayan, 1996). A total or near homogeneous caste composition of the villages ensures greater success owing to an almost similar socio-economic status as larger the group of people of different caste and origin make the programme implementation difficult. Joint Forest Management (JFM) plantation has been observed successful where major proportion of villagers or JFM Committees are solely or partly dependent on nearby common forest for their daily requirement of fuel wood and fodder (Kumar, 2006). People participation may be direct or indirect. The direct participation includes the involvement of people or stakeholders in activities like attending meetings related to forest protection, taking active part in meetings, contributing labour towards forest management, monitoring, patrolling, etc. The indirect participation talks about individuals' agreement to forest protection rules, motivating others as well as own family members for forest protection, and providing moral support to community for ensuring equity, justice, and transparency in the process of forest management (Sarin, 1996; Singh et al., 1996). It may differ while participating in a project, where participation can mean informing people about a project either through consulting them, or by delegating managerial power (Nuitjen, 1992). While the former type emphasizes on sharing of responsibilities and accountabilities jointly by project planners and the members of the community, the latter talks about total community ownership. However, individual's decision to cooperate with the community vis-à-vis project planners depends on the level of personal acceptance and conviction about the forestry project, favourable evaluation of institutional rules, and accrued benefits arise out of management (Ostrom, 1990; Sarin, 1996).

Four approaches are generally followed to involve community and are relevant to managing forest jointly by FDs and the communities. All of these approaches are found within FDs in India. The four categories includes participatory, incremental, manipulative and anti-participatory (Table 15.2).

Table 15.2 Approaches of state agencies and officials to community participation.

Approach	Characteristics
Participatory	Agencies are fully supportive of community involvement, whereas institutional reform facilitates such a process.
Incremental	Some level of official support is combined with policy and administrative ineffectiveness, leading to an ambivalent approach to implementation.
Manipulative	State supports community participation for its own ulterior motives, usually for extending social and political control over autonomous movements, or for lowering the costs of implementing development projects.
Anti-participatory	State agencies are uninterested in community involvement

Though earlier tendencies of ridden with hostility, suspicion and antagonism are now changing and the FD staff are now accepting the rights of the local communities (Chaturvedi and Godbole, 2005), there is still disinclination in giving up some of their power to the communities; and/or lake of trust on these people (Box 15.1). However, exclusive power of FD's to dissolve an Executive Committee is indication of unequal partnership in such associated work. Although it is obliged to reconstitute the committee, it can delay doing so for as long as it likes. In contrast the community has no rights or powers to take action if it thinks that the FDs are not performing its responsibilities as agreed upon. Most of the studies indicate that people participation tends to be elicited only within a pre-determined framework as the agenda itself is not open for discussion for many of a time (Kumar and Puri, 2004; Gritten et al., 2013). Likewise benefit-sharing arrangements are generally specified in advance, without asking villagers whether they want to harvest their timber or and how they would like the proceeds for benefit distribution process. However, reduced differences among the members of an institution in terms of status, access to benefit, and opportunity to share the personal knowledge and experiences in decision-making process play an important role for effective participation (Pham et al., 2013; Park and Lee, 2016).

Box 15.1: Transfer of Powers but not Accountability

Transfer of power from the forest department to the community without an accompanying transfer of accountability make the JFM implementation imbalance. The ‘pro-people’ approach results in dilution of the policing powers of the FLS and the JFMCs are empowered for protection. To protect the forests, committees are provided with ‘protection funds’, which are utilized for protection, payment of wages etc. For this field guard only is held responsible for forest offences and faces the probability of deductions from his salary to compensate for the losses because of these offences. Though such deductions of salary are rarely effected, the Forest Guard instills fear among the FLS increasing the reluctance for a transfer of power to the committees.

Source: Chaturvedi and Godbole (2005)

Individual participation in a collective action is a product of finding themselves within the institution, psychological attachment with institutional honor and respect, and identification as institutional citizen (Haslam et al., 2000; Tyler, 1999). Members of an institution develop group based pride and respect if institutional governance supports the local priorities and self-governance. These feelings promotes the institutional citizenship behaviour like: (i) greater loyalty to the organization; (ii) enhanced compliance with institutional rules; and (iii) an increased incidence of extra-role like supporting the institutional work by motivating others, putting extra labour etc. (Tyler, 1999; Park and Lee, 2016). The above process can be reinforced through the assurance of realization of social and economic needs both at collective and individual level. This happen in general in a homogeneous community or group, and therefore chances towards social identity will be more as compared to self identity (Sinha, 2014). Thus favourable characteristics of forest institution, social and economic homogeneity, freedom of rule making, better access rights, people's friendly management, graduated sanction, sincere patrolling, resolving the conflicts in more democratic manner etc. All these cause higher motivation among members of indigenous communities and thereby record higher degree of social identity, ownership, and organizational citizenship, and people's involvement in all round activities of forest management as reflected by increased forest regeneration and biomass (Murali et al., 2002; Singh and Sharma, 2010), reduction in deforestation and stress migration (Sahu and Rath, 2010; Rasolofoson et al., 2015), improved labour health (Sahu and Rath, 2010) and biodiversity (Aggarwal et al., 2006; Islam et al., 2013). However, in many of the cases JFM committees fail to elicit the same degree of people's involvement, where involvement in meetings and monitoring and plantation related activities appears to be casual unless there is any scope of wages in JFM (Box 15.2).

Box 15.2: National Afforestation Programme (NAP)

It was implemented by district level forest development agencies (FDAs) by institutionalizing participatory principles in forest management practices. By spending Rs. 15.74 billion up to 31st March 2008, it was operational in 782 FDAs covering over a million hectare forestlands. Observation after evaluating over 600 village level JFMCs out of 5,935 committees indicates that this program has:

- Mobilized 28181 villages and protected about ten million ha forest lands from threats of illicit grazing and forest fires.
- Most of the FDAs have not evolved any strategy/mechanism to manage forests outside the funding support.
- Plantation and other activities generated 90100 to 443600 man days/ year/ FDA, where plant survival under afforestation/reforestation ranged from 68 to 82%.
- Adhocism in the training so conducted.
- Lack of communities views in micro-planning and collective ownership and management of forest resources.
- People participation to the level of wage earners.
- Limited involvement of women and people from disadvantageous groups.
- Dominance of local elite groups in heterogeneous communities.
- Lack of percolation of concept of benefit sharing from forest resources to the forest committees.
- No viable resource management unit because of dependency on local forest departments for making resource available and guiding their activities.

3.2.2 Participation Index

Participation of all stakeholders is the prerequisite for the success of a programme of natural resources (Raju et al., 2011). Extent of participation can be assessed in the form of participation Index as provided below in an individual watershed activity (Badal et al., 2006) for example:

$$PI_i = \frac{\sum_{J=1}^{N} Yij}{N} \times 100$$

Where, PI_i is participation index for the ith farmer; Yj = 1, if the farmer has participated in the jth activity; = 0, if the farmer has not participated in the jth activity; and N = Total number of activities taken up in the watershed development/ forest management programme. Participation index varies depending upon the extent of participation or cooperation of community or individuals in the programme. Azeez et al. (2013) have observed that out of the fifteen indices community participation in forest management (ranging from awareness to contribution of human resource to maintenance of the project) studied using the ratio scale model, awareness about forest project appears the most important index of participation with mean People Participating Index (PPI) of 85. However, level of participation improves when requirements of the community like water, acceptance of indigenous and traditional practices, increased productivity, inspirational leadership, capacity building, off-farm employment opportunity etc. are fulfilled (Badal et al., 2006; Raju et al., 2011)

3.2.3 Enhancing People Participation

Participatory forest management means "attempts to secure and improve the livelihoods of local people dependent on forest resources by involving all the stakeholders in the process of forest management, understanding their needs and situations, allowing them to influence decisions and receive benefits, and increasing transparency" (DFID, 1996; ITTO, 2002). A participatory approach to forest resources management allow forest-dependent communities to be involved in planning, protection and management of forest resources and benefit-sharing derived. In addition to expanding responsibilities by promoting greater equity, interests of women, more democratic processes, and resolving community conflicts, the participatory approaches summarized below for natural resources management may be more effective in enhancing people participation:

3.2.3.1 Freedom of choice: Bringing people into the management process recognizes their intrinsic worth, appreciates their vital role, and respects their citizenship credentials. This approach also incorporates the role of local property rights and gives freedom of choice in every decision-making process. Diffusion of democratic rights and values is an essential prerequisite for effective participation in management of forests (McNeely, 1995; Narayan, 1996; Barton et al., 1997; Molinas, 1998).

3.2.3.2 Management of legitimacy: Effective and efficient management requires the understanding and the support of local people. Rigid management structures do not easily adjust to social, economic or ecological changes. They may also destroy any chance of long-term co-operation on economic activities (Article 8 of the CBD) (McNeely, 1995; Borrini-Feyerabend, 1996).

3.2.3.3 Preserving local rights: Scientific studies indicate that wherever people are able to establish their local rights over resources, the resources have been better managed (Raju, 1998; Sarin, 1996). Indigenous community forest management groups offer higher scope to their members to ensure social, economic, and cultural rights over resources, thereby bring forth more participation as observed at many places in the form of social fencing.

3.2.3.4 Sharing individual knowledge: Because knowledge and understanding are socially constructed, the knowledge and believes of each member is a function of unique contexts and experiences. It is essential to seek multiple perspectives on any 'problem assessment' by ensuring the wide involvement of different stakeholders and groups (Pretty and Pimbert, 1995). For example, knowledge about species preservation and selection under plantation activities, care of plantation, grazing rotation and rotation of timbers are sacred among the forest dwellers. While FD accommodate mostly commercial timber species, local people lists many non-commercial species, which not only meet the diversified local requirements but also save forest strands from disease pests (i.e., *Azadirachta indica*, *Vitex negundo* etc.). Likewise indigenously evolved technologies should be given preference rather than the technology guided by its commercial values.

3.2.3.5 Federation: Creation of clusters and federations of like-minded institutions or forest management committees also helps in resolving wider conflict, increases collective bargaining capacity, and improves the liaison with external agencies, as observed in Jhadol Block of Udaipur district of Rajasthan (Kashwan, 2003).

4. FOREST MANAGEMENT

Forest management includes silviculture, protection and forest regulation in addition to administrative, economic and social aspects. Other facets of forest management are management for aesthetics, fish, recreation, urban values, water, wilderness, wildlife, wood products, forest genetic resources and other forest produce for improved livelihoods (Gadgil et al., 1983). A sustainable forest management addresses forest degradation and deforestation while increasing direct benefits to people and the environment. At the social level, sustainable forest management contributes to livelihoods and income and employment generation, whereas at the environmental level, it contributes to ecological services like places for recreation, homes for wildlife, carbon sequestration and soil, water and biodiversity conservation. If forests are not well managed, they are often unhealthy and unproductive because of overcrowding, disease, insects, and competition for light, water and nutrients. To maintain and improve the health and productivity of a forest and to achieve various direct and indirect benefits from it a number of management techniques including timber extraction, planting and replanting of various species, cutting roads and pathways through forests, forest protection, conservation of soil and water etc. are adopted. Because of variation both in the nature of the forest resource and the impacts of different management methods in space and time the following points needs consideration while specifying a silvicultural system:

- Silviculture of species available in the stand.
- Age class distribution of stand or forest should be known.
- Status of forest hygiene in terms of health (i.e., presence of insects or disease, fire damage).
- Economics of harvesting and forest industries.
- Road network requirements.
- Quantity and quality of wood required by wood industries.
- Physiography of the forest area, i.e. slope, aspect etc.
- Forest soils quality, nutrient status and its sensitivity towards erosion.
- Habitat quality for wildlife and the effect of forest fragmentation as some species require edge, while others need forest interiors, cover, etc.
- Extent and type of recreational use of the forest area.

- Availability of indigenous species (both plant and animal) and their habitat requirements.
- Possibility of rare, threatened or endangered species of both plants and animals and their habitat requirements.
- Requirements of soil and water conservation measures and improving water availability.
- Possibility of maintaining or improving species biological diversity of the area/region.
- Possibility of maintaining or enhancing aesthetic values of forests with high public exposure and/or recreational use.
- Presence of historically or culturally sensitive areas or other special feature like old growth trees.

4.1 Historical background of forest management

Since last two centuries forest science and management has focused on optimizing the efficiency of commodity production of forests, i.e. wood for timber, pulp and fuel. In view that homogenous product are economical to produce and manipulate, the practices of forest management have led to even-aged, mono-specific or species-poor stands (Puettmann and Ek, 1999; Paquette and Messier, 2009; West, 2014). The management practices of planting or natural regeneration through coppice or natural/ seed sown, combined with weed control and stand improvement to control species composition, tree size and quality etc. are called as conventional methods of forest management. At present stands under conventional management cover about 30% of the global forest (FAO, 2010). The conventional approaches typically emphasize commodity production and view other objectives as constraints like intrinsic ecosystem values, accounting for natural processes, and maintaining species and structural diversity.

Relatively less accepted but simultaneously evolved silvicultural approaches of forest management have regain interest during last three decades (Brukas and Weber, 2009; Lindenmayer et al., 2012). Increased scientific awareness and incentive (Baker, 2011); and better understanding about the impact of conventional forest management practices on biodiversity and habitat quality (Ravindranath and Sudha, 2004; Bauhus and Schmerbeck, 2010), soils, water and nutrient cycling (Walmsley and Godfold, 2010; Laudon et al., 2011), landscape visual quality (Gobster, 1996; Paquet and Bélanger, 1997), and natural capital and ecosystem services (Singh and Sharma, 2010) motivated the development of silvicultural approaches. Besides, recreational opportunities and landscape amenities have gained importance in recent years (Urquhart and Courtney, 2011).

Aesthetic and ecological evaluation of conventional forest management between middle of 19th and 20th centuries led to an emphasis on irregular size-class distribution (a full range of age classes is maintained in the stand all the time) and single-tree selection (removal of individual trees naturally of various sizes) against the clear cuts. This has promoted the so called plenter forest and continuous cover (continuity of forest cover, i.e. no less and no more) forest (Pukala and Gadov, 2012;

Thurnher et al., 2011). On the other side, mixed-species stands are favoured because of negative environmental effects of monocultures (Gayer, 1886; Marten, 2005). The selection and shelterwood system appeared relatively more suitable for the management of tropical moist forests particularly in the forests in India, Burma, Malaya, and West Africa, where these approaches were applied until the 1960s under colonial periods and continued until recent especially in Indonesia and Malaysia. The Continuous Cover Forestry (Wilson, 2013) and Close-to-Nature forestry have mainly been followed in European countries (ProSilva, 2014).

Two strategies for managing forests for multiple values have achieved prominence in the American region in a reaction to large-scale clear cutting in natural forests and its impact on wildlife habitats, visual quality and other ecosystem functions (Franklin and Forman, 1987; Lindenmayer et al., 2012). These strategies were: (i) legacy retention with passive management and long rotations (retention forestry), and (ii) intensive management for timber with commercial thinning and long rotations (New Forestry) and spread widely to other regions of the world (Karey, 2000). Major emphasis was put on the importance of residual structures and organisms such as undisturbed vegetation patches, trees, and dead wood left behind after harvesting. These bequests are considered crucial for the speedy recovery of forest ecosystems after anthropogenic disturbances and thus for a continuation of ecosystem functioning and biodiversity and habitat values. Basic conceptual frameworks for alternative silvicultural approaches like selection (either group or single tree), pleneterwald, polycyclic, green-tree retention, multicohort, multi-age, multi-retention and Dauervald (O'hara, 2013) are the recent development. These include non-commodity values, which are basic foundation necessary to achieve high level and sustainable provision of ecosystem services, including product extraction (Evans, 2006). The alternative silvicultural approaches include complex knowledge (Puettmann, 2011; Messier et al., 2013; Filotas et al., 2014), natural disturbance-based systems (Bergeron et al., 2002; Franklin et al., 2007) and legacies and retention (Gustafsson et al., 2012; Lindenmayer et al., 2012). These silvicultural alternatives have been enacted under a variety of social, economic, and ecological conditions and a wide range of ownership objectives, as well as legal and regulatory frameworks. While less applicable to highly intensive short-rotation plantations (covering 3% of the total forest area) and areas with the primary objective of biodiversity conservation (12%), silvicultural alternatives most likely depend upon the interest of landowner primarily for commodity production (30%), multiple use (24%), soil and water protection (8%) and social services (4%) (FAO, 2010). However, the last four objectives may not be best achieved by adopting single management approach.

The five principles of alternative silvicultural regime like: partial harvest, natural regeneration, structural diversity and small-scale variability, mixed species, and avoidance of intensive operations are closely related to gradient of management intensity (Duncker et al., 2012). In this regional variations resulting from changing species composition, stand density, age structure, stand edges and site conditions have been interpreted using five ideal forest management approaches. Under silvicultural alternatives, the focus on variability in stand structures across spatial scales give emphasis on the development and harvest of individual trees or small patches of trees very similar to selective harvesting, i.e., harvesting single high-value trees. However, harvesting decisions in alternative silvicultural approaches are driven by an appreciation of the economic and ecological value of retained trees in terms of ensuring the continuity of ecosystem processes and functions. The potential advantages of this approach include biodiversity (Steventon et al., 1998; Fedrowitz et al., 2014), upholding resilience to varying factors including climate change (Schütz, 1999; Schütz et al., 2012; O'Hara and Ramage, 2013) and some other benefits compared to even-aged monocultures, though under specific sets of conditions like more uniform cash-flow (Knoke et al., 2001), higher income from high-quality wood (Hanewinkel, 2002), more diverse wildlife habitats, especially for late-seral species (Rosenvald and Lohmus, 2008), increased wind stability of individual trees (Dvorák et al., 2001), and improved recreation value and public acceptance (Tönnes et al., 2004; Ribe, 2005). However, successes of selected or improved genetic material may not necessarily be achieved in forests managed under these principles (Brang et al., 2014).

A variety of local solutions have also been developed that include planted forests and forests that are naturally regenerated by seeds or vegetative reproduction, reflecting the wide variety of ecological, economic, and social conditions. In integrated silvicultural approach the tree crop, soil and other vegetation are actively managed to optimize growth (Fox, 2000), but requires knowledge of how a tree's genetic make-up interacts with the environment to affect productivity, stem quality, wood quality and resistance to insects and diseases (Gonçalves et al., 2004). In addition, a site-specific understanding of what resources limit production and how cultural treatments can be used to ameliorate these limitations are required (Allen et al., 2005). Though the potential gains in plantation growth and value obtained through tree breeding are large, but long breeding cycles of forest trees and time needed for different testing, many plantations are still planted with open-pollinated, half-sibling families affecting yield (McKeand et al., 2006; Ratnam et al., 2014).

4.2 Forests management practices

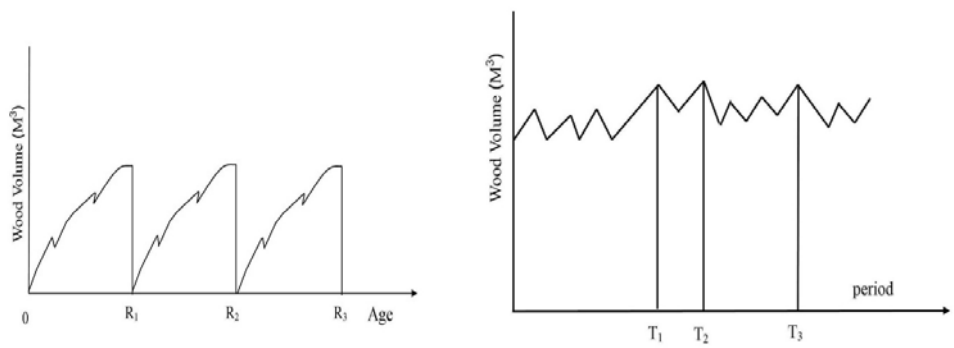
Forest management plans are generally based on biological/ecological requirement of an area, economical and organizational feasibility and social and political desire of the region. The biological or ecological characteristics include types of tree species to be grown, their growth rate, types of wildlife are going to be protected or will live in the area, etc. Likewise, silvicultural practices are prescribed to achieve the ownership objectives and are based on the ecological characteristics of the site. Different silvicultural prescriptions to manipulate forest land includes forest biomass production, carbon stocks changes in a forest, litter, soil and products, etc. These include soil scarification, forest regeneration, fertilization, pre-commercial thinning, thinning, final felling and extraction of products. Different silvicultural systems have been developed and practiced aiming to improve timber quality, optimize benefits, shorten investment period, minimize investment and maintain ecosystem health and productivity (Nyland, 1996). Ecosystem management approach is the overarching principle guiding the design of treatments in restoration programs. According to this ecosystem management includes: (i) Long-term ecological sustainability as a fundamental value (guided by historical variability and tempered by potential climate change); (ii) Clear, operational goals; (iii) Sound ecological models and understa-nding; (iv) Understanding of complexity and interconnectedness; (v) Recognition of the dynamic character of ecosystems; (vi) Attention to context and scale; and (vii) Acknowledgment of humans as ecosystem components (Christensen et al., 1996). The five ideal forest management approaches of Duncker et al. (2012) are: '**Partial harvest**' that involves partial harvesting and avoids large clear cuts; '**Natural regeneration'** put major emphasis on preferential use of natural regeneration and particular of native tree species; 'S**tructural diversity and small-scale variability**', which involves varying management approaches across a range of spatial scales, with a special emphasis on diversity of stand structures at small scales, including single-tree and neighborhood conditions; '**Mixed species**' promoting mixed-species stands; and '**Avoidance of intensive operations**', which entails minimization of intensive site preparation, fertilization and weed control practices, and reliance on natural process such as self-thinning of seedlings and small saplings.

4.2.1 Afforestation and Reforestation

Being a renewable resource trees are grown, harvested, replanted and harvested again and again in a never-ending cycle to provide clean air and water, habitat for wildlife, scenic views and thousands of products for day to day requirements. The process of growing trees in an area that previously has been harvested or cleared is called reforestation. However, trees plantation on land, which was formerly not under plant cover, to make a forest for commercial or other purposes is afforestation. Many countries have law that requires the replacement of every tree cut down by a new tree as observed in Germany. In general marginal lands or areas under crops or pasture are put under tree plantation. In some countries like Finland, incentives are given by the government to farmers for tinning arable land into forest, whereas Australia and New Zealand adopted afforestation with quick-growing conifers to increase timber supply. Two basic methods of reforestation are natural regeneration and artificial regeneration. Natural regeneration totally depends upon nature to return an area to a forestland after trees are harvested. Through natural regeneration, new trees grow from seeds that are carried by the wind, transported or buried by animals, or that are simply dropped on site by mature trees. In addition to producing seedlings from seeds, many tree species regenerate naturally by sprouting new growth from the stumps or root suckers of the harvested trees (Mostacedo et al., 2009). The artificial regeneration involves human intervention like seeds sowing or planting nursery raised seedlings. This method of forest renewal through planting has several advantages over natural regeneration. It provides better control over tree spacing, more control over the species present in the new forest, the opportunity to plant genetically improved seeds or seedlings, and a higher rate of tree survival (Arets and Veeneklaas, 2014). Although artificial regeneration is more expensive than natural regeneration, the result is usually a more productive stand in a shorter period of time (Arets and Veeneklaas, 2014). Many tropical countries like Indonesia, Zaire, Brazil, Costa Rica etc. are taking steps to protect forests including parks and reserves through afforestation and reforestation. A plantation involves high-yield crop have a larger impact on ecosystem services than conventional logging on the actual plantation area and requires only an equivalent of 11-42% of the conventional logging area due to the higher yields per unit of area allowing a larger area of primary forest to be conserved (Arets and Veeneklaas, 2014). However, this type of management lends itself to mechanised clear-cut harvesting saving money and labour but leave soil exposed to erosion, whereas monocultures eliminate habitat for many woodland species and often disrupt ecological processes, which keep forests healthy and productive. A combination of these both methods of reforestation observed more suitable to recover the site in a shorter period of time (Singh et al., 2013).

4.2.2 Better Harvesting Practices

Trees are harvested for a variety of reasons including improving the health of the forest; controlling the types of trees that grow on the site; attracting certain wildlife species; providing a source of income; producing paper, lumber and numerous other forest products; and improving access to the area for patrolling and other recreational users. Forest management also involves improvement in cutting practices in both **Even-aged** and **Uneven-aged** stands. The former represents one age class and mature tree removal is a short window of time (clear cut, shelterwood and seed tree retention), whereas latter represents at least three age classes in a stand (i.e., an age class is defined at 20% of the rotation length) with periodical removal of mature trees (selective harvesting) thus maintaining continuous canopy cover (Fig 15.1).



Clear felling with rotation times | Continuous canopy cover with harvesting intervals

Figure 15.1 Pattern of clear felling and harvesting under continuous canopy cover with interval of harvesting of a stand.

***4.2.2.1 Clear-cut harvest*:** This involves clearing all the trees from a marked area, but taking care to replant the area with tree seedlings. It includes clear strip and alternate strip system, which appears an efficient way to convert unhealthy stands to healthy ones and productive forests because they allow forest managers to control the tree species that grow on the site through natural or artificial regeneration (Arets and Veeneklaas, 2014). In regions where forests are scientifically managed, trees are farmed on a long-term system of rotation (Fig 15.1), which ensures sustainable yield of wood. This system follows a cyclic harvest-and-regeneration pattern with rotation period for an even-aged stand structure that is normally set to optimize average forest production. Rotation age of some of the tree and corresponding girth are provided in Table 15.3.

Table 15.3 Rotation age of some tree species in semi-arid regions of India.

Local Name	Botanical Name	Rotation age (Years)	Girth size (cm)	MAI (m^3/ha/yr)
Australian babul	*Acacia auriculiformis*	10		1.3-3.5
Khair	*Acacia catechu*	30	90	4 to 7
Ronjh	*Acacia leucophloea*	15	90	-
Palosa kikar	Acacia modesta Wall.	15-30		4-6
Kikar	*Acacia nilotica*	15-25	90	4-15
Kumath	*Acacia senegal* (L.) Willd	25	-	1-4
Israeli Kikar	*Acacia tortilis*	10	90	2-4
Bakyarha	*Ailanthus altissima* (Mill.) Swingle.	6-10	90	-
Ardu	*Ailanthus excelsa*	12-30	120	-
Kala siris	*Albizia lebbeck* (L.) Benth.	10-15	-	5
Safed siris	*Albizia procera* (Roxb) Benth.	30-40	-	10
Neem	*Azadirachta indica* (L.) A. Juss	8	110	5-18
Semal	*Bombax ceiba* Linn.	10-15	44-50	-
Khakhara	*Butea monosperma*	8	50	
Casuarina	*Casuarina equisetifolia* Linn.	20-30		6-18
Amaltas	*Cassia fistula* Linn.			10-12
Shisham	*Dalbergia sissoo*	40	150	7.7
Bamboo	Different species of bamboo	4	-	
Eucalyptus	*Eucalyptus camaldulensiss*	8	60	10-25
Eucalyptus	*Eucalyptus tereticornis*	15		12-25
Gambhar	*Gmelina arborea*	10-12	-	25-35
Silver oak	*Gravillia robusta* A. Cunn.	10		3.5
Leucaena	*Leucaena leucocephala* (Lam.) de Wit	10		30
Bakain	*Melia azadirach* L.	7-15		17.5
Shahtoot	*Morus alba* L.	7-30		-
Poplar	*Populus ciliata* Wal. Ex Roth	5-10		-
Poplar	*Populus* spp.	7	90	-
Khejri	*Prosopis cineraria*	30	-	3.0-5.0
Vilayati babul	*Prosopis juliflora* (Swartz.) D.C.	10		3-5
Dhaincha	*Sesbania sesban* (Linn.) Merrill	1		5 tons/ha
Farash	*Tamarix aphylla/articulata*	30-40	-	5-10
Rohida	*Tecomella undulata*	-	-	-
Teak	*Tectona grandis*	40-90	-	-
Toona	*Toona ciliata*	16	62	-
Ber	*Zizyphus jujuba* Mil	20-50	-	-

MAI: mean annual increment. Source: Shah et al. (2014); Balwan and Rai (2004); Tanvir et al. (2003); http://foreverindus.org/pdf/riverine_forest%20updownstream2008.pdf.

The objective of clear-cut systems is to obtain a higher economic benefit by a resulting sustainable flow of timber (Puettmann et al., 2009). The carbon dynamics of a clear-cut system include a rapid net carbon gain in young stands and a net carbon gain at a lesser rate after canopy closure in more mature stands and significant net biomass carbon removal at final harvest (Hyvönen et al., 2007; Diochon et al., 2009). This system is also an important management practice in creating edges – an area where two habitat types or two ages of the same habitat congregate together that provide easy access to more than one habitat and have more diverse wildlife communities.

***4.2.2.2 Seed tree harvest*:** In this more than 20-50 scattered trees per hectare are left in the harvested area to provide seeds for a new forest stand. These trees are selected based on their growth rate, form, seeding ability, wind resistance and future marketability; and are located throughout the site to provide uniform seeding in the area. In general natural seeding is considered up to distance twice the tree height. The advantage of this method is forest renewal in a cheaper way and more adaptability to the site, provides opportunity to leave a couple of different species on the site and have better genetic quality in seed production. However, seed tree harvests is also not left with disadvantage as the left over trees are at greater risk of damage from wind, lightening, insect attack, logging of nearby trees, chance of its removal because of high quality traits, suspicion about suitability of harvested sites to natural seeding occurs and better suitability for shade intolerant species are other disadvantages. Sometime seed trees may become snags or downed logs, which are important habitat, excellent food sources and nesting sites for many birds and other wildlife (Sullivan et al., 2000).

***4.2.2.3 Shelter wood harvest*:** Shelter wood harvesting involves removing mature trees in a series of two or more cuts. It is used to supply seed or provides an environment conducive to sprouting, and shelter for the regenerating stand. Strip cutting entails harvesting all the trees in a narrow corridor. This encourages regeneration and growth of medium to low shade-tolerant species because of left over trees or group of trees for "shelter" to protect (Barna et al., 2010). This includes uniform system, the group system, the ship shelter wood system, the wedge system, the irregular shelter wood system etc. This system involves three different kinds of harvests: (i) preparatory cut, (ii) seed cut, and (iii) removal cut. The 'Preparatory cut' is a thinning operation that gives selected trees room to grow large crowns. Trees with large crowns provide more seeds than trees with small crowns. This method is followed if there is a shortage of trees with large crowns on the site. In the 'Seed cut' about half the mature trees in the stand are removed, which opens up the stand, allowing sunlight to reach the forest floor, where it stimulates the germination and growth of seedlings. In 'Removal cut' all the mature trees are harvested as a single harvest or as a series of partial harvests. The removal cut is conducted after a dense carpet of saplings (seedlings taller than 1.5 metres) is established in the shelter of the mature trees. By giving the saplings full sunlight, the removal cut encourages the rapid growth of a new forest. Other type of shelter wood system is Irregular or Reserve Shelter wood where residual over story is left for an extended period of time into new rotation creating two-aged stand and has ecological/aesthetic vs. economic/operational tradeoffs and provide cover and early successional food sources for the wildlife. However, this method of harvest is generally avoided for trees with shallow root systems because the remaining trees are more susceptible to wind damage after neighboring trees are removed. Other drawback of shelterwood harvest method is requirements of roads building through the forest, and increase the risk of soil disturbance and damage to the remaining trees during harvesting time.

***4.2.2.4 Group selection harvest*:** Being a part of continuous cover forestry, group selection is basically a small-scale clearcut where groups of trees in a given area are selected and harvested over several years so that the entire stand could be harvested within a period of 40 to 50 years (Pukala and Gadov, 2012; Thurnher et al., 2011). It is characterized by selective removals from an uneven-aged forest stand structure and a continuously maintained forest cover that does not follow a cyclic harvest-and-regeneration pattern. It is observed in densely populated regions and solely in tropical forests. Examples of this type are the so-called 'plenter' forests found in France, Switzerland, Slovenia and Germany, forests in the Northern North America and in some forests of South Africa. The carbon dynamics of an uneven-age forest stand include a slow and steady carbon gain in living stand and a net biomass removal at a certain period. Despite uncertainties, a large number of standing trees existing for a longer time period in continuous-cover stands could provide larger amount of litter falls compared to clear-cut forest stands. This method is used primarily on bottomland hardwood stands to harvest high-quality timber. The size of the group cut determines the tree species that are likely to return after the harvest. Openings that are less than 0.1 hectare area favour shade-tolerant species, whereas the larger openings are beneficial for high light loving species. Group selection provides ideal pockets of young vegetation for wildlife. But it may be an expensive forest regeneration method because it requires intensive management and frequent access to all areas.

4.2.2.5 Single-tree selection harvest: Individual trees ready for harvest are removed, irrespective of their values or competition with other trees in the stand (Pukala and Gadov, 2012; Thurnher et al., 2011). Production of timber is continuous and constant, whereas new seedlings emerge to take the place of the harvested trees. Single-tree selection is the only prudent partial harvest practice because it provides strict control of residual stand stocking, and maintains a late succession forest that benefits wildlife, though marking selected stands are difficult. This method is best in small or confined areas for a variety of reasons. For example, this harvesting method requires more roads; the surrounding trees may be damaged during selected tree harvesting, and the chances of soil compaction because of frequent use of logging equipment. The light-loving trees, which are supposed to be an important source of food for wildlife, do not regenerate well under this method, whereas it also leads to develop dominance of other species (Pourmajidian and Rahmani, 2009). For this, uses of mechanical or chemical controls measures are suggested to control shade-tolerant species from taking over the site after tree harvest.

4.2.3 Stand Thinning

When trees are overcrowded they are in greater competition for sunlight, nutrients and water. As a result, they tend to be less healthy and grow less vigorously. Density dependence is thought to restrict exponential growth as well as give rise to size structure in populations. Although crowding reduces the growth rates of individuals but it is dependent on the size of individuals (Vandermeer and Goldberg 2003). In forests larger individuals can use a disproportionately large amount of resources leading to frequently observed size hierarchy in natural populations. Large individual crown volume improves the growth pattern under drought, and large stand density impaire it, whereas lower stand densities mitigate environmental stress (Rais et al., 2014). In monsoonal dry deciduous forests like that in India competition between trees is likely to be size symmetric at higher densities because below-ground resources (such as water and nutrients) are the limiting factors and below-ground plant biomass may precede stem size (Sumanta, 2007). Thus thinning is an intermediate cutting in an even-aged stand that uses to increase diameter growth on the remaining stems, recoups natural mortality, reduces the rotation age, increases stand quality and hygiene, and increases the content of more desirable species within a stand (Singh et al., 2007; Nogueira et al., 2015). Thinning may be from below (to favour dominant trees) or above (to favour most promising trees, not necessarily dominant trees) the given level of canopy. Different methods of thinning are described below:

4.2.3.1 Selection thinning: Removal of individual plants/trees normally of poor quality ones evenly throughout the stand. It is the best thinning method from biological, stand quality and aesthetic point of views.

4.2.3.2 Row or strip thinning*:* In this a complete row (in a plantation) or swath (in naturally regenerated stands) of trees is removed at regular intervals throughout the stand irrespective of trees characteristics either removed or left. It is usually the best method from a harvesting for economic benefits.

4.2.3.3 Selection thinning within leave strip*:* It is combination of selection and row thinning, where rows or swaths are removed at regular intervals and selection thinning is done in the left strips or rows.

Thinning operations may be pre-commercial or commercial. Pre-commercial thinning is the practice where the thinned material is left on site, particularly when the stands are in the sapling stage. For example first and second thinning in *Tectona grandis* plantation is done at the age of 5 and 10 years, whereas for *D. sissoo*, *Acacia* spp. the respective thinning is done when the plants are of 3-4 m and 6-8 m in height. The commercial thinning referred to thinning operations which produces a profit, though commercial thinning is now held as any thinning where the thinned material is removed from the stand for commercial use. However, extended rotation lengths and reduced thinning intensity could enhance the long-term capacity of forest ecosystems to sequester more carbon (Kaul et al., 2010). For this there is a need of proper understanding of growth processes and anticipated consequences of a particular thinning operation. In most cases, total timber volume does not appear to be a very appropriate measure for quantifying growth or yield changed by thinning operations.

4.2.4 Pruning and lopping

Tree pruning is necessary to maintain a tree in a safe condition, remove dead branches, promote growth, regulate size and shape or to improve the quality of flowers, fruit and timber. Pruning and lopping are traditional practices in western Rajasthan India, where people use to harvest *Zizyphus nummularia* bushes and prune and lope tree species like *Prosopis cineraria* to meet their fodder and fuelwood requirements (Jodha, 1995). Though general minor pruning is recommended during the early years of a tree's growth to establish the desired form and/or to correct defects or weaknesses that may affect structure in later life of the tree, pruning of old or mature tree affects nutrient returns to the soil negatively (Gupta et al., 2010). In a plantation of *Ailanthus excelsa* and *Acacia tortilis* pruning are advocated when the plantation is in 2nd, 4th and 6th year of age, whereas in case of *P. cineraria* and *Tecomella undulata* pruning can be done in 2/3 years of age or tree height of about 3 m. For larger trees crown thinning, crown lifting and crown reduction are three types of pruning. Crown thinning is the removal of a portion of smaller/tertiary branches (not more than 30%), usually at the outer crown, to produce a uniform density of foliage around an evenly spaced branch structure and allow more light to pass through the tree, reduce wind resistance and reduce weight. Crown lifting is the removal of the lowest branches, but does not normally include the removal of large branches growing directly from the trunk but older or mature trees are generally avoided from crown lifting or restricted to secondary branches or shortening of primary branches only. It increases light transmission to areas closer to the tree or to enable access and restricted to less than 15% of the live crown height. Crown reduction are used to activate mechanical stress on individual branches or the whole tree, make the tree more suited to its immediate environment or to reduce the effects of shading and light loss, etc, but does not necessarily apply to all species. Crown reduction cuts should be as small as possible and in general not exceed 10 cm diameter.

Existing literature indicates variability in extents of pruning depending upon types of species and the climatic conditions, but most of the finding indicates either no effect or negative effect of heavy pruning or lopping on diameter growth of trees (Chandrashekhara, 2007; Kishan Kumar and Tewari, 2000; Kishan Kumar and Tewari, 2006). A lopping intensity of 2/3 of crown has been recommended for *P. cineraria* and *Ailanthus excelsa* (Kishan Kumar and Tewari, 2000; Kishan Kumar and Tewari, 2001; Tewari, 1998). Likewise trees of *Erythrina indica*, *Macaranga peltata* and *Terminalia paniculata* have been recommended for 50% annual pruning while the trees of *Ailanthus triphysa*, *Albizia odoratissima*, *Artocarpus hirsutus*, *Bridelia crenulata*, *Grewia tilifolia* and *Xylia xylocarpa* have been recommended for same level of pruning intensity once in 2 years (Chandrashekhara, 2007). Lopping which are generally observed for trees on farmlands, farm boundary or roadsides refers to the removal of large side branches, whereas topping refers to the removal of large portions of the crown of the tree generally through the main stems. The tree species lopped in general for fodder values are *Acacia nilotica*, *A. leucophloea*, *Ailanthus excelsa*, *Azadirachta indica*, *Prosopis cineraria*, *Pithecelobium dulce* etc depending upon availability in a region and animal preferences (Wood et al., 2001).

4.2.5 Protection of Forests

Protection is an important technique to regenerate the forest areas. Natural hazards like fires, pests and diseases, biological invasions etc. are becoming more significant in view of climatic abrasions. Forests can be protected and saved by intensification of scientific research into the causes and methods of overcoming such natural destructive agents.

4.2.5.1 Prescribed burning: Millions hectares of forest land are burned each year intentionally under controlled conditions as a part of forest management practices (Florence and Florence, 1988; Mishra, 2009). The major benefits of prescribed fire are reduction in hazardous fuels, disposing of logging debris, help prepare sites for seeding or planting, improve wildlife habitat, management of competing vegetation, control of insects and diseases, improvement in forage for grazing, enhancement in appearance of other species, improvement in access in forest and perpetuation of fire-dependent species (Knapp et al., 2009). In addition to help control the spread of wildfire, removal of litter layer also promotes the growth of new forage and succulent plants, which are important sources of food for many wild animals (Knapp et al., 2009). Besides it also promotes the health of the forest by controlling the invasion of alien species and reducing plant competition for nutrients, water and light. This management technique is commonly used in the forests with tree species naturally resistant to fire (Florence, 1996) as well as over growth of tall grasses and weeds and the invasive species (Vasu, 2003, Khatri and Barua, 2011). However, wild fires, which are expected to increase in future (Krishna and Reddy, 2012) needs to be taken care of considering the guidelines for prevention and control of forest fires issued to all states in June 2000 by the Ministry of Environment and Forests, Government of India.

4.2.5.2 Managing forest invasive: Protecting forests from natural threats such as fire, insects and diseases etc., are integral part of sustainable forest management. Presently, invasive species poses severe threat affecting the forest ecosystem worldwide. Invasive species are many species that are non-native to a particular ecosystem and whose introduction and spread causes socio-cultural, economic or environmental harm or harm to human health and biodiversity (Raghubansi and Tripathi, 2009; Ramaswami and Sukumar, 2013; Richardson et al., 2014; Peh, 2010; Simberloff et al., 2013; Corlett, 2014). Factors that favour invasion of natural forests include tree removal, construction and use of roads and other infrastructures, cutting climbers and girdling competitors, and enrichment planting. Clear cutting of mature plantations creates large gaps that favour invasion of many light demanding species (Lake and Leishman, 2004; Leung et al., 2009). Removal of canopy trees inevitably increases light availability for the understorey, facilitating invasion by light-demanding species, whereas construction of access roads, logging camps and other facilities opens large spaces in the forest that facilitates the establishment of invaders and allow them to build up their populations. Human-induced activities like enrichment planting using native or alien species and use of heavy machinery (i.e., skidders and tractors) also facilitates dispersal of the seeds of potential invaders (Christen and Matlack, 2009; Da Silva et al., 2011; Shackleton et al., 2014). Canopy opening treatments use to provide adequate light for rapid growth (Villegas et al., 2009; Akindele and Onyekwelu, 2011), can facilitate invasions, whereas planted aliens may themselves become invasive (Table 15.4). Land preparation, tree planting and maintenance activities in young plantations can also facilitate invasion in plantation forestry, which requires careful control over potential influence on seed germination (Da Silva et al., 2011). Conflicts between timber production and preventing invasions are most likely where forests are managed for relatively light-demanding timber species, such as *Swietenia macrophylla* (Padmanaba and Corlett, 2014).

Table 15.4 Examples of alien species which have escaped from their native and invaded surrounding native or other habitats.

Species	Native Range	Problem	Habitat Invaded	References
Acacia mearnsii	Southern Australia	suppressing natural vegetation	montane "shola" forest in Kerala, South India	Sankaran et al. (2005)
Acacia mangium	Northeastern Queensland	convert the habitat to monospecific stands	disturbed heath forest and native tree plantations in Brunei	Osunkoya et al. (2005)
Alnus spp.	Northwestern Africa	form pure stands	Montane forest gaps in the Philippines	Baguinon et al. (2005)
Alstonia macrophylla	Southeast Asia	no record	secondary forests in the wet and intermediate zone of Sri Lanka	Binggeli (1998)
Chromolaena odorata	North America and Caribbean	alter the vegetation structure	humid lowland production forest in south western India	Chandrashekara and Ramakrishnan (1994)
Eupatorium odoratum	North and central America	affect plantation	Acacia, pine, eucalypt and other plantations in Vietnam	Thu (2005)
Falcataria moluccana	Molucca, New Guinea, Britain, Solomon Island	Ater the functioning of native dominated forest	Intact remnants of native wet lowland forest	Hughes and Denslow (2005)
Fraxinus uhdei	Mexico, Costa Rica, Guatemala	suppress growth of native vegetation	Natural logged forest; coast up to volcanic upper montane in Hawaii	Friday et al. (2008)
Grevillea robusta	Eastern Australia	Suppress the establishment of other species	Native dry forests of Hawaii	Denslow (2002)
Imperata cylindrica	Southeastern Asia	No record		Thu (2005)
Lantana camara	Central and south America	Reduce grazing land for wild herbivores and biodiversity	plantations and disturbed forests in Sri Lanka (and many other countries)	Weerawardane and Dissanayake (2005); Raghubanshi and Tripathi (2009)
Maesopsis eminii	Tropical west and central Africa	form monospecific forest cover	selectively logged lowland to submontane rainforests in northeast Tanzania	Sheil (1994); Cordeiro et al. (2004); Hall et al. (2011)
Myroxylon balsamum	Northern and south America	degrade the function of natural ecosystem	forest edges in the wet and intermediate zones of Sri Lanka	Weerawardane and Dissanayake (2005)

Species	Native Range	Problem	Habitat Invaded	References
Pinus caribaea	South Mexico, central America, Caribbean	no record	Ultramafic maquis of New Caledonia	Richardson (2000)
Pinus elliottii	Southeastern USA	no record	Eucalyptus forest in Australia; cerrado and other ecosystems in southern Brazil	Batianoff and Butler (2002); Zanchetta and Diniz (2006)
Prosopis juliflora	Central and southAmerica	Degrading productivity and biodiversity of rangeland, forests and agriculture land	Thorn scrublands in Sri Lanka; abandoned agricultural land, degraded pasture land and forests in India.	Pasiecznik et al. (2001); Sankaran et al. (2005)
Sorghum halapense	Mediterranean regions	no record	seasonally dry and selectively logged forest in eastern lowland Bolivia	Veldman and Putz (2010); Veldman et al. (2009)

Source: Modified from Padmanaba and Corlett (2014).

The practices required to reduce the risks of plant invasions are: (i) continued surveillance for invasive species with trained personals; (ii) minimizing canopy opening during harvesting and other silvicultural operations in natural forests; (iii) encouraging rapid canopy closure in plantations; and (iv) minimizing the width of access roads and ensure vehicles and other equipment not to transport seeds of invasive species (Ramaswami and Sukumar, 2013). Besides, one should ensure that potential invasive species are not planted in dispersal range of production forests. At the same time, there is need to ascertain that forest managers themselves should not plant species with known invasive potential. Most importantly is the removal of the invasive species particularly *Prosopis juliflora*, *Lantana camara* etc., by pooling up at the saplings stage or by uprooting to avoid resprouting from root suckers (Sundaram et al., 2015).

4.2.5.3 Protection from grazing and removals: Forests are facing problems of overcrowding of cattle, sheep and goats, which are an important source of income particularly in dry areas (Singh, 2008). But these livestock destroy the undergrowth and seedlings, thus preventing the regeneration of forests. Strict control on wood removal or vegetation damage from reserve forests or protected areas like sanctu-aries, sacred groves, biosphere reserves and national parks may reduce forest degradation and maintains all storeys of vegetations or plant lives (viz., tall trees, smaller trees or shrubs, ground cover of small shrubs or herbs) together with soil and micro-flora- a living and dynamic system of the forest. Though protections are provided by communities (if involved) through patrolling on a rotational basis or having a paid watcher against grazing, fires, illicit felling etc., but further strengthening for its effectiveness needs consideration. The effect of increasing years of protection has been reflected by a positive trend with respect to various forest and ecological parameters like grass productivity, tree count, basal area, and regeneration of trees and shrubs. Though social fencing has also been adopted to prevent and regulate incidence of grazing in forest areas in many regions, physical barriers like fencing, cattle proof walls and/or trenches are not uncommon. Despite this open grazing is still evident in many of the areas affecting forest cover. By demarcating regions and types of forest growth and effective management with equitable sharing may help forest protected.

***4.2.5.4 Pest Management and disease management*:** Incidences of pests and diseases in forest and plantation are also not uncommon. Many of the tree species are heavily affected by pests and diseases like root rot, Ganoderma, Ceratosystis and insect pests like leaf defoliator, leaf minors, etc. Managing pests and diseases are a necessary part of maintaining plantation/forests productivity. Adoption of Integrated Pest and Disease Management (IPDM) approach including biological control can help in improving forest health. Regular monitoring and reporting of tree health are important considerations in controlling forest pests and diseases. By adopting criterion of pest and disease resistance during species selection may be key element in production of high-quality planting stock. High levels of pest and disease control are achieved with minimal use of chemicals, using prescribed insecticide or fungicides, for which training in chemical use may improve efficiency. For example, teak defoliator, *Hyblaea puera* and leaf skeletonizer, *Eutectona machaeralis* are major pests in teak and are known to occur on seedlings in nurseries and also in grown up trees in plantations. Likewise, Defoliator like *Atteva fabriciella*, *A. niveigutta* and *Eligma narcissus*; the borer *Batocera rufomaculata* and the *fungi* (leafspot) *Cerc-ospora glandulosa* and *Alternaria* spp. are the major pests and disease in *Ailanthus excelsa* causing severe damage. Application of 0.1% of endosulfan and malathion will manage the insect pest to a considerable extent. Similarly, *Microtermes* is the major genus of termite infesting trees and *Odontotermes* infesting crops. Efficacy of *Calotropis procera* leaves and seed kernels of *Azadirachta indica*, azadirachtin, diazinon, chlorpyrifos and endosulfan are effective against the termites (Parihar, 1994).

4.2.6 Improving Forest Soil Resources

Most watersheds in tropical regions contain a large population of farming community, which apply different types of farming in hill slopes applying soil and water conservation functions. On the other hand, reforestation in areas degraded by increased anthropogenic pressure appears to be an expensive technical solution. Improved forest protection with people participation often lead to natural regeneration and enable secondary forest to be restored. Likewise, generating new forests on such degraded lands needs improved soil and water conservation practices along with application of fertilizer to enhance the forest/plantation productivity.

***4.2.6.1 Soil and water conservation**:* A forested watershed provides water to densely populated areas and requires protection against shifting cultivation and unplanned urbanization. In such a case management option is effective surveillance to protect forest cover. Because of degraded vegetation and poor and shallow depth soil ecological restoration is very difficult in hilly areas. Spatial arrangements of various soil and water conservation devices/system have emerged out to be more beneficial (Karahalil et al., 2009; Singh and Reddy, 2014). Structure designing and management technology of forest and grass complex system on the mild slope area; bio-engineering methods for gully erosion control, sand filtering, and bed fixation; and construction of multi-layer forest stands in mountainous region are some options of soil and water conservation in enhancing species richness and forest productivity (Zhiqiang, 2002; Singh et al., 2013). Likewise, soil and water conservation in forests in accordance with dams, ponds, and adjoining agricultural fields to form an interwoven agro-forestry system on the slopes, protection of forests according to gully erosion control and hydraulic works, farmland construction to achieve stream/river bank stabilization, bed fixation and sand filtering to improve vegetation structure, water quality and availability and people livelihood in the region, which may help effective people participation in forest protection and management.

***4.2.6.2 Use of fertilizers*:** In plantations, plant debris including branches and bark is left in the field to maximise retention of nutrients, reduce erosion, and reduce the need for artificial fertilizer. The cultivation of plantations requires the addition of fertilizers in order to maintain and enhance plantation yields. Application of fertilizer is done in such a way that it minimizes its impact on off-site effects through prevention of groundwater and surface water eutrophication. Procedures such as the dosage and type of fertilizer to be applied are formulated depending upon species and climatic regions. Forest soil mapping and site classification is an important aspect in designing the dose of fertilizer application in plantations of an area (Bala, 2015). Though application of fertilizer is generally restricted to irrigated plantations and varies between regions, use of nitrogen fixing herbaceous or under shrub species may also be useful in enhancing soil fertility. Application of fertilizers generally recomm-ended during the peak growing period with sufficient soil water availability.

5. INITIATIVES OF GOVERNMENT OF INDIA

Government of India has approved National Mission for a Green India in February 2014 as a Centrally Sponsored Scheme for a total cost of Rs 130 billion, having a plan outlay of Rs 20 billion for the 12th Five Year Plan (FYP) with a spillover of 1 year in the 13th FYP along with Rs 4 billion from 13th Finance Commission Grants towards State's Share. The Centre: State share are 75:25 ratio for all States except for North-Eastern States and Jammu & Kashmir for which it is in the ratio of 90:10. The approval also brings out convergence with MGNREGA for Rs.40 billion, CAMPA for Rs. 60 billion and National Afforestation Programme (NAP) for Rs.6 billion. Budget allocation for the Mission in 2015-16 is Rs. 0.64 billion. Government of India has also introduced the Compensatory Afforestation Fund Bill, 2015 in Parliament to create appropriate institutional mechanism required for expeditious utilization of unspent money in lieu of forest land diverted for non-forest purpose and put under Compensatory Afforestation Fund Management and Planning Authority (CAMPA). A major part of CAMPA (i.e., Rs. 380 billion) is planned to be utilized for tree plantations. Similarly, about Rs. 60 billion from the money to be realized in lieu of forest land likely to be diverted for non-forest purpose in future along with annual interest to be accrued on will also be utilized for tree plantations (http://www.orissadiary.com/CurrentNews.asp?id=60709). Other Centrally Sponsored Scheme are National Afforestation Programme for regeneration of degraded forests and adjoining areas through people's participation implemented through a decentralized mechanism of State Forest Development Agency (SFDA) at State level, Forest Development Agency (FDA) at Forest Division level and Joint Forest Management Committees (JFMCs) at village level with a total cost of Rs. 1 billion in 2015-16.

6. CONCLUSIONS AND WAY FORWARD

Intensive felling and overexploitation of forest resources for meeting the industrial needs and greed coupled with increased human and livestock pressure on forest resources lead to forest degradation extensively. Forest management has undergone many changes since last two centuries ranging from totally government control to community forest management and conventional methods of forest management to alternative silviculture to maximize community participation and improve people livelihood. Though varying with regions and depending upon the regional requirements and climatic conditions various forest management strategies are afforestation or reforestation, improvement in wood harvesting practices, thinning, pruning and lopping operations, forest protection from fire, grazing, invasive species etc., and forest resource conservation. In dry regions of India, major strategies adopted for regeneration of degraded sites are natural regeneration, enrichment planting, protection from fire and grazing and artificial plantation including gap plantations. Utilization of forest resource in a rational and controlled manner could save soil and trees both because of less number of trees growing under low soil fertility in hilly areas. For this production forests should be cultivated on flat land and managed for high production. Clearly demarcated area under intensive plantation forestry will provide significantly higher benefits, making greater areas to conserve under conservation forestry. Combined strategies of assisted natural regeneration and plantation development have been observed beneficial and cost effective especially in areas where mosaics of different degradation states and other land uses are found.

Forest protection and conservation is a national problem so it should be tackled with perfect coordination between forest department and other line departments, where people's participation is of vital importance and we must get them involved in this national task. However, evidences indicate that functioning of JFM committees is critical towards reducing poverty (Danwar et al., 2008). Though communities have been involved in many activities of forest management including fire management, enrichment planting, growing medicinal plants and fuel and fodder species, protection etc., but lots are still required in effective participation of the community, where level of participation is limited to wage labours only. Further, attempts of closing or total ban against grazing appears ineffective in absence of alternatives like raising pasture area/plots and introduction of stall-feeding and livestock improvement. To manage forests effectively with increased people participation following points need consideration:

- Increased need of fuel, fodder and non-timber forest produce for their livelihoods can only be met in a sustainable way when forest productivity is increased through improved forest technology and management.
- Introduction of fodder trees, legumes and grasses with extensive soil and water conservation measures along with protection and planting are beneficial for rehabilitation of degraded forests of dry areas. Increase in

fodder supply through encouraging fodder inter-cropping in agriculture fields or forest land in each JFM areas may also be considered at broader scale.

- Illegal cutting of trees in the forests should be stopped at all costs, including unholy nexus between corrupt officials and timber mafias for checking the rapid loss of forest cover. Simultaneously grasslands should be intensively regenerated.
- Provisions of dispensing in a top-down manner lack communication and facilitation, and consequently are not sufficiently effective in improving local livelihoods and conservation, particularly in tribal communities.
- Addressing local development needs, encourage women's participation (more emphasis on tribal women) in community forestry, and work toward dispute settlement of community forest-user groups sustains long-term community participation in environmental conservation (Bose, 2011; Kobbail, 2012).
- Enhancing the quality of governance would result in decrease in deforestation and long-term carbon storage in forests globally. Effective local institutional arrangements to govern forests substantially will also influence carbon storage and livelihood contributions.
- Suitable measures should be taken to avoid discontinuity of funds that negatively affects the sustainability of the village-level institutions involved in forest management programmes (Balooni and Inoue, 2009).
- Provision of material benefits like conservation incentives, technical assistance etc. and responsibility and accountability, should be properly explained to beneficiaries in advance for developing a sense of ownership particularly to disadvantaged or marginalized populations (Gebara, 2013; Ota et al., 2014).
- Eco-certification is also an option that could lead to more efficient protection and participatory management of the forest resources.
- Priorities of increasing local people awareness about their rights and improving their relations with the formal forest stewards help in sustainable forest management (Macura et al., 2011).
- Capacity building of even encroachers and forest-dependent families could help improvement in resource, whereas utilization of human capital through alternative livelihood strategies provide security, improve livelihood, promotes participation and help control shifting cultivation (Islam et al., 2013).
- The role of non-governmental organizations is also important in people mobilization and community forest management particularly in forest reserves.
- There is a need for the establishment of criteria and indicators based credible local monitoring, local rule-making and local enforcement systems in every village-level organization to facilitate learning and adaptation (Rawat et al., 2008; Singh and Pandey, 2010).

- Probable changes in climate modify forest structures towards more ecological stability and economical flexibility, which may affect the provision of ecosystem services of the forests.
- Understanding the links between determinism and the provision of ecosystem services is necessary as higher the demand for specific ecosystem services, the more deterministic the management approaches, which invariably lead to simplification of forest structures.
- High adaptability and flexibility of forests are required to cope with increasing uncertainty due to climate change. More complex structures in forests like multiple species, their age, diameter etc., generally show high ecological stability than do simplified forests that have been shaped by deterministic management approaches (Puettmann et al., 2009).
- Long-term adaptability and flexibility is now gaining importance. For this application of monitoring approach should be both problem- and scale-oriented, which can facilitate adaptive management.
- A single approach canot offer a strategy with a high probability of both recent and future success for forest management which means new combinations of management tools should also be explored to make forest ecologically and economically sound.
- Use of techniques such as data from Global Position Satellites (GPS), Geographical Information System (GIS), remote sensing etc. help in accessing information on forest fires, loss of forests due to anthropogenic activities, etc. and in taking timely action for forest protection and monitoring.

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