Greening Salty and Waterlogged Lands Through Agroforestry Systems for Livelihood Security and Better Environment

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Abstract

Nearly, one billion hectares of arid and semi-arid areas of the world are salt-affected and remain barren due to salinity or water scarcity. In India, about 6.75 Mha lands are either sodic or saline in nature and 6.41 Mha land is degraded due to waterlogging. These lands constrain plant growth owing to the osmotic effects of salt, poor physical conditions leading to poor aeration, nutrition imbalances, and toxicities. To meet the requirements of food and other agricultural commodities for the burgeoning population is a big challenge for agricultural community. With the increasing demand for good quality land and water for urbanization and development projects, in future, agriculture will be pushed more and more to the marginal lands and use of poor quality water for irrigation is inevitable. With use of appropriate planting techniques and salt-tolerant species, the salt-affected lands can be brought under viable vegetation cover. Further, in most of the arid and semi-arid regions the groundwater aquifers are saline. Usually, cultivation of conventional arable crops with saline irrigation has not been sustainable. Concerted research efforts have shown that by applying appropriate planting and other management techniques (e.g., sub-surface planting and furrow irrigation), the degraded salty lands (including calcareous) can be put to alternative uses (agroforestry) and salt-tolerant forest and fruit trees, forage grasses, medicinal and aromatic, and other high value crops can be equally remunerative. Such uses have additional environmental benefits including carbon sequestration and biological reclamation. Agroforestry is not only a necessity for increasing tree cover and hence decreasing pressure on natural forests, but also a most desired land use especially for reclaiming

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and rehabilitating the degraded lands. In developing countries like India, there seems to be little scope for bringing the fertile lands under forestry cover. It may be emphasized here that we can bring unproductive wastelands and waterlogged areas under forest cover and take agroforestry tree plantation on nonforest community and farmlands. The long-term studies conducted show that salt-affected and waterlogged areas and saline waters can be utilized satisfactorily in raising forest and fruit tree species with improved techniques, forage grasses, conventional and nonconventional crops, oil-yielding crops, aromatic and medicinal plants of high economic value, petro-crops, and flower-yielding plants. Opportunities for raising salt-tolerant crops and alternate land uses through agroforestry on salty and waterlogged areas, especially in arid and semi-arid regions have been discussed in this chapter.

Introduction

Among the various degradative processes, the salinity afflictions of landscapes constitute a major threat. In fact, the salt-affected soils are not alien to land; these have been associated with mankind since the inception of agriculture. Civilizations in Mesopotamia, Nile Valley, Mohenjo-Daro and several other places and their subsequent fall are the testimony to the occurrence of salinity in agriculture. Salinity afflicted landscapes, which now occupy nearly a billion hectares (about 7 % of land area), have their origin either due to natural or man-induced causes. The salinity caused due to anthropogenic factors (secondary salinization) is related to clearing of natural deep-rooted vegetation and large-scale development of irrigated agriculture without adequate drainage. Due to secondary salinization, the world is losing at least 3 ha of arable land every minute (Bridges and Oldeman 1999) representing a serious threat to the expanding needs of food, fuel, fodder, and fiber production. Worldwide experiences show that though human-induced salinity problems can develop rapidly while the hydrological, agronomic, and biological solutions put forward for reclamation are very expensive and time consuming. Moreover, implementation of these solutions is constrained due to the socioeconomic and political considerations. Thus, despite the availability of technical know-how, the rehabilitation of the salty and waterlogged lands is progressing at a very slow pace. The use of agroforestry systems is now being put forward as a viable alternative. Though the salinity and waterlogging stresses can be as hostile for the woody tree species, these are known to tolerate these stresses better than the annual species.

The history of planting trees on salt-affected soils in India goes back to the follow-up of the recommendations of *Reh* Committee, which was set in 1879 to deliberate on the origin of salts in soils. While tracing the history of salt-affected soils in India, Singh (1998) mentioned about the scheme of experiments recommended by Reh Committee, which was directed toward preparing the soil for profitable cultivation by (i) removal of salts, (ii) drainage, (iii) silting, (iv) deep cultivation, (v) manuring, and (vi) ploughing of green crops. A conference was held in 1879 at Aligarh, during which it was decided to set up a series of experiments for the reclamation of salt lands and the decisions of the conference have been documented by Leather (1897). In one of the experiments near Aligarh, reclamation of *usar* (alkali land) was commenced with land and planting of trees. Plantations were later made at other locations in Aligarh and Kanpur districts. Various degrees of success was obtained when farm manure was used along with initial leaching through embankments of enclosed plantations and grassland. Greig (1883) visited one of the plantations at Pardilnagar near Sikandra Rao in the Aligarh district and seven plantations near A-wargarh and made some important observations on the heterogeneity in salt lands. He recorded that a simple and reliable way of finding good patches in an *usar* plot was to stop grazing for a year and then examine the ground. *Dub* (*Cynodon dactylon*) and other grasses will appear on good patches but on soil highly impregnated with *reh* only one kind of grass will grow that had not found on any other soil (we call these as indicator species). According to him, good *usar* was the soil that could grow *Acacia* tree without any special soil treatment. In real *usar,* the trees only did well if the pits were filled with good soil and when the pits were deep enough to let roots grown in good soil to extend beyond 90–120 cm of *reh* into a less-deteriorated soil below. These observations are forerunner of the auger hole method of planting trees in alkali soils advocated by the Central Soil Salinity Research Institute, Karnal (Singh 1998).

Though the records of plantations on alkali soils in India and elsewhere are available from 1874 (Oliver 1881; Leather 1897; Moreland 1901) no systematic experimentations were conducted to raise vegetation until recent past. Khan and Yadav (1962) observed that successful afforestation of alkali soils was not possible unless these are reclaimed to the desired level through appropriate techniques. Later on, it was suggested (Pande 1967; Yadav 1972; Yadav et al. 1975) that such soils could be planted using soil replacement technique in which the soil from $90 \times 90 \times 90$ cm^3 pit was replaced by a normal soil brought from out side. These measures, however, suffered from some intrinsic drawbacks like higher amendment needs, laborious and time consuming operation, leaving the $CaCO_3$ layer (which usually is located at about 0.5–0.7 m depth) untreated, and difficulties in preparing pits of this dimension in alkali soils. The difficulties were overcome through the development and perfection of the tree planting technique termed as the auger hole planting technique (Sandhu and Abrol 1981; Gill 1985; Singh and Gill 1992; Dagar et al. 2001a; Singh and Dagar 1998, 2005).

Moreover, the research efforts in the recent past have greatly enhanced the understanding of biology and management of forestry plantations on salt lands and with the use of saline waters (Lieth and al Masoom 1993; Lieth and Lieth 1993; Singh et al. 1993; Dagar et al. 2001b; Dagar 2003; Tomar et al. 2003a, b, Singh and Dagar 2005). Evidences are that subject to some of the obligatory changes in reclamation technologies, the salt lands can be successfully put to alternate land uses through agroforesty programmes. In addition to meeting ameliorative and long-term ecological goals on these landscapes, the alternate land use systems can be as economical as some cropping alternatives. Therefore, an attempt is made here to collate the existing information on afforestation technologies for the varied agroclimatic situations demanding site-specific solutions and agroforestry systems/practices evolved for saline and waterlogged environments and utilizing saline waters. Some of the plausible benefits including environmental and socioeconomic impacts of rehabilitation of salt lands are also presented in this chapter.

Salt-Affected Soils and Saline/Sodic Waters

Salt-Affected Soils and Their Distribution

All soils contain a certain quantity of water-soluble salts, which are indeed essential for healthy growth of plants. If the quantity of soluble salts in a soil exceeds a certain threshold value (which in turn depends on the geochemical and environmental conditions, physicochemical properties of soil, and chemical composition of salts causing salinity), the growth of the most plants is adversely affected. Such soils are designated as *salt-affected*. These soils occur under different environmental conditions and have different morphological, physicochemical, and biological properties, but one common feature is the dominating influence of electrolytes on the soil-forming processes (Szabolcs 1979). Historically, the salt-affected soils have been referred to soils where growth of the most of the crops gets adversely affected either by the presence of excess soluble salts, sodium on the exchange complex or both. Thus, attempts have been made to classify the soils on the basis of total soluble salts measured in terms of electrical conductivity of the soil's saturation paste extract (ECe) or various dilutions (soil: water 1:2 or 1:5), exchangeable sodium percentage (ESP) or sodium adsorption ratio (SAR), and pH of the saturation paste (pHs) or other dilutions. The US Salinity Laboratory Staff in 1954 (USSL 1954) originally proposed the three categories of salt-affected soils on the basis of these parameters, i.e., saline, saline-alkali, and alkali soils.

The definitions in respect of these three categories were slightly modified later by Soil Science Society of America (SSSA 1987). It was described that owing to excess salts (ECe > 4 dS m^{-1}, or > 2 dS m^{-1} later on) and absence of significant amount of sodium (ESP < 15), saline soils are generally flocculated and as a consequence their conductivity is equal to or even greater than their nonsaline counterparts. A saline-alkali soil (ECe > 4 dS m^{-1}; ESP > 15) was described similar to that of saline soils as long as sufficient salts are present; whereas upon leaching, these soils become alkaline (pH > 8.5) leading to dispersion and their permeability reduces to levels those affect crop growth. The term "alkali" was discarded later on to be replaced with "sodic" and these soils contain sufficient exchangeable sodium (ESP > 15) to affect the physical behavior of soils and interfere with growth of the most of the crops.

The Indian classification of salt-affected soils is also based on the above criteria but in place of three categories of salt-affected soils (saline, sodic, and saline-sodic), these soils were classified into two groups based on the nature of plant responses to the presence of salts and the management practices desired for their reclamation. Abrol and Bhumbla (1978) concluded that "The so called 'saline sodic' soils" are in fact, of rare occurrence. It has been argued that usually recognized two categories of salt-affected soils "saline" and "saline-sodic" are no different from each other and that both should be categorized as "saline" because in these soils plant growth is not adversely affected due to the effect of excess exchangeable sodium or soil physical properties or lack of calcium. Soils containing sodium carbonate are necessarily sodic in nature. Bhumbla and Abrol (1979) argued that the so called "saline-sodic or saline-alkali" soils are rendered normal rather than sodic with lowering of SAR once the salts are leached. However, the term "alkali' has been invariably used for "sodic" in the Indian literature to represent soils which have both excess of exchangeable sodium and have salts capable of alkali hydrolysis, e.g., carbonate and bicarbonates of sodium or both. Therefore, Gupta and Abrol (1990) defined that the alkali soils in narrower context are the soils having (i) both high pHs (>8.2) and sodicity (ESP > 15) and containing soluble carbonates and bicarbonates of sodium such that $Na/Cl + SO_4 > 1$.

Looking at some of the recently modified classifications in the world literature, Rengasamy et al. (1984) have proposed a scheme based on the TEC concept where the soils have been classified into dispersive, potentially dispersive, and flocculated soils. The scheme has been further modified by Sumner et al. (1998) who have classified the salt-affected soils into nine classes based on EC and SAR of 1:5 (soil : water) extracts. Sodic soils have been differentiated into three categories based upon the dispersibility of soils, i.e., spontaneous dispersive, mechanically dispersive, and flocculated. Levels of ESP and SAR (1:5 extracts) used to describe corresponding soil sodicity are: no-sodic (SAR1:5 ≤ 3, ESP ≤ 6), sodic (SAR1:5 3–10, ESP 6–15), and very sodic (SAR1:5 > 10, ESP > 15). Each sodicity level has been combined with three levels of salinity (nonsaline, saline and very saline) with increasing limits of EC (1:5). A definite advantage of this scheme seems to be the use of EC and SAR of 1:5 extracts, while conventionally the saturation extract values have been used. It may be pointed out that the former gives little idea of salt release component, which is so important in maintaining the infiltrability in salt-affected soils containing sparingly soluble salts like gypsum and/or lime.

The salt-affected soils have been classified into three categories viz. nondispersive saline, dispersive saline-sodic, and sodic/alkali soils and based on the severity of the sodicity problem, further categorization has been proposed for different textured soils (Minhas and Sharma 2003).

Salt-affected soils are found distributed in all the continents covering about 954.832 million ha (Mha), which is ~10 %, of the total surface of dry land (Szabolcs 1989). As per recent FAO/UNESCO Soil Map of the World (FAO/AGL 2000), the total salt-affected area is 831 Mha, out of which 397 Mha are saline and 434 Mha sodic soils. Oldeman et al. (1991) reported that of the current 230 Mha of irrigated land, 45 Mha is salt-affected and of almost 1,500 Mha of dry land agriculture, 32 Mha are salt-affected to varying degrees by human-induced processes. Thus, globally almost 77 Mha of land is salty due to human-induced salinization (Oldeman et al. 1991; Bridges and Oldeman 1999). Recent figures indicate that in India salt-affected soils are distributed almost throughout the country (Fig. 9.1) over about 6.75 Mha (Table 9.1), 3.8 Mha being sodic and rest saline.

Saline and Sodic (alkali) Waters

Beneath many of the world's deserts are reserves of saline water. These include the Thar Desert of Indian sub-continent, the Arab Desert of the Middle East countries, the Sahara Desert in North Africa, the Kalahari Desert in Southern Africa, the Atacama Desert in South America, the California Desert in North America, and the West Australian Desert. Groundwater surveys in India indicate that poor quality waters being utilized in different states are 25–84 % of the total groundwater development (more in arid and semiarid regions); 84 % in Rajasthan, 62 % in Haryana, 47 % in Uttar Pradesh, 38 % in Karnataka, 30 % in Gujarat, 32 % in Andhra Pradesh, and 25 % in Madhya Pradesh (Minhas 1998). Many more areas with good quality aquifers are endangered with contamination as a consequence of excessive withdrawals of groundwater.

For assessing the quality of irrigation water, main parameters determined are: salt content (EC, dS m^{-1}), sodium adsorption ratio ($SAR = Na^+/\sqrt{[(Ca^{2+} + Mg^{2+})]}$, mol l^{-1}), residual alkalinity [$RSC = (CO_3^{2-} + HCO_3^-) - (Ca^{2+} + Mg^{2+})$ meq l^{-1}], divalent cation ratio ($DCR = \sum M^{2+}/\sum M^{n+}$), and presence of specific ions such as NO_3, F, B, and Se. Based on the characteristic features of majority of groundwaters in use with the farmers in different agroecological regions and the above indices, irrigation waters have been broadly grouped (Minhas and Gupta 1992) into good water ($ECiw < 2$ and $SAR < 10$), saline water ($ECiw > 2$ and $SAR < 10$), high SAR saline water ($ECiw > 4$ and $SAR > 10$), and alkali waters (ECiw variable, SAR variable, and $RSC > 2.5$). Globally, mass (1985, 1990) and Rhoades et al. (1992) produced the exhaustive data for the limits of salt tolerance of plants while in India very useful information has been generated on salinity limits of irrigation waters for different arable crops (Table 9.2), particularly for arid and semi-arid regions.

Natural Vegetation of Salt Lands

Saline habitats are usually characterized by sparse vegetation and highly saline soils are often barren "scalds". Based on their genetic potential to counter the defect of root zone salinity, the plants differ in their capacity to adapt to saline habitats. The capacity to lower the osmotic potential of cell sap, salt exclusion, salt secretion, and succulence are common but differentially expressed attributes of salt land vegetation. Thus, the plants, which are able to grow on saline habitats, possess special adaptive procedures and collectively are called halophytes. Based on the adaptability, Sen et al. (1982) classified the halophytes into the following three categories:

True (obligate) halophytes: Plants mainly attaining optimal growth on saline soil (above 0.5 % NaCl level) e.g. *Suaeda fruticosa, Cressa cretica, Aeluropus lagopoides, Salsola baryosma, Haloxylon recurvum* and *Zygophyllum simplex*.

Facultative halophytes: Those plants which can grow and achieve optimal growth on saline soil (at 0.5 % NaCl level) like true halophytes, as well as on nonsaline soils e.g., *Trianthema triquetra, Tamarix dioica, Salvadora persica,*

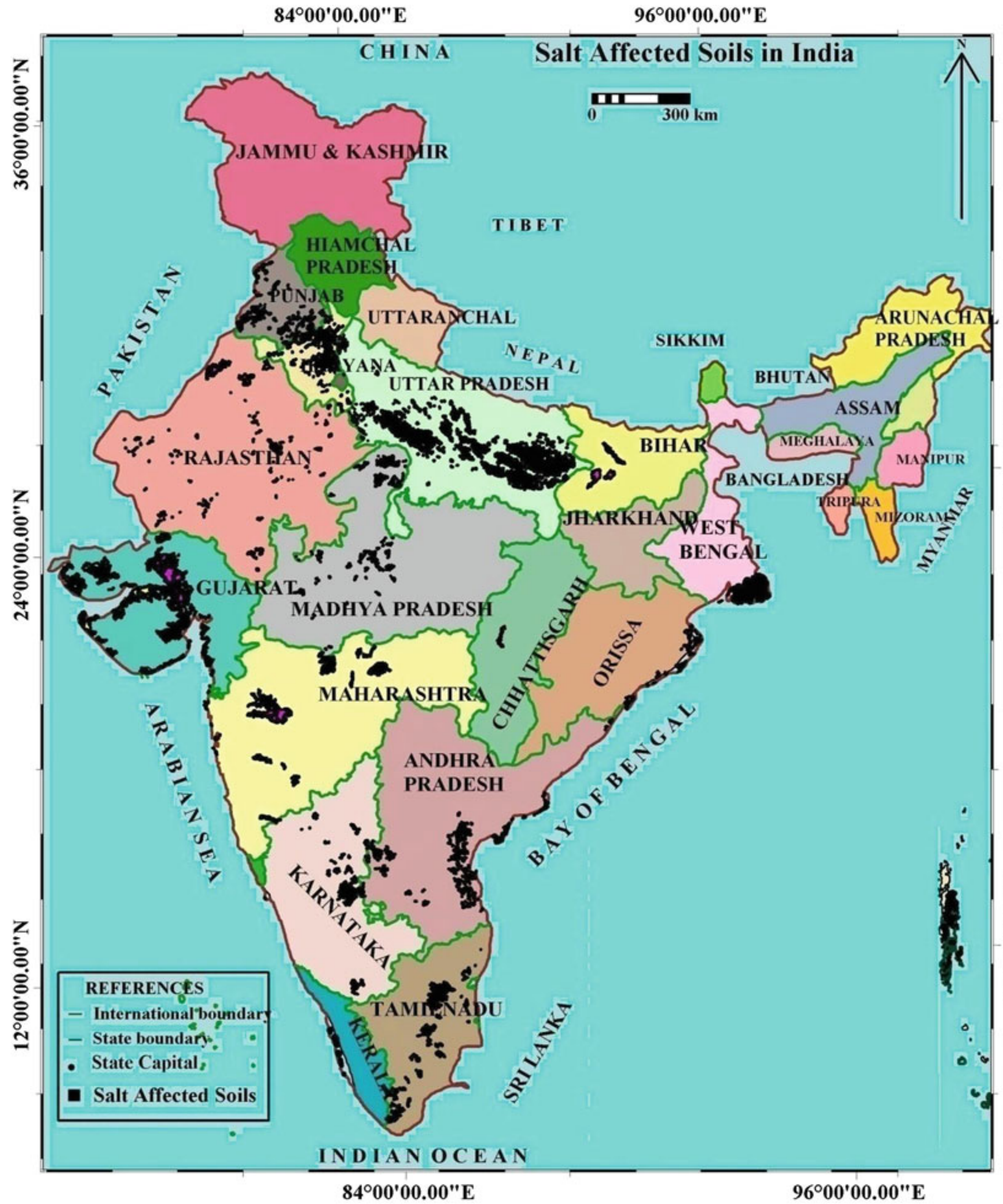

Fig. 9.1 Distribution of salt-affected soils in India (Based on the map prepared by NRSA Hyderabad, CSSRI Karnal, and NBSS & LUP, Nagpur 1997)

Launaea nudicaulis, Eragrostis pilosa, and many others.

Glycophytes or transitional halophytes: Plants of nonsaline habitats, which always grow and achieve optimal growth at nonsaline niches of the salt basins. For example, *Haloxylon salicornicum, Sporobolus helvolus, S. marginatus*, etc.

Dagar (1982, 1995, 2003, 2005b, 2006, 2008) described the halophytic vegetation inhabitating the mangrove swamps, littoral woodlands (behind mangroves), coastal salt marshes, saline

Table 9.1 Extent of salt-affected soils in India (000 h[a])

States	Sodic	Saline	Total
Andhra Pradesh	196.6	77.6	274.2
Andaman & Nicobar Islands	0	77.0	77.0
Bihar	105.9	47.3	153.2
Gujarat	541.4	1,680.6	2,222.0
Haryana	183.4	49.2	232.6
Jammu & Kashmir	17.5	0	17.5
Karnataka	148.1	1.9	150.0
Kerala	0	20.0	20.0
Madhya Pradesh	139.7	0	139.7
Maharashtra	422.7	184.1	606.8
Orissa	0	147.1	147.1
Punjab	151.7	0	151.7
Rajasthan	179.4	195.6	375.0
Tamil Nadu	354.8	13.2	368.0
Uttar Pradesh	1,347.0	22.0	1,369.0
West Bengal	0	441.3	441.3
Total	3,788.2	2,956.9	6745.1
		(Say 6.75 Mha)	

Source Mandal et al. (2010). (Based on NRSA data of 1996 and recon ciled during 2006 jointly by NRSA, CSSRI and NBSS & LUP, Nagpur)
[a] Exact figures may slightly differ because of rounding off the data

Table 9.2 Guidelines for saline irrigation waters (RSC < 2.5 me l^{-1}) in India

Soil texture (% clay)	Crop tolerance	Upper limits of ECiw (dS m^{-1}) in rainfall region (mm)		
		<350 mm	350–550 mm	550–750 mm
Fine soil (>30 %)	Sensitive	1.0	1.0	1.5
	Semi-tolerant	1.5	2.0	3.0
	Tolerant	2.0	3.0	4.5
Moderately fine soil (20–30 %)	Sensitive	1.5	2.0	2.5
	Semi-tolerant	2.0	3.0	4.5
	Tolerant	4.0	6.0	8.0
Moderately coarse soil (10–20 %)	Sensitive	2.0	2.5	3.0
	Semi-tolerant	4.0	6.0	8.0
	Tolerant	6.0	8.0	10.0
Coarse soil (<10 %)	Sensitive	–	3.0	3.0
	Semi-tolerant	6.0	7.5	9.0
	Tolerant	8.0	10.0	12.5

Source Minhas and Gupta (1992)

sand formations (beaches), inland salt marshes, and alkali/sodic lands.

Recently, it has been felt that these lands can effectively be utilized for salt-tolerant biological systems (Pasternak 1982; Le Houe'rou 1986; NAS 1990; Lieth and Al Masoom 1993; Dagar 1991, 1994, 1996, 2003, 2005a, b, 2006; Dagar and Singh 1998, 2007). For evaluation and identification of suitable salt-tolerant species for a specific situation, it is important to have a catalog of salt-tolerant species describing their distribution with respect to ecoclimate, habitat, and soil salinity.

Aronson (1989) set the criterion of ECe/ECiw (soil/irrigation water) of 7–8 dS m^{-1} salinity for a species to be designated as salt-tolerant, when plants were found growing well on this salinity without any significant yield reduction. Following the same criteria, Dagar (2003) and Dagar and Singh (2007) described the vegetation of saline habitats in India. Halophytes are not a single taxonomic group, but are represented by several thousand species of forbs, grasses, shrubs, and trees. These represent a wide range of habitats and there are about 1,560 species in which salt tolerance has already evolved (Aronson 1989).

Of the 500 halophytic genera of flowering plants listed in Aronson's database of 1989, almost 50 % belong to only 20 plant families. Chenopodiaceae (368 species) and Poaceae (136 species) have the largest number of species followed by Fabaceae (82), Asteraceae (62), Plumbaginaceae (58), Aizoaceae (52), Cyperaceae and Papilionaceae (46 each), Tamaricaceae (32), Zygophyllaceae (28), and Arecaceae and Mimosaceae (21 species each). In India, Dagar (2003) and Dagar and Singh (2007) have documented 1,140 species represented by 541 genera and 131 families of flowering plants distributed in saline and waterlogged including mangrove habitats.

The sodic soils support very restricted natural vegetation, comprising only a few species. *Prosopis juliflora* (an introduced species) has gregariously established widely especially on abandoned lands and along road sides. Among other species *Acacia nilotica, Capparis decidua, C. sepiaria, Salvadora oleoides, S. persica* and *Clerodendrum phlomidis* are prominent woody species on very high pH soils while *Acacia leucophloea, A. eburnea, Mimosa hamata, Prosopis cineraria, Butea monosperma, Diospyros tomentosa, Balanites roxburghii* and *Maytenus emarginata* are frequent on slightly low (up to 9) pH. Among herbaceous species *Sporobolus marginatus, S. coromandelianus, Desmostachya bipinnata, Chloris virgata, C. barbata, Leptochloa fusca, Cynodon dactylon, Kochia indica, Suaeda fruticosa, S. maritima, Pluchea lanceolata,* and *Portuleca oleracea* are important among herbaceous species.

In saline areas, *Suaeda fruticosa, Aeluropus lagopoides, Salsola baryosma, Haloxylon salicornicum, H. recurvum, Heliotropium curassavicum, Cressa cretica*, and *Sporobolus marginatus* are predominant in high salinity areas. Many salt-tolerant species such as *Sporobolus diander, S. tremulus, Eleusine compressa, Solanum xanthocarpum, Zygophyllum simplex, Portulaca oleracea, Fagonia cretica*, and *Dactyloctenium aegyptium* are frequently found on saline patches. Among woody species, *Prosopis juliflora* and *Salvadora persica* are dominant while *Ziziphus nummularia* is also quite frequent.

Along the Indian coast in tidal zone mangroves (species of *Avicennia, Aegiceras, Ceriops, Rhizophora, Bruguiera, Sonneratia, Heriteria, Excoecaria, Scyphiphora, Nypa,* and *Xylocarpus*); and mangrove associates such as *Terminalia catappa, Pongamia pinnata, Cynometra ramiflora, Pandanus spp., Salvadora persica, Arthrocnemum indicum, Acrostichum aureum, Barringtonia acutangula, Brownlowia tersa, Caesalpinia crista, Calophyllum inophyllum, Clerodendron inerme, Dalbergia spinosa, Hibiscus tiliaceus, Ochrosia oppositifolia, Salicornia brachiata,* and *Wrightia tomentosa* are predominant. Cultivaed species such as *Casuarina equisetifolia, Anacardium occidentale, Acacia auriculaeformis, Azadirachta indica, Cocos nucifera, Eucalyptus* spp., and *Pandanus* sp. are frequently found grown especially along the beaches of eastern coast.

Agroforestry for Salty Environments

For the successful establishment of agroforestry systems, site-specific system is required for management of salinity. This is because of the reason that the tree component of the system is (i) deep rooted, thus demanding characteristics of even deeper soil strata, and (ii) long-lived and thus major changes in salts may occur from establishment to maturity. Moreover, the systems on the most sites have to thrive on natural rainfall and other climatic conditions as against the preferential input of amendments, nutrients, water, etc. for crop production activities. The level of productivity is of course the most important criteria for assessing the suitability of agroforestry systems on the normal soils, but their environmental benefits and also the amelioration of soils are given due consideration for greening of salt lands. In addition to other site characteristics like climate and soil types, the nature of salts also defines the performance of different plant species. Therefore, the performance of species is discussed separately under sodic/alkali and saline conditions.

Developing Suitable Agroforestry Practices/Systems for Alkali/Sodic Soils

Alkali soils have a compact hard sub-surface layer or a caliche (calcite) bed (of nodulated or amorphous $CaCO_3$) in lower depths, which imposes physical impediment to root penetration/development and correspondingly poor aeration when wet (due to dispersion of clay colloids by sodium); nutrition imbalances including deficiencies of zinc, calcium, and magnesium (due to high pH); and toxicity of specifications (e.g., sodium and boron). Unlike soil reclamation for arable crops, where only plough layer is sought to be improved in the first instance, deep-rooted trees require reclamation of the soil to lower depths. The planting technique should further ensure efficient utilization of rainwater, and leaching of reaction products after interaction of amendments and to root development in the soil profile, soil structural improvement for increased water retention to encourage rapid root penetration in the vertical rather than horizontal direction, and minimize direct sodium toxicity hazards. Keeping this in view, several attempts were made to develop suitable techniques for planting trees on such lands. Several forest and fruit trees, grasses, medicinal and aromatic plants, nonconventional, and arable species were evaluated for their tolerance to sodicity and successful and most suitable species were identified for agroforestry.

Planting Methods for Sodic/Alkali Soils

As discussed earlier, alkali soils have a compact hard sub-surface layer or a caliche (calcite) bed (of nodulated or amorphous $CaCO_3$) in lower depths, which imposes physical impediment to root penetration/development. The viable planting technique should ensure efficient utilization of rainwater and leaching of reaction products after interaction of amendments and help to root development in the soil profile, soil structural improvement for increased water retention to encourage rapid root penetration in the vertical rather than horizontal direction, and minimize direct sodium toxicity hazards. Keeping this view, several attempts were made to develop suitable techniques for planting trees on such lands. In the past, planting methods like pits and trenches of various shapes and sizes were used for raising trees in alkali soils with some intrinsic drawbacks and the difficulties were overcome through the development of tree planting technique termed as the auger hole planting technique as mentioned earlier in this technique the auger is mounted on a tractor and used for making holes of dimensions 20–25 cm diameter and 1.2–1.8 deep (Fig. 9.2). This technique recognizes that in trees, owing to their deep root systems, management of the root zone by modifying the soil environment to greater soil depths using a limited quantity of amendments, has a vital role to play in terms of success in sapling establishment, cost of plantation, and practical adaptability.

Many forests and fruit tree species can be raised on highly alkali soil (pH > 10) but some of the fruit trees like pomegranate (*Punica granatum*) and bael (*Aegle marmelos*) are unable to tolerate water stagnation during rainy season. Raised and sunken bed technique of agroforestry was developed for such situations (Dagar et al.

Fig. 9.2 Making auger holes in alkali soil to pierce *kankar* pan ($CaCO_3$ layer) for planting tree sapling *source* CSSRI, Karnal

2001a). After refilling the auger holes with soil mixture in a leveled field as mentioned in the above-mentioned technique, the auger holes are marked with sticks. Parallel bunds, each of 1–2 m height and 1–2 m width, are then constructed leaving 4–5 m space between them taking soil from interspaces. The seedlings are raised on middle of bund at marked places and small rings are made around seedlings for initial irrigation. The interspaces can be cultivated growing water-loving crops such as *kallar* grass (*Leptochloa fusca*) or rice (salt-tolerant variety like CSR 10, CSR 13, CSR 30, CSR 36) during rainy season and Egyptian clover (*Trifolium alexandrinum*) or wheat (vars. KRL 1–4, KRL 19, KRL 210, KRL 213) during winter.

Afforestation of Sodic Soils

During the last three decades, numbers of studies were conducted in India to establish positive benefits of the recent planting techniques and to identify most suitable species for alkali soils. Chaturvedi (1984) reported that a 30 % reduction in biomass was observed at pH 10 as compared to pH 7 in tree species like *Acacia nilotica, Terminalia arjuna* and *Pongamia pinnata* whereas at pH 9.5 in *Eucalyptus tereticornis*, *Casuarina equisetifolia* and *Acacia nilotica* could grow well in soil with ESP 30.6, whereas *Pongamia pinnata* and *Dalbergia sissoo* survived only up to pH 9.5 and ESP of 15.2 (Yadav and Singh 1986). Based on the performance of tree saplings planted in soils of different pH (7–12), relative tolerance was reported (Singh et al. 1987) in the order: *Prosopis juliflora* > *A. nilotica* > *Haplophragma adenophyllum* > *Albizia lebbeck* > *Syzygium cuminii*.

In one experiment on high pH (10.3) soil, traditional pit method was compared with auger hole technique (Gill 1985, Gill and Abrol 1993) for establishing *Eucalyptus tereticornis* and *Acacia nilotica* plantations. The results obtained after 6 years of plantation indicated no mortality in both the species when planted with auger hole of 10–15 cm diameter and 120–180 cm depth and confirmed the superiority of the technique to the traditional laborious pit method. Afforestation has tremendous potential for soil amelioration and carbon sequestration not only in aboveground C biomass but also root C biomass in deeper soil depths. *Acacia nilotica* and *Eucalyptus tereticornis* plantations were to have a considerable ameliorative effect on soil properties when planted in alkali soil. Both pH and salinity (EC 1:2) were found to be reduced (Fig. 9.3) significantly. Reduction was greater in the surface soil than at depth. The soil organic carbon content increased to about double the initial value for *Eucalyptus* but tripled under *Acacia* plantation. This was largely due to greater litter accumulation in the *Acacia* stand, the intrinsically higher rates of decomposition and the higher C: N ratio for the litter in *Acacia*. Das and Itnal (1994) reported that organic carbon content was about double in agri-horticultural and agroforesry systems as compared to sole cropping.

Another trial was conducted by Singh et al. (1989) by planting *Prosopis juliflora* on a highly alkali soil. The planting methods compared were auger hole (15 cm diameter, 90 cm deep), pit (30 × 30 × 30 cm), and trench planting (30 cm wide and 30 cm deep dug across the plot). A uniform dose of gypsum at 3 kg per plant was mixed in the dugout soil and refilled in auger holes, pits, and trenches. Later, Singh (1994) extended the site suitability studies to 20 alkali soil sites in Ganga-Yamuna Doab. Barren alkali soils, represented by Natric Comborthids and

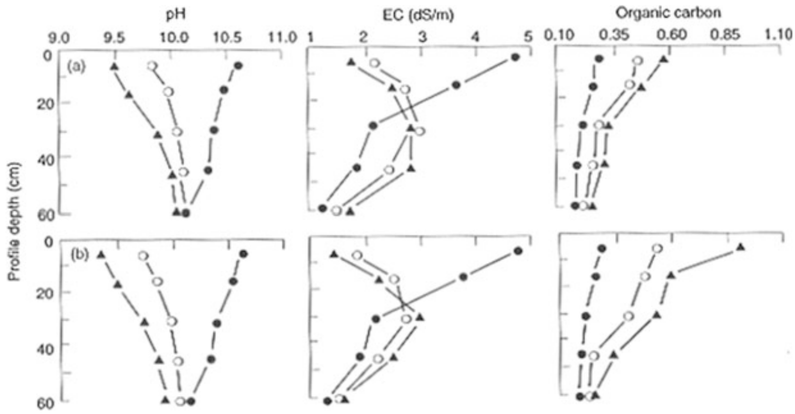

Fig. 9.3 Changes in pH (in 1:2 suspension), electrical conductivity EC (in 1:2 suspension), and percentage organic carbon with soil depth under **a** *Eucalyptus tereticorrais* and **b** *Acacia nilotica* plantations before planting (● = 1st year), after 2 years growth (○), and after 4 years (▲). Modified from Gill and Abrol (1993)

Calciorthids, had pH of 10–10.5, ESP of 60–95, and ECe between 1 and 43 dS m^{-1} and constituted mainly by carbonates and biocarbonates of sodium. *Prosopis juliflora* was found to grow in typic Natrutalfs with a maximum pH of 10.0, ESP up to 60, and ECe < 3 dS m^{-1} in the rooting zone, even though the top 44 cm of soil had pH 10.3, ESP of 70, and ECe at 12 dS m^{-1}. Other planted species failed to grow in this soil. Along with some natural vegetation, *P. juliflora* and *A. nilotica* established well on typic Natrustalfs with an average pH of 9.5, ESP 50, and ECe 10 dS m^{-1}. Other species like *Dalbergia sissoo, Pongamia pinnata, Albizia lebbeck, Terminalia arjuna, Butea monosperma, Capparis decidua* and *Salvadora persica* did well on soil with a pH < 9.1, ESP up to 44 and ECe up to 7.5 dS m^{-1}. The growth of all these species except *P. juliflora* was arrested with a *kankar* pan within 80 cm soil depth. In one study, Singh et al. (1993) observed that 6-year-old plantations of *Prosopis juliflora*, *Acacia nilotica*, *Casuarina equisetifolia*, and *Eucalyptus tereticornis* a biomass (firewood + small timber) of about 26, 21, 19, and 15 t ha^{-1} per annum, respectively, was obtained (Table 9.3) when planted with auger hole technique.

Many workers (Chhabra et al. 1987; Singh et al. 1988a, b, 1991, 1997; Dagar et al. 2001; Singh and Dagar 2005; Singh et al. 2008) conducted experiments with different combinations and doses of amendments applied in auger holes and concluded that original soil mixed up with 3–5 kg gypsum (50 % of gypsum requirement in the auger hole) and 8–10 kg farm yard manure (FYM) in each auger hole (to meet the nutrient requirement of sapling) is most suitable for alkali soils of high pH (up to 10). Application of small dose of nitrogen in the auger hole filling mixture and its regular application every year

Table 9.3 Growth performance and biomass production by four trees raised on high pH soil

Growth parameters	*Prosopis juliflora*	*Acacia nilotica*	*Casuarina equisetifolia*	*Eucalyptus tereticornis*
Height (m)	12.9	11.6	14.5	14.9
DBH (cm)	12.5	13.6	12.0	11.0
Bole weight (kg $tree^{-1}$)	112.6	85.4	84.2	65.6
Branches + leaves (kg $tree^{-1}$)	43.2	43.8	28.4	23.5

Source Singh et al. (1993)

thereafter (25 g both in monsoon and winter) proved beneficial in nonleguminous tree species. Alkali soils are usually deficit in zinc; hence, application of about 25 g $ZnSO_4$ per auger hole is essential. Rings of about 1 m diameter are made around the auger holes and 7 to 9-month-old saplings of salt-tolerant tree species are planted just after rains during monsoon season. Two to three irrigations are applied with buckets. Later on, the rings are connected with furrow channels for irrigation (if available). Spacing of 4 m × 4 m between plants and rows is ideal. For fuelwood plantation, close spacing of 2 m × 2 m may be kept. After 2–3 years, the alternate trees may be harvested for fuelwood. For agroforestry purposes, wider spaces between rows help to grow arable crops in interspaces.

In a well-conducted site-specific field study at Saraswati in semi-arid Haryana, out of 30 tree species planted in highly alkali soil (pH of profile 10.1–10.6), only three species *Prosopis juliflora* (Fig. 9.4), *Acacia nilotica,* and *Tamarix articulata* were found economically suitable with biomass production of 51, 70, and 93 t ha^{-1}, respectively, in 7 years (Dagar et al. 2001; Singh and Dagar 2005). *Tamarix articulata* ameliorated the soil by inducing the maximum reduction of exchangeable sodium percentage (ESP) and pH values followed by *P. juliflora* and *A. nilotica*. Increase in organic carbon in the surface 15 cm layer under respective species was 0.23, 0.26, and 0.10 %. At the same site, species of *Prosopis* such as *P. juliflora*, *P. alba, P. articulata, P. levigata*, and *P. nigra* produced high biomass. All these can successfully be used as energy plantations and even in gassy-fires to generate electricity in rural employment programmes.

From a long-term experiment, Singh et al. (2008) reported a total biomass ranging from 19.2 to 56.5 t ha^{-1} from different species after 10 years of plantation in high sodic soil of pH 10.6 in Uttar Pradesh (Fig. 9.5). These tree species improved soil in terms of reduction of pH and exchangeable sodium percentage (ESP), and increase in organic carbon significantly (Table 9.4). When harvested after 14 years of plantation, maximum biomass production was achieved in *Eucalyptus teretcornis, Acacia nilotica, Prosopis juliflora* and *Casuarina equisetifolia* giving 231, 217, 208, and 197 kg bole weight per plant, respectively, whereas *Prosopis alba, Pithecellobium dulce, Terminalia arjuna, Pongamia pinnata, Azhadirachta indica* and *Cassia siamea* provided relatively lower

Fig. 9.4 Plantation (*Prosopis juliflora*) in highly sodic soil at Saraswati Range Forest site (The original barren sodic land is in front) *source* Singh and Dagar (2005)

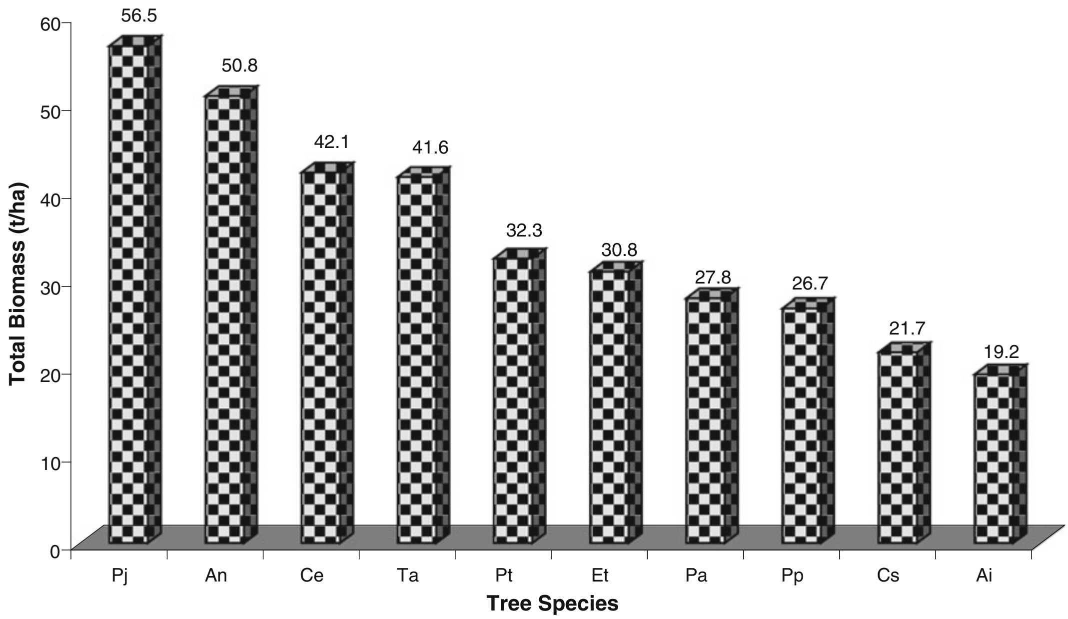

Fig. 9.5 Above-ground air-dried biomass (t ha^{-1}) of different trees grown in sodic soil Pj *Prosopis juliflora*, An *Acacia nilotica*, Ce *Casuarina equisetifolia*, Ta *Terminalia arjuna*, Pd *Pithecellobium dulce*, Et *Eucalyptus tereticornis*, Pa *Prosopis alba*, Pp *Pongamia pinnata*, Cs *Cassia siamea,* Ai *Azadirachta indica* (*Source* Singh et al. (2008))

bole weight of 133, 100, 97, 84, 83, and 52 kg per plant, respectively.

Singh and Gill (1992) reported that 20-year-old plantations of *P. juliflora, Acacia nilotica, Eucalyptus tereticornis*, *Albizia lebbeck* and *Terminalia arjuna* ameliorated the alkali soil through litter and root decomposition (Table 9.5) to the extent that arable crops could be grown successfully on this soil.

While evaluating different species on alkali soils it was observed that there was heterogeneity in soil as this is a well-known fact that alkali soils have patches of different pH in the same field. At the same time, there was also difference in the growth of trees of the same species because large interspecific and intraspecific differences are found in many genera. In species such as *Eucalyptus camaldulensis* and *E. occidentalis* intraspecific variation is so wide that to a tolerance classification at species level appears to be dubious. Researchers have exploited this intraspecific variation and selected individual plants with high salt tolerance from different areas. These selections have been propagated vegetatively through micropropagation or cuttings. In India, plantations established with nursery seedlings from available seed sources showed very high genetic variation and poor productivity; hence, a well-thought strategy with clear-cut objectives of developing genetically improved, uniform, fast growing, high yielding, disease-resistant, and locality-specific *Eucalyptus* clones was finalized at ITC Bhadrachalam Paper Boards Ltd., Andhra Pradesh in 1987 and several clones were tested at 82 different locations. A comparison between plantation from seed source and clonal stock is shown in Fig. 9.6.

From 1987 to 1995, 6,185 farmers in 1,138 villages were assisted to promote 7,441 ha of *Eucalyptus* plantations with 17.4 million seedlings. More than 613 selections of candidate plus trees (CPTs) of *Eucalyptus tereticornis*, *E. camaldulensis*, and Mysore Gum (*Eucalyptus* Hybrids—*E. botrryoides* x *E. tereticornis* and *E. robusta* x *E. tereticornis* from Mysore) have been cloned and are being evaluated scientifically at a number of locations. On the basis of their performance, 89 clones have been identified (Piare Lal et al. 1997; Piare Lal 2006) which are fast growing and disease resistant with productivity

Table 9.4 Ameliorative effects (after 10 years) of different species

Tree species	pH (1:2)	EC_2 (dS m^{-1})	OC (g kg^{-1})	ESP	Bulk density (t m^3)
Initial	10.6	1.43	0.8	89	1.57
Terminalia arjuna	9.8	0.39	3.5	60	1.47
Azadirachta indica	9.8	0.33	2.7	56	1.48
Prosopis juliflora	9.5	0.30	4.3	51	1.32
Pongamia pinnata	9.7	0.61	4.0	54	1.36
Casuarina equisetifolia	10.0	1.26	3.6	71	1.21
Prosopis alba	9.9	0.63	3.3	64	1.37
Acacia nilotica	9.7	0.77	3.5	56	1.29
Eucalyptus tereticornis	9.8	0.86	2.4	62	1.38
Pithecellobium dulce	9.9	0.70	2.7	65	1.25
Cassia siamea	10.0	0.69	2.6	71	1.46
LSD ($p = 0.05$)	0.26	0.31	1.6	4	0.05

Source Singh et al. (2008)

Table 9.5 Ameliorating effect of 20-year-old trees in alkali soils on 0–15 cm soil layer

Species	pH_2	EC_2 (dS m^{-1})	Organic C (%)	Available (kg ha^{-1})	
				P	K
Acacia nilotica	8.4	0.25	0.85	59	499
Eucalyptus tereticornis	8.5	0.44	0.66	33	359
Prosopis juliflora	7.5	0.51	0.93	111	702
Terminalia arjuna	7.9	0.32	0.86	68	410
Albizia lebbeck	7.9	0.32	0.62	43	387
Initial	10.2	1.18	0.22	28	278

Source Singh and Gill (1992)

ranging from 12 to 58 m^3 ha^{-1} $year^{-1}$ under nonirrigated conditions compared to 6–10 m^3 $ha^{-1}year^{-1}$ from seed-originated plantations.

After seeing the progress of these trials, attempts were made by the Forest Department of Haryana and some clones were introduced at Seonthi Research Station in Kurukshetra District from Bhadrachalam in 1993. The Forest Department encouraged farmers of Ambala district in 1999 under Social Forestry Programme by planting clonal *Eucalyptus* in alkali soil (pH up to 9.6) after bringing from Bhadrachalam, Andhra Pradesh. Some progressive farmers planted three clones (C-3, C-7, and C-10) along with seeded *Eucalyptus* under rain-fed condition. The performance of these plantations showed that the farmers could easily get 29.5 t ha^{-1} $year^{-1}$ wood biomass. They earned net profit of INR 52,738 (1US \$ = 45 INR) ha^{-1} $year^{-1}$ (Forest News 2005). The results clearly indicated that cloned *Eucalyptus* plantations have more survival, height, and girth as compared to seed-origin plantations (Fig. 9.6). Moreover, the coefficient of variation in all these parameters in cloned plantations is very less as compared to seeded showing the uniformity in these plantations. In addition to this, the crown of clonal plants is thin which facilitates more sunlight to the ground crops. Moreover, these have been developed from superior genotypes with better adaptability, faster growth, higher yield, good bole form, and resistance to major known diseases like *Cylindrocladium* blight and wind damage. Thus, the planting of cloned *Eucalyptus* may be encouraged in agroforestry plantations. The adoption reflects a great success story of closed plantations on farmers' fields on wider scale.

Further, it has been observed that fruit trees are comparatively less tolerant than some forest trees. Singh and Singh (1990) observed that

Fig. 9.6 *Eucalyptus (Photo Courtsy Dr Piare Lal)* plantations; *Left* Raised from saplings of seed origin; *Right* From cloned saplings

Emblica officinalis, Carissa carandas, Ziziphus mauritiana, Syzygium cuminii, Grewia asiatica, Psidium guajava, Aegle marmelos, and *Vitis vinifera* when grown on alkali soil could produce 6.0–20.5 t ha^{-1} fruits at different pH (Table 9.6).

Out of 10 fruit tree species tested on highly alkali soil (pH > 10) using different soil amendments (Singh et al. 1997; Dagar et al. 2001a; Singh and Dagar 2005), *Ziziphus mauritiana, Syzygium cuminii, Psidium guajava* (Fig. 9.7), *Emblica officinalis* and *Carissa carandas* were found the most successful species showing good growth and also initiated fruit setting after 4–5 years of plantation. After 10 years, these could produce 12–25 t ha^{-1} fruits annually.

On sodic vertisols tree species such as *Prosopis juliflora, Azadirachta indica, Salvadora persica,* and *Acacia nilotica* are found to be highly successful when planted in auger holes. *Cassia siamea* and *Leucaena leucocephala* also performed satisfactorily (Sharma et al. 1992). Species such as Acaciaauriculaeformis, *Dalbergia sissoo, Casuarina equisetifolia, Dendrocalamus strictus* and *Hardwickia binata* did not survive for longer period. Tree species also improved clayey vertisols significantly in terms of reducing soil pH and ESP and increasing soil carbon (Table 9.7).

Based on the evaluation of more than 60 forest and tree species (through series of experimentation on sodic soils), it could be concluded that *Prosopis juliflora* was the best performer for the sodic soils of high pH (> 10) followed by *Tamarix articulata* and *Acacia nilotica*. Species such as *Eucalyptus tereticornis, Terminalia arjuna, Salvadora oleoides, Cordia rothii* and fruit trees (with improved management) such as *Carissa carandus, Emblica officinalis,* and *Psidium guajava* can be grown with great success in moderate alkali soil, preferably at pH around 9.5 or less (Table 9.8).

Silvopastoral Systems

The grazing lands of sodic soils are very poor in forage production under open grazing, but when brought under judicious management these can be explored successfully for sustainable fodder production. Based on a series of long-term experiments (Kumar and Abrol 1983a, b, 1984, 1986; Kumar 1988a, b, 1990, 1998; Singh and Dagar 2005), it was found that Kallar grass (*Leptochloa fusca*) could be rated the most tolerant grass to highly sodic soil and waterlogged conditions as compared to other grasses producing 45 t ha^{-1}

Table 9.6 The fruit yield and optimum sodicity tolerance of some fruit trees when cultivated in alkali soil

Species	Optimum pH of sodicity tolerance	Fruit yield (t ha^{-1})
Emblica officinalis	10.0	20.5
Carissa carandas	10.0	5.2
Ziziphus mauritiana	9.5	15.5
Syzygium cuminii	9.5	16.0
Grewia asiatica	9.2	6.0
Psidium guajava	9.0	12.5
Aegle marmelos	8.5	6.5
Vitis vinifera	9.0	18.3

Source Singh and Singh (1990)

Fig. 9.7 Four-year-old guava (*Psidium guajava*) plantation in highly sodic soil. Source CSSRI, Karnal

green forage without applying any amendment. It produces more biomass in alkali soil than normal soil. It withstands prolonged stagnation of water and also ameliorates soil quickly (Kumar and Abrol 1986). Another interesting grass is Rhodes grass (*Chloris gayana*), which could produce 60–65 t ha^{-1} green biomass and did not show any reduction in biomass up to pH 10, whereas it produced 50 t ha^{-1} forage at pH 10.4 (Kumar 1998). Gutton panic (*Panicum maximum*) produced 60 t ha^{-1} up to pH 9.6 and 45 and 35 t ha^{-1} at pH 10 and 10.4, respectively, and Para grass (*Brachiaria mutica*) produced 90 and 70 t ha^{-1} at pH 9.2 and 9.6, respectively, and 50 and 40 t ha^{-1} at pH 10.0 and 10.4, respectively, showing their potential for sodicity tolerance. *Panicum antidotale, P. laevifolium, P. purpureum*, and *Setaria anceps* were other successful grasses up to soil pH

Table 9.7 Soil properties (0–15 cm soil depth) of alkali black clay soil under different trees after 7 years of plantation

Species	pHs	ECe (dS m^{-1})	ESP	Organic C (%)	Average of N (kg ha^{-1})	Average P_2O_5 (kg ha^{-1})	Hydraulic conductivity
Prosopis juliflora	8.5	1.29	10.2	0.71	263	8.0	0.25
Azadirachta indica	8.5	1.30	14.0	0.62	235	9.6	0.50
Eucalyptus tereticornis	8.2	1.24	20.2	0.67	240	16.8	0.85
Albizia lebbeck	8.5	1.40	20.0	0.57	215	5.6	0.25
Cassia siamea	8.1	1.42	15.6	0.50	235	8.0	0.25
Initial	8.8	4.00	35.0	0.35	185	3.4	Negligible

Source Sharma et al. (1992)

Table 9.8 Relative tolerance of forest and fruit tree species for soil sodicity

Mean pH_2 (0–1.2 m)	Fuelwood/fodder/timber species	Fruit tree species
>10	*Prosopis juliflora, Acacia nilotica, Tamarix articulata*	Not recommended
9.6–10.0	*Eucalyptus tereticornis, Capparis decidua, Pithecellobium dulce, Prosopis alba, P. cineraria, Casuarina equisetifolia*[a], *Salvadora persica, S. oleoides, Terminalia arjuna*	*Carissa carandas, Psidium guajava, Ziziphus mauritiana, Emblica officinalis*[a]
9.1–9.5	*Cordia rothii, Albizia lebbeck, Cassia siamea, Pongamia pinnata, Sesbania sesban, Parkinsonia aculeata, Dalbergia sissoo, Kigelia pinnata, Butea monosperma*	*Punica granatum*[b], *Phoenix dactylifera, Achrus zapota*[a], *Tamarindus indica*[a], *Syzygium cuminii, Feronia limonia*
8.2-9.0	*Grevillea robusta, Azadirachta indica, Melia azedarach, Leucaena leucocephala, Hardwickia binata, Moringa oliefera, Populus deltoides, Tectona grandis*	*Grewia asiatica, Aegle marmelos*[b], *Prunus persica, Pyrus communis, Mangifera indica, Morus alba, Ficus* spp, *Sapindus laurifolius, Vitis vinifera*

[a] (Frost sensitive)
[b] Does not stand water stagnation, may be raised on bunds
Compiled from various sources

9.6. These grasses can be grown successfully with most promising tree species such as *Prosopis juliflora, Acacia nilotica, Tamarix articulata, Casuarina equisetifolia* (susceptible for frost), *Terminalia arjuna*, and *Pongamia pinnata*.

Based on 4 years of study, it was found that on an average 15.6 t ha^{-1} forage of *Leptochloa fusca* could be obtained with *Prosopis juliflora*,, 16.2 t ha^{-1} with *Acacia nilotica*, 17.0 t ha^{-1} with *Dalbergia sissoo*, and 17.4 t ha^{-1} with *Casuarina equisetifolia*. However, among trees *P. juliflora* and *A. nilotica* performed the best followed by *Dalbergia sissoo* and *Casuarina equisetifolia* (Singh and Dagar 2005). Singh et al. (1988, 1989, 1991), Dagar et al. (2001b) and Singh and Dagar (2005) evaluated several tree and grass species for their performance in highly sodic soil and mesquite (*Prosopis juliflora*) and Kallar grass silvopastoral practice were adjudged the most promising for firewood and forage production and also for soil amelioration. *Leptochloa fusca* grown with *P. juliflora* produced 46.5 t ha^{-1} green forage in 15 cuttings over 50-month period without application of any fertilizer or other amendment (Singh et al.

Table 9.9 Biomass production in 6 years by *Prosopis juliflora* and Kallar grass (*Leptochloa fusca*) under different spacing on high pH (10.0–10.2) soils

Spacing	Biomass (t ha^{-1})			
	Prosopis juliflora			Kallar grass
	Lopped	Harvested	Total	
2 m× 2 m	49.1	112.2	161.3	55.6
3 m× 3 m	31.6	55.2	86.8	68.7
4 m× 4 m	25.0	36.1	61.1	80.9

Source Singh et al. (1993)

1988, 1989a, b, 1991, 1993) and *P. juliflora* yielded 161.3 t ha^{-1} air-dried firewood in 6 years when planted at 2 × 2 m^2 spacing besides 55.6 t ha^{-1} *Leptochloa fusca* grass forage (Table 9.9). This system also ameliorated soil to greater extent in terms of reducing soil pH and increasing organic carbon and nutrients (Table 9.10). An associative nitrogen-fixing bacterium, *Azoarcus*, occurs as an endophyte in the roots of *Kallar* grass (*L. fusca*)-a pioneer species of alkali soils that yields 9–12 t ha^{-1} of dry biomass without application of any nitrogen fertilizer, nearly half of the plant N of 90–120 kg ha^{-1} is derived from associative fixation (Malik and Zafar 1984; Malik et al. 1986) and helps the plants survive in adverse habitats. Growth of native nonsymbiotic bacteria is improved by applying amendments (Rao 1998). Symbiotic nitrogen fixation by *Rhizobium* has been extensively investigated in salt-affected soils (Rao and Ghai 1995) and their survival is not a problem as they have considerable tolerance to high pH.

This system improved the soil to such an extent that less tolerant but more palatable fodder species such as Persian clover (*Trifolium resupinatum*), Egyptian clover (*T. alexandrinum*), Lucerene (*Medicago sativa*), and Sweet clover (*Melilotus denticulata*) could be grown under mesquite trees after 52 months producing 23.1, 21.3, 10.3, and 8.0 t ha^{-1} forage, respectively (Singh et al. 1993). The proposed model is shown below:

Sodic land (pH > 10)
↓
Prosopis juliflora + *Leptochloa fusca* grass
↓ 5 years
Replacement of *L. fusca* with *Trifolium resupinatum/Melilotus parviflora/Medicago sativa*
↓ 10 years
Reclaimed land fit for growing almost all crops as intercrops between tree rows.

Grewal et al. (1987) developed a silvopastoral system for rainwater conservation and production of fuel and forage from alkali lands by planting *Acacia nilotica*, *Eucalyptus tereticornis* and *Parkinsonia aculeata* trees on ridges and establishing *kallar* grass (*L. fusca*) in the trenches between ridges. This system conserved rainwater during monsoon, which in turn increased the biomass of trees and intercrops of grasses. In addition to firewood and forage

Table 9.10 Effect of *P. juliflora—L. fusca* silvopastoral system on soil properties (0–15 cm soil depth) of an alkali land

Soil properties	Initial	After 6 years of planting
pH_2	10.3	8.9
EC_2 (dS m^{-1})	2.2	0.36
Organic C (%)	0.18	0.58
Available N (kg ha^{-1})	79	165
Available P (kg ha^{-1})	35	30
Available K (kg ha^{-1})	543	486

Source Singh et al. (1993)

production, this system was found useful in checking runoff and soil loss.

In one silvopastoral experiment conducted by Kaur et al. (2002a, b) on highly sodic soil (pH > 10), the extent of storage of carbon in aboveground parts of the tree + *Desmostachya bipinnata* system (t ha^{-1}) was: 4.95, 6.03, and 14.80 in *Acacia nilotica* + *D. bipinnata*, *Dalbergia sissoo* + *D. bipinnata*, and *Prosopis juliflora* + *D. bipinnata*, respectively, accounting for 66–80 % of total carbon content of the vegetation. The total carbon storage in the tree + *Desmostachya* systems ranged from 6.80 to 18.55 t C ha^{-1} across the treatments. Carbon content in total plant biomass was 1.44 t C ha^{-1} and 12.32 t C ha^{-1} in case of *Dalbergia sissoo* + *Sporobolus marginatus* and *Prosopis juliflora* + *S. marginatus*, respectively (Table 9.11). The amount of total carbon input through net primary production in the trees + *D. bipinnata* systems (t ha^{-1}yr^{-1}) was: 2.81 (*A. nilotica* + *D. bipinnata*), 5.37 (*D. sisoo* + *D. bipinnata*), and 6.50 (*P. juliflora* + *D. bipinnata*). At the same site, Kaur et al. (2002a) also observed a significant relationship between microbial biomass carbon and plant biomass carbon (r = 0.92) as well as the flux of carbon in net primary productivity (r = 0.92). Nitrogen mineralization rates were found greater in silvopastoral systems compared to sole grass stand. Soil organic matter was linearly related to microbial biomass carbon, soil N, and nitrogen mineralization rates (r = 0.95–0.98, $p < 0.01$). Therefore, silvopastoral systems were found to be promising for the highly sodic soils for improving the fertility and carbon sequestration.

In the same study, soil microbial biomass carbon was measured by using the fumigation extraction technique and nitrogen mineralization rate using aerobic incubation method. The microbial biomass carbon in the soil under grasses (*D. bipinnata* and *S. marginatus*) was low. In silvopastoral systems, microbial biomass carbon increased due to the increase in the carbon content in the soil–plant system. A significant relationship was found between microbial biomass carbon and plant biomass carbon (r = 0.83) as well as the flux of carbon in net primary productivity (r = 0.92). Nitrogen mineralization rates were found greater in silvopastoral systems compared to "grass only" systems. Soil organic matter was linearly related to microbial biomass carbon, soil N, and nitrogen mineralization rates (r = 0.95 to 0.98, $p < 0.01$).

The continuing shortage of fuelwood and manures has sparked a renewed interest in woody perennials as a source of biomass and nitrogen. Green-matter production of 17 accessions of *Sesbania* averaged 26 t ha^{-1} (6 t DM) at 54 days of growth, N uptake was 154 kg ha^{-1} and N fixation was 105–150 kg ha^{-1} (Rao and Gill 1993). At 100 days after sowing, green stem and leaf production in semi-reclaimed alkali soil was obtained to be 21.5 and 9.4 t ha^{-1} with a biofertilizer value in leaf and upper tender stems of 125, 5, 81, and 12 kg ha^{-1}, respectively of N, P, K, and S (Rao and Gill 1995). *Sesbania* is also a useful source of firewood and at 200 days after sowing dry stem yield was 20 t ha^{-1} with a calorific value of 4,730 kcal kg^{-1}. Another useful short-duration legume Pigeon pea (*Cajanus cajan*) yielded 9.1 t ha^{-1} dry woody stem and 2 t ha^{-1} litterfall, which led to the recycling of 39.5, 2.1, 7.3, and 2.1 kg ha^{-1} of N, P, K, and S, respectively, to the benefit of next crop in rotation and N fixation in the growing season was 115 kg ha^{-1} (Rao and Gill 1995). Of the various species of perennial *Sesbania*, *S. sesban* had the highest biomass production and nitrogen-fixing ability. The N accumulation in aerial

Table 9.11 Carbon content (t ha^{-1}) of *Acacia nilotica* (An), *Dalbergia sissoo* (Ds), and *Prosopis juliflora* (Pj) along with *Desmostachya bipinnata* (Db) and *Sporobolus marginatus* (Sm) in silvopastoral systems on a sodic soil

Plant component	An + Db	An + Sm	Ds + Db	Ds + Sm	Pj + Db	Pj + Sm
Tree foliage, branches & bole	4.95	-	6.03	0.33	14.80	9.28
Coarse & fine roots	1.48	-	2.06	0.11	3.66	2.80
Grasses	0.37	1.18	1.01	1.00	0.09	0.24

'-'denotes nonsurvival of *A. nilotica* due to high pH
Source Kaur et al. (2002a)

and root parts was 180 and 41 g per tree, amounting to 449 and 102 kg ha^{-1}. In high density plantation managed by coppicing for 6 years, dry biomass production was 25–35 kg ha^{-1}year^{-1} and nitrogen fixation was nearly 350 kg ha^{-1}year^{-1} in the first 3 years and 170–240 kg ha^{-1}year^{-1} in next 3 years (Rao et al. 1990). In a tree-legume (4 years)—cereal crops (6 years) sequential agroforestry system, N fixation by *Sesbania sesban* in the legume phase was 260–330 kg ha^{-1}year^{-1} (Table 9.12). Soil nitrogen enrichment in the 0–60 cm soil layer was 388 kg ha^{-1} and in cereal phase, rice and wheat were grown without application of nitrogen. Total N uptake in six crops each of rice and wheat was higher by 185 kg ha^{-1} in the plots in which *Sesbania* was grown earlier vis-à-vis those maintained fallow. The maximum residual effects were observed in the first 2 years; rice could be sustained at 5.3 t ha^{-1} in subsequent years whereas wheat yields at 1.9 t ha^{-1} were low in comparision with urea fertilization. Even after 6 years of cropping without addition of nitrogen, organic C, available N, and microbial activities were higher in the plots in which *Sesbania* was grown.

The salty soils of black soil zone (saline/sodic vertisols) are generally either contemporary or of secondary origin. The contemporary salty soils exists in the topographic situation having poor drainage conditions. However, the soils that have become sodic due to unjudicious use of irrigation water can be encountered in the irrigation command area. In 14 years of plantation it was found that *P. juliflora* and *Azadirachta indica* were most successful species for these soils. Among grasses, *Aeluropus lagopoides, Leptochloa fusca, Brachiaria mutica, Chloris gayana, Dichanthium annulatum, Bothriochloa pertusa* and species of *Eragrostis, Sporobolus,* and *Panicum* are most successful and form suitable silvopastoral system.

In another experiment on alkaline vertisol it was found that after 7 years of plantations of *P. juliflora* and *Azadirachta indica* forming silvopastoral system with Kallar grass soil pH, ECe, and ESP reduced from 8.8, 4 dS m^{-1} and 35 to 8.5, 1.29 dS m^{-1} and 10, respectively, under *Prosopis*-based system and these values reduced to 8.5, 1.3 dS m^{-1}, and 14, respectively under *Azadirachta* system. The experiments conducted in sodic vertisols with ESP 40 growing grasses like *Leptochloa fusca, Brachiaria mutica*, and *Vetiveria zizanioides*, showed that all these grasses performed well and the forage biomass increased during second year. The uptake of sodium by *L. fusca* was highest followed by *B. mutica* at every stage of cutting. During 3 years, these grasses could remove 144.8, 200.0, and 63.5 kg ha^{-1} sodium from soil, respectively (AICRP 2000–2004).

A large proportion of salt-affected lands (particularly in Indian subcontinent) does not belong to individual farmers, but is either government land or in the custody of village *Panchayats*. Reclamation of such lands for crop production is not feasible because of common property rights. Raising suitable trees and grasses would appear to be a promising use of these lands. As mentioned earlier, the most promising tree species for highly alkali soils such as *Prosopis juliflora, Acacia nilotica*, and *Tamarix articulata* blended with highly salt-

Table 9.12 Nitrogen balance (kg ha^{-1}) in *Sesbania sesban* grown at selected spacings in an alkaline soil

Inter-row spacing (m)→ N (kg ha^{-1}) ↓	0.5	1.0	2.0	3.0
Initial soil N	2,986	3,006	3,026	3,132
Tree biomass N	444	336	237	168
Litter N	247	2,28	243	220
Final soil N	3,221	3,487	3,421	3,574
N balance	+876	+995	+825	+780
N fixation kg ha^{-1}yr^{-1}	292	332	275	260

Source Rao (1998)

tolerant and high biomass producing grass species like *Leptochloa fusca, Brachiaria mutica, Chloris gayana,* and species of *Sporobolus* and *Panicum* form ideal silvopastoral system. The grasses can be managed through "cut and carry" system between the interspaces of trees. Thus, we find that for highly sodic soils as well as alkaline vertisols silvopastoral systems (especially Kallar grass-*Prosopis* based) have shown promise in terms of biomass production as well as soil amelioration.

Performance of Forest and Fruit Trees-Based Cropping Systems (Agri-Silvicultural Systems)

In this land use system, forest or fruit trees are raised in wider spaces (row-to-row 5–6 m, at times even more and plant-to-plant 4–5 m) and the arable crops are cultivated in the interspaces on high pH soils. In one trial, Egyptian clover (*Trifolium alexandrinum*), wheat, rice, onion, and garlic were grown successfully for 3 years in the interspaces of fruit trees *Carissa carandas, Punica granatum, Emblica officinalis, Psidium guajava, Syzygium cuminii* and *Ziziphus mauritiana*; and 10.6–16.7 t ha^{-1} forage from *Leptochloa fusca* grass, 1.6–3.0 t ha^{-1} grains from wheat, 1.8–3.4 t ha^{-1} onion bulb, and 2.3–4.1 t ha^{-1} garlic were harvested (Tomar et al. 2004) showing that during establishment of fruit trees, suitable arable crops can successfully be harvested from the interspaces of trees. As shown earlier, many forests and fruit tree species can be raised in alkali soil (pH up to 9.8) but some of these like pomegranate (*Punica granatum*) and Bael (*Aegle marmelos*) are unable to tolerate water stagnation during rainy season which may be cultivated on raised bunds. Dagar et al. (2001a) planted pomegranate on bunds and water-loving kallar grass (*Leptochloa fusca*) and salt-tolerant rice (variety CSR-30) in sunken beds during rainy season. In winter season, Egyptian clover (*Trifolium alexandrinum*) and wheat (var. KRL 1–4) could be grown in sunken beds. Results showed that on an average, 4.3–4.9 t ha^{-1} rice and 1.2–1.4 t ha^{-1} wheat were obtained. In the second rotation, 21.3–36.8 t ha^{-1} fresh forage of Kallar grass and 44.9– 47.8 t ha^{-1} fresh forage of Egyptian clover were obtained. There was no yield reduction due to plantations at initial stage of growth. Another advantage was that after 2 years, soil amelioration in terms of reduction in soil pH and increase in organic matter and nitrogen contents was significant.

Many progressive farmers of Indo-Gangetic plains like to grow fast-growing trees and intercrops on partial reclaimed soil. To get more income, they reclaim the soil by applying amendment like gypsum before sowing crops. Because of the establishment of several pulpwood industries in Yamunanagar area in Haryana, large number of farmers grow *Populus* and *Eucalyptus* on their farm especially in rice–wheat rotation cropping system both in the field (Fig. 9.8) and as boundary plantations.

Fig. 9.8 Commercial agroforestry plantations in Indo-Gangetic plains *Left Eucalyptus* with wheat; *Right Populus* with wheat (Leaves shedded during winter) (Photo courtsy Dr Pyare Lal)

Singh et al. (1995) evaluated this agroforestry approach on a moderately alkali soil (pH 9.2) in irrigated condition of Haryana by planting three commercial trees namely poplar (*Populus deltoides*), eucalyptus (*Eucalyptus tereticornis*), and kikar (*Acacia nilotica*) in association with rice–wheat, rice–Egyptian clover, pigeonpea/sorghum–mustard rotations, and sole trees and sole crops as control. Results showed that intercrops of Egyptian clover, rice, wheat, and mustard can successfully be grown along with these trees during the initial 3 years (Table 9.13). Later on, these crops may be replaced with shade-loving crops such as turmeric. These intercrops help *Populus* and *Eucalyptus* grow faster but adversely affect the growth of low water demanding trees like *Acacia*. Soil amelioration measured in terms of decrease in pH and improvement in organic carbon and available N, P, and K contents followed the order: *Acacia*-based system > *Populus*-based system > *Eucalyptus*-based system > sole crops (Table 9.14). The benefit: cost ratio was highest (3.30) in case of poplar with rice–wheat followed by poplar with rice–Egyptian clover (2.95), and the lowest (1.76) in *Acacia* with rice–Egyptian clover (Table 9.15). Among trees alone, poplar was most profitable followed by *Acacia* and *Eucalyptus*. Growing trees along with crops should not be viewed only as a better and economically viable in terms of food, fodder, timber, and firewood production system, but also as a promising option to maintain long-term sustainability and also a practical solution for sequestering C in the soil and mitigating climate change.

Singh et al. (1995), Dagar et al. (1995, 2004) and Dagar and Singh (2003, 2004) evaluated the performance of arable crops in the interspaces of several forest and fruit trees such as *Tectona grandis, Ailanthus excelsa, Casuarina equisetifolia*, and *Tamarindus indica* in irrigated system on reclaimed alkali soil and concluded that from irrigation and fertilizer application to crops all the trees were benefitted showing better growth and during initial years of establishment normal crop yield was obtained without any yield reduction but during later stages due to larger canopy there was drastic yield reduction in almost all the crops grown with all the tree species except that the remunerative yield of potato could be obtained under partial shade of *Casuarina* and there was no significant yield reduction as compared to when cultivated in open rather there was no risk of frost under canopy.

Table 9.13 Performance in terms of yield (t ha^{-1}) of different crop rotations with three commercial tree species when grown on partial reclaimed alkali soil for 5 years

Plantations → Crop rotation ↓	*Eucalyptus tereticornis*	*Acacia nilotica*	*Populus daltoides*	Control (without plantation)
Rice–Egyptian clover/cowpea-Egyptian clover Rice (G)	14.4	12.5	11.8	21.6
Egyptian clover (F)	239.7	212.7	234.6	389.1
Cowpea (F)	18.0	4.6	2.5	45.0
Rice–wheat/guinea grass–oats Rice (G)	13.4	11.8	10.3	21.0
Wheat (G)	9.0	8.1	8.4	16.0
Guinea grass (F)	18.1	12.3	2.5	30.0
Oats (F)	23.8	24.0	25.6	42.0
Pigeon pea–mustard/turmeric Pigeon pea (G)	0.7	0.8	0.2	0.7
Mustard (G)	2.3	1.8	2.0	4.0
Sorghum (F)	18.3	8.6	22.8	50.0
Turmeric (R)	22.3	5.9	8.3	22.1

Depictions *G* grain, *F* fodder, *R* rhizome
Source Singh et al. (1997)

Table 9.14 Changes in soil properties (0–30 cm) in 5 years under different tree–crop combinations

Cropping system	Organic carbon (%)	Available nitrogen (kg ha^{-1})
Sole crop	+0.07	+10
Eucalyptus tereticornis based	+0.12	+21
Acacia nilotica based	+0.20	+31
Populus deltoides based	+0.17	+25

Source: Singh et al. (1997)

Table 9.15 Benefit:cost (B:C) ratio, net present worth (NPW), and pay-back period (PBP) of various land uses in three plantations and different intercrops

Land use	B:C	NPW (Indian Rupees)	PBP (Months)
Eucalyptus	1.99	13,618	72
Eucalyptus + rice + Egyptian clover	2.23	48,797	27
Eucalyptus + rice + wheat	2.06	38,820	24
Acacia	2.02	22,569	72
Acacia + rice + Egyptian clover	1.76	31,033	24
Acacia + rice + wheat	1.80	29,347	21
Poplar	2.38	15,807	66
Poplar + rice + Egyptian clover	2.95	80,668	24
Poplar + rice + wheat	3.30	81,804	27
Rice + Egyptian clover	2.39	53,724	–
Rice + wheat	2.79	49,007	–

Source Singh et al. (1997)

In one experiment conducted in Gujarat on alkaline vertisol having ESP values of 25, 40, and 60 it was found that the fruit trees gooseberry (*Emblica officinalis*) and *ber* (*Ziziphus mauritiana*) were the most successful for these soils followed by sapota (*Achrus zapota*). Through series of experiments conducted on raised and sunken beds, it was concluded that both forest tree species such as *Azadirachta indica* and fruit trees like pomegranate (*Punica granatum*), Jamun (*Syzygium cuminii*), and goose berry (*Emblica officinalis*) could successfully be grown on raised bunds and rain-fed rice could be grown during rainy season in sunken beds (CSSRI 2002–2003 to 2012–2013). Seed spices such as fennel (*Foeniculum vulgare*), dill (*Anethum greveolens, A. sowa*), and cumin (*Cuminum cyminum*) and oil crops like sesame (*Sesamum indicum*) could be grown successfully in sunken beds. Castor (*Ricinus communis*) is another successful species for these soils. This technique helps in moisture conservation as in sunken beds rain water accumulates and moisture is retained for a longer period in clayey soil.

Many of the medicinal and aromatic underexplored crops are in great demand for both internal requirements and export. But since these crops are nonconventional in nature, it is not always feasible to produce these on fertile land, which is generally used for arable crops. The marginal lands, specifically the salt lands, where profitable returns are not possible from arable crops, can successfully be utilized for the cultivation of these high value crops with marginal inputs. Results of several experiments conducted by Dagar et al. (2004, 2006a, b) clearly indicated that aromatic grasses such as palmarosa (*Cymbopogon martini*) and lemon grass (*C. flexuosus*) could successfully be grown on moderate alkali soils up to pH 9.2, while vetiver (*Vetiveria zizanioides*) which withstands both high pH and stagnation of water could successfully be grown without significant yield reduction on highly alkali soils. Anwar et al. (1996)

reported safe limit of sodicity tolerace in terms of pH and exchangeable sodium percentage (ESP) to be 9.5 and 55 for both palmarosa and vetiver; 9.0 and 50 for lemon grass; and 10.0 and 55 for Jamrosa (*Cymbopogon khasans*). They also reported pH 9.5 to be a safe limit for German chamomile (*Matricaria chamomilla*) and periwinkle (*Catharanthus roseus*), while safe limit for Rye (*Secale cereale*) for ergot (*Claviceps purpurea*) is reported to be pH 10. Medicinal psyllium (*Plantago ovata*) produced 1.47–1.58 t ha^{-1} unhusked grain at pH 9.2 and 1.03–1.12 t ha^{-1} at pH 9.6 showing its potential at moderate alkali soil (Dagar et al. 2006). *Matricaria chamomilla, Catharanthus roseus*, and *Chrysanthemum indicum* were other interesting medicinal and flower-yielding plants which could be grown on moderate alkali soil (Dagar et al. 2009). All these crops can be blended suitably as intercrops in agroforestry systems on moderate alkali soils.

Agroforestry for Saline Soils

The saline soils suffer from excessive concentration of salts, high water table often leading to water logging and occurrence of poor-quality underground waters in many areas. Poor root zone aeration caused by high water table (water logging) and excess presence of salts, which operate simultaneously, impairs success of plantations on such soils. The planting techniques should be such that salt concentration in the root zone remains at a low level and the plants are able to escape the adverse affects of high salinity.

Developing Suitable Planting Techniques

Through a series of experiments, techniques of plantations on waterlogged saline soils were developed. To provide better aeration and to avoid excessive salinization, planting on high ridges was often considered beneficial for establishing tree plantations on waterlogged saline soils where the salinity is usually more in the surface layers and the same decreases with depth down the water table. On the contrary, the soil moisture is minimum near the surface and maximum in the capillary fringe of water table. Therefore, to encash the advantage of low salinity and better soil moisture regimes in subsurface layers, Tomar and Gupta (1984–1994) tried the sub-surface planting of saplings (at a depth of 30 cm below surface) and compared it with ridge planting (40 cm high). Substantially, higher salts accumulated in the ridges that resulted in poor survival and sapling growth. It was observed that the greater the surface area of the ridge, the more salts accumulated in the surface 1 m root zone of ridge planted trees. Difficulty of conserving rainwater on the ridge tops and the presence of salts causing higher susceptibility to soil erosion were the other disadvantages encountered with ridge planting. In contrast, under the sub-surface planting method, roots were encountering a milder saline transmission zone and were meeting most of their water requirement from the phreatic zone.

The performance of trees was better when planted with sub-surface method but need for spot irrigation was the main problem. This method was then improved upon by planting the saplings in the sole of furrow (60 cm wide and 20 cm deep), which was subsequently used for irrigating the tree saplings. Tomar et al. (1998) conducted a series of long-term experiments in semi-arid regions (average rainfall 630 mm). The soils were sandy loam (Hyperthermic comborthids) containing high concentrations of chlorides and sulfates of sodium, calcium, and magnesium. The soil pH of entire profile was 7.2 and ECe ranged from 25 to 80 dS m^{-1} (average 36.4 dS m^{-1}) in upper 30 cm layer and gradually decreased with depth. Groundwater was highly saline (EC 30 dS m^{-1}) and remained close to ground surface during rainy season. The mean salinity of groundwater fluctuated and was highest (46 dS m^{-1}) during summer and minimum (2 dS m^{-1}) during rainy season.

During these studies, the sub-surface and furrow planting methods were compared with traditional ridge-trench method (Fig. 9.9) and

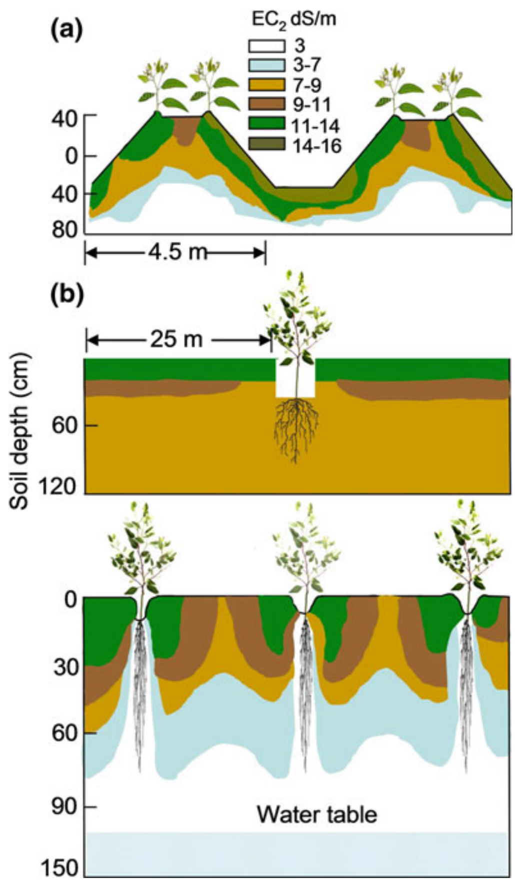

Fig. 9.9 Salt distribution patterns under **a** Ridge-trench, **b** Sub-surface and **c** Furrow planting methods in waterlogged saline soils

more than three dozen woody perennial species were planted under different methods of planting. In the furrow technique, a tractor-driven furrow maker was used to create about 60 cm wide and 20 cm deep furrows. The saplings of a tree species were planted at the base of the furrow. These furrows were subsequently used for irrigating the tree saplings. Establishment of saplings with furrow method was better than sub-surface method of planting. In addition to reducing the water application costs and increasing uniformity in water application, downward and lateral fluxes of water and salts from these furrows helped to create zones of favorable low salinity below their bases, especially when low-salinity irrigation water was used. Creation of such low "salt-niches" favored the establishment of young tree seedlings. With the furrow planting technique, salt concentrations were kept lower in the rooting zone of trees, such that the trees were able to escape the adverse effects of high salinity. Moreover, the furrow system seems more viable than the other techniques from a practical point of view for undertaking large-scale plantation of trees.

Performance of Trees Species and Agroforestry Systems

Singh and Yadav (1985a, b) and Yadav and Singh (1986) observed that *Casuarina equisetifolia* was most tolerant to salinity and was able to survive at ECe 32.5 dS m^{-1}, followed by *Acacia nilotica* and *Pongamia pinnata*. Gupta et al. (1987a, b) reported that salinity for 50 % reduction in the growth of *A. nilotica* and *Eucalyptus camaldulensis* was 5 dS m^{-1} in clay soil, but they grew satisfactorily at ECe 10 dS m^{-1} in sandy soil. They also observed a significant reduction in dry plant weight at ECe 2.5 dS m^{-1} in *Leucaena leucocephala* and *Peltophorum pterocarpum* and at ECe 5 dS m^{-1} in *E. tereticornis* and *Albizia lebbeck*; and at ECe 7 dS m^{-1} in *A. nilotica*. The data on biomass production after 9 years of plantation (Tomar et al. 1998) showed that *P. juliflora* and *Casuarina glauca* was highest (98 and 96 t ha^{-1}), followed by *Acacia nilotica* (52–67 t ha^{-1}) and *A. tortilis* (41 t ha^{-1}) when planted with subsurface or furrow technique showing their potential for saline waterlogged soils (Table 9.16).

On the basis of performance of trees for 6–9 years after planting in saline waterlogged soils (Tomar and Gupta 1984–1994, Tomar and Minhas 1998, Tomar et al. 1994, 1998) it was found that species like *P. juliflora, Tamarix articulata, T. traupii, Acacia farnesiana*, *Parkinsonia aculeata*, *Salvadora persica,* and *S. oleoides* were most tolerant to waterlogged saline soil and could be raised successfully up to salinity levels of ECe 30–40 dS m^{-1}; and species like *A. nilotica, A. tortilis, A. pennatula,*

Table 9.16 Biomass estimation of trees after 9 years of planting on saline soils

Tree species	Method of planting	Range of soil salinity ECe at 0–120 cm depth (dS m^{-1})	Range of water table salinity ECe (dS m^{-1})	Estimated biomass (t ha^{-1})
Acacia nilotica	Subsurface	10.6–25.3	27–33	52
	furrow	11.1–21.0	17–27	67
A. tortilis	Subsurface	6.8–28.1	12–33	41
	ridge	19.7–29.1	12–33	6
Eucalyptus camaldulensis	Furrow	10.0–17.9	10–35	28
Prosopis juliflora	Subsurface	10.3–24.0	32–36	98
	ridge	23.5–57.5	32–36	65
Casuarina equisetifolia	Furrow	5.6–20.7	10–31	28
C. glauca	Furrow	6.5–33.9	12–19	96
C.obesa	Furrow	9.0–19.5	12–19	38
Leucaena leucocephala	Subsurface	6.9–23.9	10–25	30
Tamarix sp.	Furrow	8.2–21.3	10–32	12

Source Tomar et al. (1998)

Casuarina glauca, C. obesa, C. equisetifolia, Callistemon lanceolatus, *Eucalyptus camaldulensis, Feronia limonia, Leucaena leucocephala* and *Ziziphus mauritiana* could be grown on sites with ECe 10–20 dS m^{-1}.

Casuarina glauca was found as an interesting species which withstood prolonged waterlogging and regenerated naturally as many seedlings were found under its canopy (Fig. 9.10). Other species such as *Casuarina cunninghamiana, Eucalyptus tereticornis, Terminalia arjuna, Albizia carbaea, Dalbergia sissoo, Emblica officinalis, Guazuma ulmifolia, Punica granatum, Pongama pinnata, Samanea saman, Acacia catechu, Syzygium cuminii*, and *Tamarindus indica* could be grown satisfactorily only at ECe < 10 dS m^{-1}. Based on the salinity level at which growth of species was satisfactory, tree species have been grouped (Tomar et al. 1998) into highly tolerant, tolerant, and moderately tolerant categories (Table 9.17).

Fig. 9.10 *Casuarina glauca* on highly waterlogged saline soil (Under canopy are regenerated seedlings)

Silvopastoral Systems

In waterlogged saline areas, many grasses such as *Leptochloa fusca*, species of *Aeluropus, Eragrostis, Sporobolus, Chloris, Panicum, Brachiaria* etc. can successfully be cultivated along with salt-tolerant trees and salty bushes such as *Atriplex, Kochia* and *Salvadora* constituting a viable and sustainable silvopastoral

Table 9.17 Relative salt tolerance by different tree species established with saline water on saline soils

Range of soil ECe ($dS\ m^{-1}$)	Tree species
>35 (highly tolerant)	*Prosopis juliflora, Salvadora persica, S. oleoides, Tamarix ericoides, T. troupii*
25–35 (tolerant)	*Tamarix articulata, Acacia farnesiana, Parkinsonia aculeata*
15–25 (moderately tolerant)	*Casuarina (glauca, obesa, equiselifolia), Acacia tortilis, A. nilotica, Callistemon lanceolatus, Pongamia pinnata, Eucalyptus camaldulensis, Crescentia alata, Albizia lebbeck*
10–15 (less tolerant)	*Casuarina cunninghamiana, Eucalyptus tereticornis, Acacia catechu, A. ampliceps, A. eburnea, A. leucophloea, Terminalia arjuna, Samanea saman, Albizia procera, Borassus flabellifer, Prosopis cineraria, Azadirachta indica, Dendrocalamus strictus, Butea monosperma, Cassia siamea, Feronia limonia, Leucaena leucocephala, Tamarindus indica, Guazuma ulmifolia, Ailanthus excelsa, Dichrostachys cinerea, Balanites roxburghii, Maytenus emarginata, Dalbergia sissoo, Salix babylonica*

Source Tomar et al. (1998)

system to sustain live stock productivity. As advocated earlier, *Leptochloa fusca* grass was found to have special advantages in terms of forage production from stagnant waters and having no ill effects on animal health and playing role in soil amelioration. *Aeluropus lagopoides, Sporobolus helvolus, Cynodon dactylon, Brachiaria ramosa, Paspalum* spp., *Echinochloa colonum, E. crusgalli, Dichanthium annulatum, Digitaria ciliaris, Vetiveria zizanioides*, and *Eragrostis* sp. are important grasses which are tolerant to both salinity and stagnation of water and can successfully be grown in silvopastoral systems on these habitats. Species of *Ziziphus, Atriplex, Kochia, Suaeda, Salsola, Haloxylon* and *Salvadora* are prominent forage shrubs of saline regions and relished by camel, sheep and goats (Dagar 2003, 2005b).

Now a days, in search for potential halophytic crops, work is progressing in number of countries and a number of potential halophytic genera have been identified which include *Acacia, Arthrocnemum, Atriplex, Avicennia, Batis, Bruguera, Cassia, Casuarina, Ceriops, Chloris, Coccoloba, Cressa, Crithmum, Distichlis, Grindelia, Juncus, Kochia, Kosteletzkya, Leptochloa, Limonium, Lumnitzera, Maireana, Pongamia, Panicum, Porterasia, Prosopis, Rhizophora, Salicornia, Salvadora, Simmondsia, Sonneratia, Spergularia, Sporobolus, Suaeda, Taxodium, Thinopyrum, Xylocarpus, Ziziphus*, and *Zostera* to name a few. In India, species of *Phragmites, Rumex, Polygonum, Typha, Coix, Brachiaria, Paspalum, Echinochloa, Panicum, Scirpus, Cyperus, Saccharum*, and *Vetiveria* are among the predominant herbaceous/grasses and species of *Salicornia, Suaeda, Haloxylon, Salsola, Tamarix*, and *Ipomoea* are prominent shrubs or undershrubs found in waterlogged saline situations (Dagar 2003, Dagar and Singh 2007). *Paspalum vaginatum* has an amazing ability to thrive in wet salty areas. *Leptochloa fusca, Brachiaria mutica*, and species of *Paspalum* are excellent fodder grasses which can be cultivated under waterlogged situations in the Indian subcontinent. *Juncus rigidus* and *J. acutus* can successfully be explored for paper and fiber making. *Vetiveria zizanioides*, a tall aromatic grass of waterlogged areas, may be propagated from rootstocks both for fodder and aromatic oil from its roots.

Most of the area in Rann of Kutchh along Gujarat is highly saline and because of low rainfall and high evapotranspiration, the problem becomes more severe. In many areas, natural salt is prepared in evaporation saltpans. *Prosopis juliflora, Salvadora persica, Tamarix articulata, T. troupii* and many halophytes are found growing naturally in these areas with stunted growth. A silvopastoral system may be developed incorporating suitable salt-tolerant forages such as species of *Atriplex*, *Kochia indica,*

Fig. 9.11 *Salvadora persica* on highly saline vertisol

Aeluropus lagopoides, Dichanthium annulatum, Leptochloa fusca, and *Sporobolus helvolus*. High value trees such as *Salvadora persica, Pongamia pinnata* and *Terminalia catappa* and firewood trees like *P. juliflora, Acacia nilotica*, and *Casuarina glauca* may be raised in furrows and above-mentioned grasses in interspaces. Oil-yielding *Salicornia begonia* is being grown at many places as industrial crop. Oil-yielding saltbush *Salvadora persica* performed well both in dry as well as waterlogged situations in saline soils (Fig. 9.11). In a study, *S. persica* based silvopastoral system was developed with *Leptochloa fusca, Eragrostis* sp., and *Dichanthium annulatum* forage grasses on clay loam saline vertisol (clay 40 %, silt 31 %, sand 29 %; pH ranging from 7.2 to 8.9; ECe from 25–70 dS m^{-1}) in Gujarat. The underground water was 0.5–2 m from surface with EC_{iw} ranging from 55 to 60 dS m^{-1}. Based on growth pattern in terms of height, canopy spread, and seed yield, a planting density of 4 m × 4 m was found as optimum for *S. persica*. During fourth year, the seed yield of *Salvadora persica* ranged form 1.84 to 2.65 t ha^{-1} with oil contents ranging from 576 to 868 kg ha^{-1} (Table 9.18) at different salinity levels (Rao et al. 2003). These grasses, (*L. fusca*, *D. annulatum*, and *Eragrostis* sp.) when planted on 45 cm high ridges, could produce 3.17, 1.85, and 1.09 t ha^{-1} forage, respectively. When planted in furrows, these could yield 3.75, 1.76, and 0.54 t ha^{-1}, respectively, showing their potential for these highly degraded lands.

Multienterprise/Integrated Farming Systems

In India, marginal and small categories of farmers, representing more than 86 % of farm families with holding size below 1.2 ha, are living in risk-prone diverse production conditions. At times, the land is quite degraded due to sodicity or salinity problems. Small and fragmented land holdings do not allow these farmers to have better independent farm resources. To fulfill the basic needs of households including food (cereals, pulses, oil seeds, milk, fruit, honey, fish, meat, etc.) for human consumption, feed and fodder for cattle, fuel and fiber, a well-focused attention toward Integrated Farming System (IFS) research is warranted. Scattered experiments based on IFS approach have been carried out in the country over the years (Balusamy et al. 2003; Singh et al. 2008, 2011; Gill et al. 2009) but the findings of these activities could not be converted into recommendations and failed to reach the real stakeholders. This fact was realized by both the Planning Commission and ICAR; and Project Directorate of Cropping System was renamed as Project Directorate of Farming System Research (PDFSR) with changed mandate in 2009. Research findings of a project on “Development of an integrated farming system model for small land holders of western plain zones of Uttar Pradesh” carried out during 2004–2010, revealed that IFS approach applied on 1.5 ha irrigated land, besides fulfilling all the requirements of seven members household food and fodder demand inclusive cost of production, could create an additional average annual savings of INR 47,000 in the first 4 years of its establishment and more than INR 50,000 in subsequent years (Singh et al. 2011). This saving could assist the family to meet other liabilities including health, education, and social customs improving the livelihood of small farm holders.

Table 9.18 Seed and oil yield of *Salvadora persica* (during different period) grown on saline black soil of different salinity

Soil salinity (dS m^{-1})	Seed yield (t ha^{-1})				Seed oil (%) content			
	First year	Second year	Third year	Fourth year	First year	Second year	Third year	Fourth year
25–35	1.08	1.27	2.41	2.65	32.3	32.8	32.6	32.7
35–45	0.84	1.02	1.35	1.72	32.3	32.2	31.8	31.6
45–55	0.60	0.88	1.29	1.58	31.3	30.6	30.1	30.1
55–65	0.38	0.74	1.27	1.40	29.7	29.8	29.3	29.8
Mean	0.72	0.98	1.58	1.84	31.4	31.9	31.0	31.1

Source Rao et al. (2003)

In this system, out of 1.5 ha area, 0.72 ha was used for cultivation of cereals, pulses, oilseeds, potato, flowers, and sugarcane. An area of 0.22 ha was allotted for a multistoried unit of horticulture containing a mixed plantation of mango, guava, pear, citrus, papaya, and banana. In the interspace, a number of short-duration vegetables and fodder crops were grown. Along the boundary, *Carissa carandas* was planted as hedge which gave additional fruits.The third component was dairy having buffalo and cow as milch animals. To ascertain the supply of green fodder round the year, fodder crops were rotated in 0.32 ha with other field crops. Other components included apiary (a unit of 10 bee boxes), pisciculture (mix of rohu, katla, mirgal, grass carp, and common carp) in 0.1 ha fish pond, poultry, vermicomposting, and goat unit (with 15 females and one male).

One study was initiated in 2006 at Central Soil Salinity Research Institute (CSSRI) on semi-reclaimed sodic land as a model for 2 ha land with interdisciplinary approach integrating various components (Fig. 9.12) which could be divided into two broader categories, i.e., crop component-1.8 ha (rice–wheat–green gram-0.2 ha, maize–wheat–green gram-0.2 ha, soyabean–maize-0.2 ha, pigeon pea–mustard–fodder maize-0.2 ha); fodder production -0.4 ha; horticulture/fruits production-0.2 ha, vegetables-0.2 ha, floriculture 0.2 ha); and subsidiary component 0.2 ha (fish production-0.2 ha, dairy, fruits, and vegetables on pond dykes, ducks and poultry, and bee keeping). The crop component gives income usually on half yearly basis when the crops are harvested, while the subsidiary component generates income on regular basis.

For the initial 5 years, the system was maintained by the scientists of the Institute. The net annual income from crop components was INR 1,15,844 and from subsidiary components INR 1,52,164 with a total of 2,68,007 having net saving of INR 734 per day.

When the same system is being operated in farmers' participatory mode, the gross and net income in 5 months was INR 1,78,888 and 51,155, respectively, with a daily net saving of INR 341 (CSSRI 2007–2012). The difference is in the maintenance of the system. On another pond constructed on alkali soil, various species of carp fish (*Catla catla, Labeo rohita, Cirrhinus mrigala, Hypopthalmichthys molitrix, Ctenopharyngodon idella*, and *Cyprinus carpio*) were cultivated in pond producing a fish biomass of 4.5 t ha^{-1} $year^{-1}$; and dykes were used for growing vegetables and fruits. The overall B: C ratio of the farming system was 5.5 (CSSRI 2011–2012).

Further, about 0.35 Mha of the land in Sharda Sahayak Canal Command is affected by waterlogging and sodicity. Traditional gypsum-based sodic land reclamation technology is not sustainable for reclaiming waterlogged sodic soils. In seepage prone areas of sodic soil (Fig. 9.13), pH generally decreases with increasing depth of soil. The initial soil pH at the site before digging out fish pond was 10.1, 9.7, 9.5, 9.2, 8.9, and 8.8 at 0–15, 15–30, 30–45, 45–60, 60–90, and

Fig. 9.12 Components of one multienterprise farming (agroforestry) system on partially reclaimed alkali soil at *source* CSSRI, Karnal

Fig. 9.13 Waterlogging in sodic soils (*Left*) due to seepage in Sharda Sahayak Canal Command areas of Uttar Pradesh (*Right*) *source* CSSRI, Karnal

90–120 cm depth, respectively. It is obvious that lower depths of soil have low pH. Thus, if soil having low pH is prevalent below 1–2 m depth, the land modification with IFS approach can successfully be employed for bringing waterlogged sodic lands back to cultivation.

Keeping this in view, a fishpond-based IFS model was developed over an area of 1 ha. A fish pond was dug up to a depth of 1.75 m and the soil was spread on adjacent sodic field. Due to mixing of low pH soil from lower depth, the pH of surface 0–15 cm soil was reduced to 9.1. *Eucalyptus* and banana were planted on bunds of the pond and are performing well. Fruit trees such as goose berry (*Emblica officinalis*) and guava (*Psidium guajava*) can also be planted on bunds of fish pond. In this particular case rice, wheat, sorghum, mustard, garlic and onion could be grown successfully on embankment and elevated field beds. Net return from the system was INR 34,694 with B: C ratio 4.45 (CSSRI 2011–2012).

Agroforestry for Combating Waterlogging (Biodrainage)

Introduction of canal irrigation in arid and semi-arid regions without provision of adequate drainage causes rise in groundwater table leading to waterlogging due to seepage and secondary salinization. Presently, about one-third of the world's irrigated area faces the threat of water logging, about 60 Mha is already waterlogged and 20 Mha is salt-affected (Heuperman et al. 2002). In India, the total degraded land due to waterlogging is 6.41 Mha out of which 1.66 Mha is due to surface ponding and 4.75 Mha is under sub-surface waterlogging (Maji et al. 2010). For the reclamation of waterlogged saline soils, the conventional technique is sub-surface drainage which is relatively expensive and generates harmful drainage effluents. A viable alternative of the above technique could be biodrainage, which is "pumping of excess soil water by deep-rooted plants using bioenergy." The root systems of trees intercept saturated zone or unsaturated capillary fringe above water table to control the shallow water table. These plants are known as *phreatophytes.*

Biodrainage is economical because it requires only initial investment for planting the vegetation, and when established, the system provides economic returns by means of fodder, wood, or fiber harvested and additionally sequesters carbon in the timber and soil. Reliance on capability of vegetation to reduce water table has been reported promising both in India (Chhabra and Thakur 1998; Naik and Manjunath 2000; Jeet Ram et al. 2011; Jena et al. 2011; Roy Chowdhury et al. 2011) as well as in other countries (Stirzaker et al. 1999; Zangs1999; Bhutta and Choudhry 2000). Fast-growing plants such as cloned *Eucalyptus* can successfully be grown on ridge particularly in areas where salinity is low. The impact of block plantations of *Eucalyptus tereticornis* on reclamation of waterlogged areas was tested and found effective at the Indira Gandhi Nahar Project (IGNP) site in Rajasthan and Dhob-Bhali research plot in Haryana (Heuperman et al. 2002; Jeet Ram et al. 2007). On these sites it was established that the transect of trees such as species of *Eucalyptus, Acacia, Populus, Prosopis, Casuarina, Pongamia, Terminalia, Syzygium, Dalbergia,* etc. when planted along canals successfully checked seepage and helped in mitigating waterlogging. During the studies conducted in IGNP area (Kapoor and Denecke 2001; Heuperman et al. 2002), groundwater under the tree plantation was reported to fall by 15.7 m over a period of 6 years. At 100 m from the edge of the plantation, the level of the groundwater was about 9 m higher than at the edge, with a draw down of 6.7 m. The higher groundwater level further away from the plantation edge is apparently the result of recharge from irrigation of areas under cultivation. Through these observations, Heuperman et al. (2002) concluded that the plantations act like groundwater pumps, pumping water at the rate of 34,460 $m^3 year^{-1}$ or 3.93 m^3 $h^{-1} ha^{-1}$ of plantation and the water used by plantations in the IGNP command was 3,446 mm $year^{-1}$, which was about 1.4 Class A pan. They further stated that the drawn down of the groundwater table under the plantations could even be 15 m or even more. No abnormal increase in salinity levels of soils and groundwater was observed under these plantations. Jena et al. (2011) planted *Acacia mangium* and *Casuarina* *equisetifolium* with intercropping of pineapple, turmeric, and arrowroot was taken successfully in Khurda district of Orissa coast. The depth to premonsoon water table changed from 0.5 m to 1.67 m after one year of plantation and to 2.20 in next year and to 3.20 during third year due to biodrainage. *Acacia* was better performer than *Casuarina*. Roy Chowdhury et al. (2011) also summarized the role of plantations (*Eucalyptus* and *Casuarina*) for reclamation of waterlogged situations in Deltaic Orissa which has been dealt in detail under agroforestry systems of coastal regions in Chap. 7.

In a controlled lysimeter study, conducted by Chhabra and Thakur (1998), it was concluded that *Eucalyptus tereticornis* could biodrain 2,880, 5,499, 5,518, and 5,148 mm of water in the first, second, third, and fourth year, respectively, from nonsaline groundwater and a water table depth of 1.5 m. The amount of water biodrained was more at 1.5 m as compared to 1 and 2 m water table depths because of maximum lateral roots in that zone. Further, the biodrainage capacity of trees was significantly affected by the salinity of the groundwater; however, even at a salinity of 12 dS m^{-1}, the plants biodrained 53 % of that under nonsaline conditions. In these experiments, the *Eucalyptus* plants could control water table rise up to 1.95, 3.48, 3.76, and 3.64 m in first, second, third, and fourth year, respectively; while in similar situations, the bamboo (*Bambusa arundinacea*) could control water table rise up to 1.09, 1.86, 2.46, and 2.96 m in first, second, third, and fourth year of growth, respectively. The secondary salinity developed in the root zone, up to 45 cm depth, did not exceed 4 dS m^{-1} even at a water table depth of 1 m with salinity of 12 dS m^{-1}.

To find out the optimum density of *Eucalyptus* for utilization of sewage water of municipal areas for production of wood biomass, an experiment was initiated at CSSRI Karnal in October 2000 by planting saplings in Nelder's competition wheel with 10 concentric rings (8 observation rings at radii 1.98, 3.30, 4.62, 6.47, 9.06, 12.68, 17.75, and 24.85 m and two guard rings at 0.6 and 31.95 m) of 18 plants each. The wheels were irrigated with sewage water following climatological approach, i.e., applying irrigation (D_{iw} 7.5 cm) when the cumulative open pan values (CPE) equal D_{iw} (or D_{iw}/CPE = 1.0). The observations were presented for very high density VHD (6,530 stems per ha), high density HD (1993 stems per ha), moderate density MD (517 stems per ha), and low density LD (162 stems per ha). Transpiration rate was measured using Sap Flow Sensors (Dynamax Flow 32) based on principal of thermodynamics. When data averaged for the period August 2002 to January 2003, transpiration rates for sewage-irrigated plantations was computed to be 23.0 and 17.3 l per day per plant at LD and MD densities. The average transpiration rates in 3-year-old plantations from May to December 2003 were found to be 29.5, 19.8, and 14.4 liters per day per plant in low, optimum, and high density plantations, respectively, which comes to be 189, 339, and 945 mm during this period. In August to December 2005 (5-year-old plantations), the transpiration values increased to 56.5, 30.7, and 18.9 liters per day per plant in respective densities, after 6 years, annual total consumptive use of water was 2,200 mm in high density and 1,300 mm in low density, which is quite reasonable amount of water (CSSRI 2002–2003 to 2007–2008).

The studies conducted by Jeet Ram et al. (2007, 2008) indicated that a block plantation of 18-year-old *Eucalyptus tereticornis* (2.6 ha with 300 trees) could influence the lowering of water table up to a distance of more than 730 m from the edge of plantation in the adjacent crop fields. In one experiment, Jeet Ram et al. (2011) constructed parallel ridges in the north–south direction on the bunds of agricultural waterlogged fields in Haryana. Ridge-to-ridge distance was 66 m. Each ridge was about 1 m high, 2.6 m wide at the base, and 2.0 m wide at the top. Plantations of cloned *Eucalyptus* (clone C-7) were raised as strip plantations (Fig. 9.14). Every strip-plantation contained two rows of plants. The row-to-row and plant-to-plant distance was 1 m, resulting in a total of 1,440 plants in 4.8 ha with a density of 300 plants per ha. The area under strip plantations was about 4 % and the rest 96 % was available for raising

Fig. 9.14 Three-year-old *Eucalyptus* planted in paired strips to lower down the water table in the agricultural field in canal commond area in Haryana

agricultural crops, thereby making it an agroforestry model for biodrainage.

The groundwater table was measured through observation wells installed in two parallel transects which were installed perpendicular to the strip plantations. Distance between the two transects was 60 m. The transpiration rate was measured using thermal dissipation probes (Dynamax, USA-make). In this experiment, it was observed that the groundwater table underneath the strip plantations was lower (1.61 m) than the groundwater table in the adjacent agricultural fields (1.43 m) resulting in a drawdown of 0.18 m by 2-year-old strip plantations. The total drawdown of groundwater table during a period of 3 years was 0.85 m (Fig. 9.15).

Further, the roots of 5.4-year-old trees of *Eucalyptus* penetrated in the soil profile up to a depth of 3.30 m. Therefore, the upper 0.50 m portion of the roots was above the ground level (in the bunds) and the remaining 2.80 m portion below the ground level where the soil was totally wet. It indicated that the roots have reached in the zone of capillary fringe located above the groundwater table for the absorption of groundwater and the strip plantations of clonal *Eucalyptus* were working as biopumps. The average above ground oven dry biomass was 99.9 kg tree^{-1}, of which 92.1 kg (92.3 %) was of timber (poles), 3.3 kg (3.3 %) of fuelwood, and 4.5 kg (4.5 %) of twigs and leaves resulting in 24.0 t ha^{-1} total oven dry above ground biomass of 240 surviving trees. The average below ground oven dry biomass of roots was 37 kg tree^{-1} (about 37.1 % of the average above ground oven dry biomass) resulting in 8.9 t ha^{-1} total oven dry below ground biomass of 240 surviving trees ha^{-1}. Thus, the total above and below oven dry biomass of 240 surviving trees was 32.6 t ha^{-1} (Table 9.19). The carbon percent in the oven dry biomass was 47.0 % in timber, 43.5 % in fuelwood, 43.9 % in twigs and leaves, and 48.0 % in the roots. Therefore, the weight of carbon in 5.4-year-old 240 surviving trees ha^{-1} of clonal *E. tereticornis* was 10.4 t ha^{-1} in timber, 0.3 t ha^{-1} in fuelwood, 0.5 t ha^{-1} in twigs and leaves, and 4.3 t ha^{-1} in roots resulting in a total carbon content of 15.5 t ha^{-1}, which was equivalent to 56.7 t ha^{-1} of CO_2 (Table 9.20).

The average rate of transpiration (measured by sap flow technique) of groundwater by the clonal *E. tereticornis* ranged from (liters day^{-1} tree^{-1}) 44.5 to 56.3 in May, 30.5 to 34.0 in July, 24.1 to 28.3 in October, and 14.8 to 16.2 l day^{-1} tree^{-1}in January. The annual rate of transpiration by 240 trees ha^{-1} was equal to 268 mm per annum. The total decline in the wheat grains yield due to the shading effect of 5-year-old strip plantations of clonal *E. tereticornis* was 11.7 % (0.29 t ha^{-1}). But, in spite of decline in wheat grains yield due to the adverse effect of strip plantations, the wheat grains yield was 2.15 t ha^{-1} as compared to 0.64 t ha^{-1} in the nearby untreated fields without plantation. Therefore, the wheat grains yield research plot was 3.36 times the yield in the nearby untreated fields. The farmers earned INR 72,000 ha^{-1} at a rotation of 5 years and 4 months resulting in a benefit–cost ratio of 3.5:1 at 12 % discount rate of interest. Further, the stools of young felled trees of *E. tereticornis* gave excellent coppice shoots. Therefore, there is no need to artificially regenerate the felled area. The only operation to be carried out is the singling of coppice shoots

Fig. 9.15 Comparision of drawdown of water table by cloned *Eucalyptus* in a crop fields and under plantations of 3 years old (X) and 5 years old (▲)

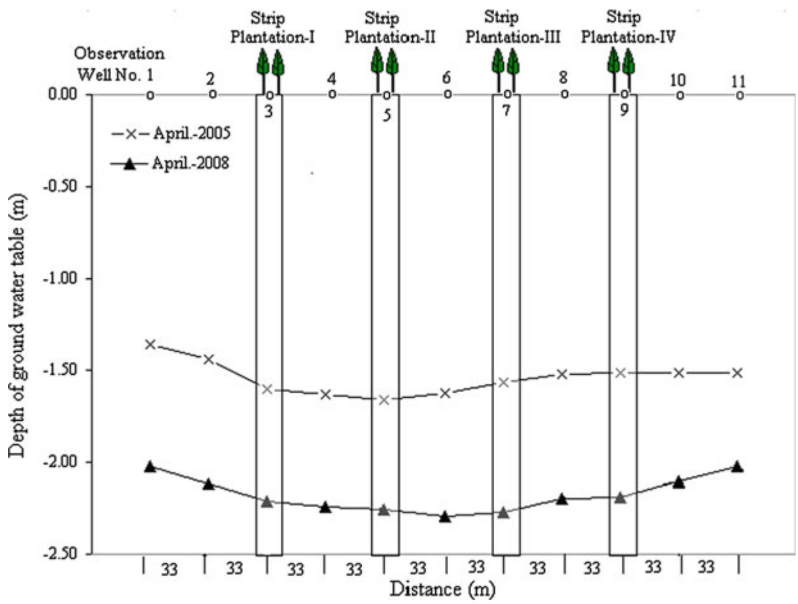

Table 9.19 Fresh and dry biomass of 5.4-year-old trees of clonal *E. tereticornis* in biodrainage plantation

Tree components	Fresh biomass		Dry biomass	
	kg $tree^{-1}$	t ha^{-1}	kg $tree^{-1}$	t ha^{-1}
Timber	131.6	31.6	92.1	22.1
Fuelwood	4.6	1.1	3.3	0.8
Twigs and leaves	6.4	1.5	4.5	1.1
Total above ground biomass	142.7	34.2	99.9	24.0
Roots	51.4	12.3	37.0	8.9
Grand total	194.1	46.6	136.9	32.9

Source Jeet Ram et al. (2011)

Table 9.20 Carbon and CO_2 sequestered by 5.4-years-old trees of clonal *E. tereticornis*

Tree components	Oven dry biomass (t ha^{-1})	Carbon (%)	Carbon content (t ha^{-1})	CO_2 content (t ha^{-1})
Timber	22.1	47.0	10.39	38.10
Fuelwood	0.8	43.5	0.34	1.25
Twigs and leaves	1.1	43.9	0.47	1.74
Roots	8.9	48.0	4.26	15.63
Total	32.8	182.4	15.47	56.72

Source Jeet Ram et al. (2011)

so that the retained shoots can get maximum growing space. In this way, about 3–4 rotations of coppice crop (each of 5–6 years) can be taken by incurring negligible expenditure on singling of coppice shoots. Thus, the benefit–cost ratio of next 3–4 rotations of coppice crop of *E. tereticornis*, each of 5–6 years, would be much higher due to zero cost of raising and negligible cost of maintenance.

Agroforestry survey, involving 411 farmers of 15 villages belonging to 11 development blocks of 6 waterlogged districts, was conducted to access the availability of waterlogged areas for raising biodrainage plantations. The response of the farmers was very encouraging as 99 % farmers showed their willingness. The total agricultural land owned by these farmers was 1,972 ha, of which 1,877 ha was waterlogged out of which about 79 % of the land was offered for planting biodrainage plantations. Government of Haryana is very keen in mitigating the climate change as is evident from the fact that it is implementing the first small-scale afforestation Clean Development Mechanism (CDM) Project in the world registered with the United Nations Framework Convention on Climate Change under the Kyoto Protocol. Keeping in view the increasing demand of the farmers, the Haryana Government raised biodrainage plantations on 5,000 ha of farmers' agricultural waterlogged fields during the financial year 2008–2010 (Jeet Ram, personal communication).

It is now established fact that trees play very important role in controlling the waterlogging due to seepage along canals. The trees are planted along the canals at close space (1–2 m) in lines. These intercept the seepage and control water logging and salinity. The companion halophytes such as species of *Atriplex, Suaeda, Haloxylon, Kochia,* and *Salsola* and grasses such as *L. fusca, B. mutica, V. zizanioides* and species of *Paspalum* will cover the soil and check upward flux of salts which would follow if water evaporates directly from the soil surface. Considering the local agroclimatic and socioeconomic factors, appropriate trees and companion grasses/shrubs/crops can be chosen. When trees are raised in wider rows, the interspaces may be planted with forage grasses. The grasses in combination with trees are more efficient than the trees alone.

In one experiment, conducted at Gangawati in Karnataka on saline vertisol involving tree species (*Hardwickia binata, Sesbania grandiflora, Acacia nilotica, Dalbergia sissoo, Casuarina equisetifolia* and *Azadirachta indica*) in combination with grasses such as hybrid napier it was found that *A. nilotica* intercepted highest incoming seepage (86.4 %) from canal as compared to control (without trees) followed by *D. sissoo* with 84 % interception (Tomar and Patil 1998). The interception was directly correlated with canopy spread. The trees when planted with napier grass in interspaces showed more efficiency in controlling seepage (Table 9.21) showing the importance of silvopastoral system in such areas.

Among other species *Terminalia arjuna, Pongamia pinnata, Eucalyptus camaldulensis, E. tereticornis* and *Syzygium cuminii* among trees and *Leptochloa fusca, Phragmites australis, Dichanthium annulatum, D. varicosum, Brachiaria mutica* and *Paspalum* spp. among grasses have credibility for such situation.

Table 9.21 Relative efficiency of tree species in controlling canal seepage along 12-m-long strip

Treatment	Seepage ($m^3\ day^{-1}$)		Increase in interception (%)		Canopy width (cm)	
	Tree alone	Tree + napier grass	Tree alone	Tree + napier grass	Tree alone	Tree + napier grass
Control (no tree)	0.90	0.90	0.0	0.0	–	–
Azadirachta indica	0.36	0.29	60.0	68.0	102.8	89.9
Hardwickia binata	0.87	0.25	68.0	72.0	92.5	105.98
Casuarina equisetifolia	0.25	0.25	72.0	72.0	316.2	308.1
Sesbania grandiflora	0.25	0.25	72.0	76.0	160.0	149.9
Dalbergia sissoo	0.14	0.18	84.0	80.0	389.7	314.0
Acacia nilotica	0.12	0.12	96.4	86.5	421.8	379.2

Source Tomar and Patil (1998)

Agroforestry Suited to Saline Irrigation

Farmers besides irrigating arable crops also utilize salty waters for cultivation of fruit trees such as date palm (*Phoenix dactylifera*), *ber* (*Ziziphus mauritiana*), guava (*Psidium guajava*), goose berry (*Emblica officinalis*), etc. on coarse-textured saline soil having ECe from 15–20 dS m^{-1}. The rehabilitation of degraded drylands is limited to two possibilities: (i) the exploitation of plants native to arid environments, and (ii) devising efficient cropping systems and techniques for using limited saline groundwater resources judiciously. In the past, efforts toward utilization of saline waters were mainly aimed at enhancing the production of annual arable crops and notion of irrigated forestry or fruit trees, growing forages and other nonconventional high value crops was considered to be less attractive leading to poor economic production. But recent research efforts have shown that agroforestry has greater potential for utilizing degraded lands using saline water for establishment of trees and profitable and sustainable agroforestry systems.

Planting Methods with Saline Irrigation

The traditional approach for sustaining the use of saline water is to irrigate more frequently and provide for leaching requirements (Ayers and Westcot 1985). Nevertheless, such practices demand for application of additional quantities of saline water and thereby also result in the enhancement of salt loads of soils. These approaches were advocated for shallow-rooted crop plants in arid environments mainly because the added salts could be pushed beyond the rooting zone. But in deep-rooted tree plantations, the additional salts going into the soil through enhanced frequency of irrigations during their establishment may rather aggravate the problem as these are likely to persist within their expanding rooting zones and may subsequently hinder the growth of trees. Therefore, irrigation with saline waters should aim to create favorable niches for the better establishment of saplings and also eliminate the over salinity buildup. This could be achieved by irrigating only the limited area under furrows planted with tree saplings (Minhas et al. 1997a, b; Tomar et al. 1994, 2003b; Dagar et al. 2008). In this technique, furrows (15–20 cm deep and 50–60 cm wide) are created at 4–5 m intervals with a tractor-drawn furrow maker. Auger holes (0.2 m diameter and 1.2 m deep) are dug at the sill of these furrows spaced at 2–4 m intervals depending upon the space to be kept between plants. These are refilled with the mixture of original soil plus 8 kg of farmyard manure, 30 g superphosphate, 15 g zinc sulfate, and 15 g of iron sulfate. Six to nine-month-old tree saplings are transplanted during rainy season (July–August) at sites where auger holes are dug. The irrigation with saline water is given in furrows only. The technique is known as subsurface planting and furrow irrigation system (SPFIS).

The irrigation may be provided for the initial 3 years (4–6 times in a year) and thereafter, plantations may be irrigated once during the winter only. Salt storage in soil profile may increase during irrigation period but the added salts get distributed in soil profile as a consequence of seasonal concentration of rainfall during monsoons and some episodic events of rainfall during the following years. Along with forest and fruit trees, arable annual crops such as barley, wheat, clusterbean, pearl millet, mustard grasses such as *Leptochloa fusca, Chloris gayana, Agropyron elongatum,* etc. and medicinal plants such as *Plantago ovata*, *Aloe vera, Withania somnifera* and *Cassia angustifolia* could be cultivated successfully (Minhas et al. 1997a, b; Tomar and Minhas 2002, 2004a, b; Tomar et al. 2003a, b, 2005, 2010; Dagar et al. 2006a, b, 2008; Dagar 2012).

Performance of Forest Trees on Degraded Land Using Underground Saline Water

With increasing demands of food, forage, fuelwood, timber, and other necessities for ever-increasing population and limited availability of good quality water the saline water irrigation is now considered as an imperative necessity for the sustainable agricultural development, which includes the use of saline groundwater, saline drainage water, and sewage wastewater for irrigation. Agroforestry is sustainable option for utilizing poor quality waters. A long-term field trial with 31 tree species was conducted over 20 years on calcareous soils in a semi-arid region (annual rainfall about 350 mm) of northwest India using furrow method of irrigation.

The saplings were established irrigating with saline water (EC 8–10 dS m^{-1}) for the initial 3 years (4–6 times in a year) and thereafter plants were irrigated once in a year during winter up to the age of 8 years. Most of the tree species (except *Syzygium cuminii, Bauhinia variegata,* and *Crescentia alata*) showed quite high survival rate (71–100 %) during the first 3 years. Ranking in order of survival, growth, and biomass yield showed that *Tamarix articulata, Acacia nilotica, Prosopis juliflora*, *Eucalyptus tereticornis, Acacia tortilis* and *Cassia siamea* were most successful species (Tomar et al. 2003b). After 8 years of planting, the highest shoot biomass was harvested (Fig. 9.16) from *Tamarix articulata* (71.9 t ha^{-1}) followed by *Acacia nilotica* (23.4 t ha^{-1}), *P. juliflora* (20.2 t ha^{-1}), and *Eucalyptus tereticornis* (14.8 t ha^{-1}). After 16 years of growth, these trees produced 206, 197, 110, and 57 t ha^{-1} biomass, respectively. *Cassia siamea, Acacia tortilis*, and *Azadirachta indica* produced 94, 87, and 67 t ha^{-1} biomass because of their higher survival rate. Based on several experiments, a cafeteria of tree species has been prepared (Table 9.22) which depicts very promising and promising performers when established with saline irrigation.

The soil organic carbon content under these plantations was more than 3.5 g kg^{-1}. Litter fall from the most of tree species resulted in an improvement of organic carbon content of the underlying soils. The prominent species where considerable enhancements in organic carbon contents (>0.4 % in upper 30 cm layer) were observed included: *Acacia tortilis, Cassia siamea*, and *Prosopis juliflora*. There was substantial increase in organic carbon in soil which

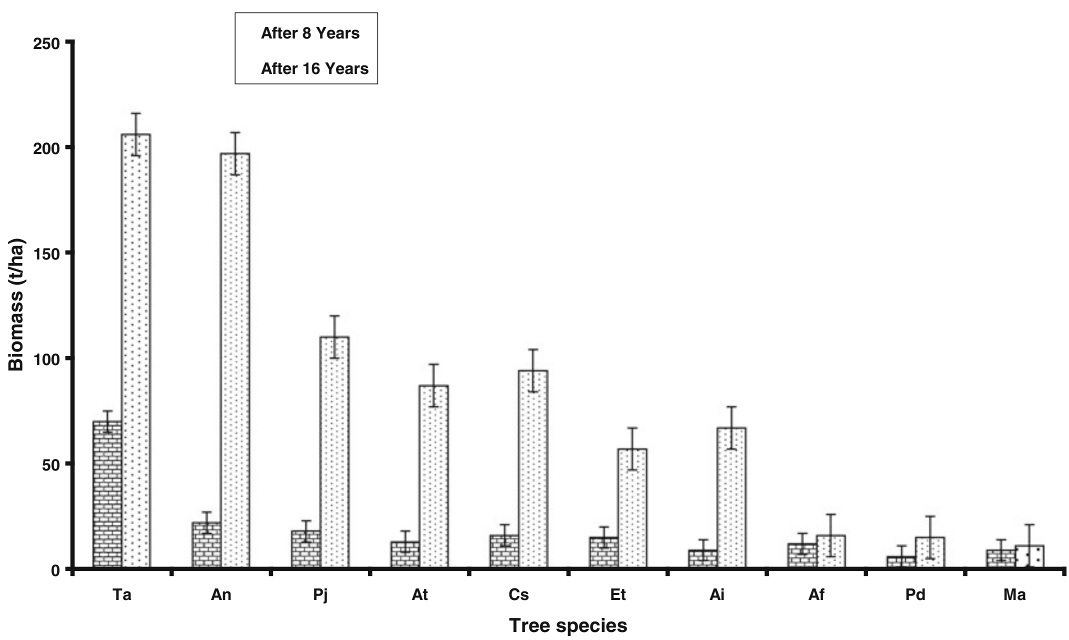

Fig. 9.16 Biomass of some selected individual trees of successful species after 8 and 16 years of growth (Af *Acacia farnesiana*, An *A. nilotica*, At *A. tortilis*, Ai *Azadirachta indica*, Cs *Cassia siamea,* Et *Eucalyptus tereticornis,* Ma *Melia azedarach*, Pd *Pithecelobium dulce*, Pj *Prosopis juliflora,* Ta *Tamarix articulata)*

Table 9.22 Performance of forest and fruit tree species with saline water irrigation (ECiw 10 dS m^{-1})

Performance rating	Forest tree species	Fruit tree species
Very promising	*Tamarix articulata, Azadirachta indica, Acacia nilotica, A. tortilis, A. farnesiana, Cassia siamea, Faidherbia albida, Eucalyptus tereticornis,, Prosopis juliflora, P. cineraria, Pithecellobium dulce, Salvadora persica, S. oleoides*	*Carissa carandas, Aegle marmelos, Cordia rothii, Phoenix dactylifera, Feronia limonia*
Promising	*Melia azedarach, Cassia fistula, Acacia auriculaeformis, Bauhinia variegata, Cassia glauca, C. javanica, Crescentia alata, Pongamia pinnata, Tecomella undulata*	*Ziziphus mauritiana, Vitis vinifera, Syzygium cuminii, Emblica officinalis, Psidium guajava, Punica granatum*

Source Tomar et al. (2003a, b)

was more with increase in age due to more contribution by litter and soil root decomposition (Fig. 9.17).

While studying water storage due to saline irrigation for establishment of trees in dry regions computations showed that out of the total water added (832 mm rain plus 324 mm irrigation) during 3 years, only 17–277 mm was the additional water stored in soils for future extraction by tree saplings when the supplemental irrigation was discontinued. The water storage at this stage ranged between 24.2–26.0 cm/3.0 m soil under some of the better extracting species like *Acacia nilotica, Azadirachta indica* and *Eucalyptus tereticornis* whereas it got improved to 48.3–51.0 cm under poor performing species like *Casuarina equisetifolia* and *Cassia javanica*. The water use efficiency in dry regions is very important parameter. Estimates (Tomar et al. 2003b) show that some of the tree species like *Tamarix articulata, Acacia nilotica*, and *Prosopis juliflora* are very efficient water users with their water use efficiency (WUE) being more than 35 kg cm^{-1} of water (Table 9.23).

The most of the vigorous tree species continued to extract higher amounts of water during their later growth also. Keeping in view the seasonal changes vis-à-vis growth patterns of

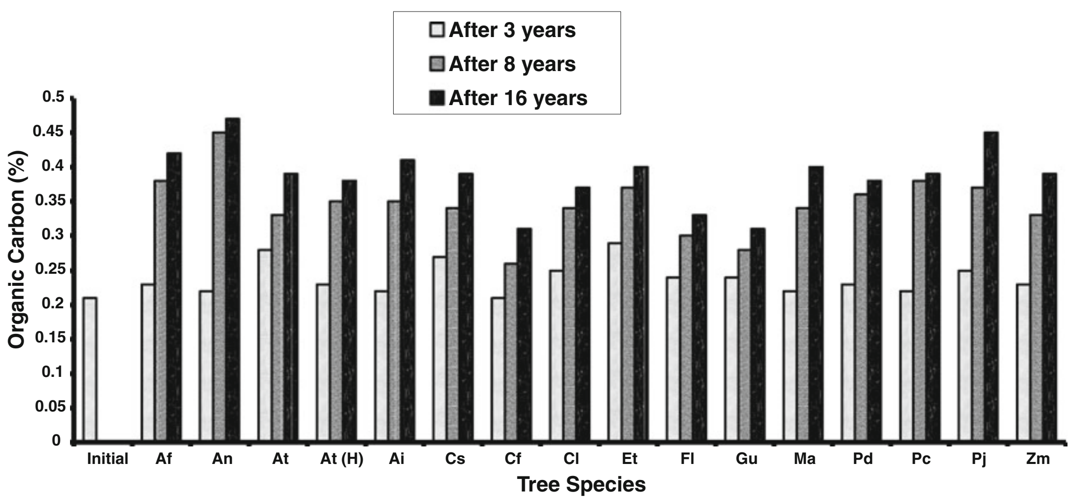

Fig. 9.17 Soil organic carbon status under different trees species at different intervals (Af-*Acacia farnesiana*, An *A. nilotica*, At *A. tortilis*, At(H) *A. tortilis* (hybrid), Ai *Azadirachta indica*, Cs *Cassia siamea*, Cf *C.fistula*, Cl *Callistemon lanceolata*, Et *Eucalyptus tereticornis*, Fl Feronia limonia, Gu *Guazuma ulmifolia*, Ma *Melia azedarach*, Pd *Pithecellobium dulce*, Pc *Prosopis cineraria*, Pj *P.juliflora*, Zm *Ziziphus mauritiana*]

Table 9.23 Water extract and water use efficiency (WUE) of different tree species (as calculated between April, 1994 to January, 1998)

Species	Mean water extraction (mm day^{-1})	WUE (kg cm^{-1})
Acacia farnesiana	1.79	20.5
A. nilotica	3.23	45.0
A. tortilis (hybrid)	3.41	25.7
A. tortilis	3.52	23.0
Azadirachta indica	3.47	13.7
Casuarina equiselifolia	3.34	0.3
Cassia javanica	3.51	6.6
C. siamea	3.33	21.1
Eucalyptus tereticornis	3.42	23.2
Guazuma ulmifolia	3.52	4.5
Melia azedarach	3.40	21.7
Moringa oleifera	3.39	0.9
Pithecellobium dulce	3.41	11.9
Prosopis cineraria	3.56	1.5
P. juliflora	3.46	37.6
Ziziphus mauritiana	3.45	5.3

Source Tomar et al. (2003b)

tree species affecting water extractions, the annual data were partitioned into post-monsoon and monsoon periods. Tree species like *Feronia limonia, Acacia farnesiana, Cassia siamea, Azadirachta indica, Prosopis juliflora, P. cineraria* and *Callistemon lanceolatus* were showing higher water extractions during monsoon season whereas species like *Cassia fistula, Guazuma ulmifolia, Acacia nilotica, Acacia tortilis* (hybrid), *Pithecellobium dulce*, and *Moringa oleifera* extracted more water during the post-monsoon periods. *Guazuma ulmifolia, Acacia tortilis, P. cineraria, P. juliflora, Feronia limonia*, and *Cassia fistula* showed an overall low water extraction but continued to extract soil moisture through out the year. In general, the soil water extraction by different tree species matched well with their growth behavior.

Cultivation of Arable Crops with Fruit Trees Using Underground Saline Water

Till recently, arable crops used to be preferred for cultivation using saline water for irrigation. In recent years as is evident from above-mentioned results that tree-based agricultural systems can successfully be developed through utilizing saline water for irrigation. Fruit trees such as *Ziziphus mauritiana, Carissa carandas, Feronia limonia, Emblica officinalis*, and *Aegle marmelos* could be established irrigating with saline water up to EC 10 dS m^{-1} and intercrops in wider spaces between rows (5 m) such as pearl millet, cluster bean, and barley could be cultivated with success (Fig. 9.18) applying one or two irrigations (Tables 9.24, 9.25). This is very much sustainable and economically viable agroforestry system for calcareous degraded soils. *Karonda* (*Carissa carandas*) started bearing fruits just after 2 years (75 % bushes started bearing) yielding about 1 t ha^{-1} fruits. During the third year, it could produce 1.2–1.8 t ha^{-1} fruits. Karonda–barley is quite sustainable agroforestry system with providing limited saline irrigation for dry region. Goose berry (*Emblica officinalis*) started bearing after fouth year but it was found to be sensitive to frost. There is an initial problem of establishment when planted from grafted seedlings. In-situ grafting may be more successful method of plantation. Bael (*Aegle marmelos*) also started bearing after fourth year and produced fruits up to 3 t ha^{-1} (Dagar et al. 2008).

Fig. 9.18 Performance of arable crops with fruit trees with saline irrigation (*Left*): Barley with Karonda (*Carisa carandas*) (*Right*): Clusterbean with goose berry (*Emblica officinalis*)

In arid regions, *Ber* (*Ziziphus mauritiana*) has performed very well when irrigated with saline water of EC_{iw} 8 dS m^{-1} using drip irrigation. The results in terms of fruit yield indicated that the fruit yield was maximum at 0.6 PE of best available water-BAW (64.6 kg per tree) followed by 0.6 PE of saline water of EC_{iw} 8 dS m^{-1} (56.7 kg per tree) and this yield was better than all other treatments including 0.8 and 0.4 PE of BAW (AICRP 2010–2012) showing its potential for dry region.

Silvopastoral Systems Established with Saline Irrigation

On calcareous sandy loam soils, silvopastoral systems involving fodder trees from the abovementioned forest trees and several local and introduced grasses may be developed with great success which may sustain the live stock and livelihood of the resource poor and landless farmers of dry regions. In tree plantations when protected from grazing local grasses predominated by *Cenchrus ciliaris, C. setigerus* and *Dactyloclenium sindicum* covered the interspaces. These could produce 3–4 t ha^{-1} forage and if irrigated once with saline water during summer green forage could be available during dry period when there is scarcity of green forage. The results of one trial conducted by Tomar et al. (2003a) on perennial grasses irrigating with saline water (EC 10 dS m^{-1}) at different frequency showed that *Panicum laevifolium* and *P. maximum* were most suitable species producing annually 11–17 t ha^{-1} dry forage (Table 9.26). About 25–30 % of total forage was also available during lean period of summer when most of the people become nomadic along with their cattle. The water use efficiency was also highest in these two species. These grasses along with native *Cenchris setigerus* and *S. ciliaris* can successfully be grown with trees mentioned above and one irrigation with saline water which is always available during summer can produce reasonably good biomass for live stock in dry regions.

Medicinal and Arromatic Plants with Saline Irrigation

Salt tolerant and low water requiring medicinal and aromatic plants can provide viable alternative to effectively utilize the degraded calcareous lands. Tomar and Minhas (2002, 2004a, b); Tomar et al. (2005, 2010) and Dagar et al. (2008, 2009, 2013) in series of experiments evaluated the performance of aromatic and medicinal plants and winter annual flowers under saline irrigation (EC 8–10 dS m^{-1}) in isolation as well as in partial shade of trees. Among the species tested for medicinal value, the most promising was psyllium (*Plantago ovata*) with average seed yield of 1,050 kg ha^{-1} and did not show any adverse impact when compared with canal water irrigation. When different frequencies of irrigation were compared using water of low salinity (ECiw 4.0 dS m^{-1}), high salinity (EC 8.6 dS m^{-1}), and providing irrigation with waters of low and high salinity alternately, the average unhusked seed

Table 9.24 Mean grain and straw yield (t ha^{-1}) of intercrops (mean of 2 years) along with three fruit trees during initial establishment of trees

Fruit trees	Crops	T_1		T_2		T_3		T_4	
		Grain	Straw	Grain	Straw	Grain	Straw	Grain	Straw
Karonda	Pearl millet	2.45	11.2	2.51	11.28	2.35	11.25	2.18	10.65
	Cluster bean	0.85	2.63	0.91	2.96	0.79	2.51	0.7	2.46
Anola	Pearl millet	2.5	10.98	2.64	11.32	2.25	11	1.98	10.48
	Cluster bean	0.96	3.31	1.03	3.43	0.95	3.2	0.91	2.86
Bael	Pearl millet	2	10.45	2.25	11.05	1.84	10	1.72	9.85
	Cluster bean	0.92	3	0.97	3.31	0.9	2.95	0.86	2.74
LSD (p = 0.05)									
		Grain				Straw			
		Pearl millet	Cluster bean			Pearl millet	Cluster bean		
Between fruit trees (A)		0.134	0.073			NS	0.425		
Between treatments (B)		0.097	NS			NS	0.189		
Interactions (A) x (B)		NS	NS			NS	NS		

Treatments depict as: Planting methods T_1 Traditional pit method irrigated with water of low salinity (ECiw 5–6 dS m^{-1}), T_2 Planted in furrows and irrigated with water of low salinity, T_3 planted in furrows and irrigated alternatively with low and high salinity, T_4 planted in furrows and irrigated with water of high salinity (ECiw 10–12 dS m^{-1})

yield was found to be 1,102, 885, and 1,159 kg ha^{-1}, respectively, showing significant advantage when the crop was irrigated alternately with water of low and high salinity. There was increase in yield with increase of frequency of irrigation. Among eight varieties, the best performance was shown by variety JI-4 followed by Sel-10, Niharika, HI-5, GI-2, GI-1, local, and HI-34, in descending order (Tomar et al. 2005, 2010). Psyllium did not show any yield reduction with *Acacia nilotica* trees even at later stages showing its suitability for partial shade tolerance.

Lemon grass (*Cymbopogon flexuosus*) was also found promising crop with saline irrigation (Dagar et al. 2013). The average fresh foliage yield was found to be 12.0–13.0, 6.7–8.3, and 9.1–9.8 t ha^{-1}, respectively, when irrigated with water of low salinity (ECiw 4.0 dS m^{-1}), high salinity (ECiw 8.6 dS m^{-1}), and alternately with two waters. There was increase in yield with increase of frequency of irrigation particularly during second year. Furrow planting was a superior planting method than other methods including the flat planting method. Among the cultivars tested, RRL-16 and OD-58 showed better performance followed by Praman and Krishna (Dagar et al. 2013). The overall results indicated the possibilities of raising Lemongrass on degraded calcareous soil using saline water up to EC 8.6 dS m^{-1} (Tomar and Minhas 2004a; Dagar et al. 2008, 2013) without build up of soil salinity if normal rainfall occurs once in 3–4 years. There was no impact on quality of oil due to salinity. The aromatic grasses such as vetiver, lemon grass and palmarosa, when irrigated with saline water (EC 8.5 dS m^{-1}) could produce on an average 90.9, 10.4, and 24.3 t ha^{-1} dry biomass, respectively (Tomar and

Table 9.25 Grain and straw yield (t ha^{-1}) of cluster bean and barley with three plantations after three years

Fruit tree	Treatment	*Yield of* cluster bean		Yield of barley	
		Grain	Straw	Grain	Straw
Karonda	T_1	0.88	1.46	3.58	3.88
	T_2	0.86	1.38	3.47	3.97
	T_3	0.81	1.27	3.45	3.71
	T_4	0.76	1.15	3.10	3.32
Anwla	T_1	0.79	1.29	4.19	3.40
	T_2	0.81	1.33	3.63	3.83
	T_3	0.76	1.24	3.24	3.34
	T_4	0.69	1.18	2.87	3.00
Bael	T_1	0.75	1.23	3.27	3.45
	T_2	0.71	1.21	3.22	3.35
	T_3	0.67	1.06	2.73	2.86
	T_4	0.63	1.02	2.52	2.64
LSD ($p = 0.05$)					
Factor A (species)		0.13	NS	0.12	0.17
Factor B (treatment)		0.02	0.11	0.14	0.15
Interaction (A x B)		NS	NS	0.24	0.26

Treatments depict as: Planting methods T_1 Traditional pit method irrigated with water of low salinity (ECiw 5–6 dS m^{-1}), T_2 Planted in furrows and irrigated with water of low salinity, T_3 planted in furrows and irrigated alternatively with low and high salinity, T_4 planted in furrows and irrigated with water of high salinity (ECiw 10–12 dS m^{-1})

Table 9.26 Gross dry-matter yield (Average of 3 years) and water use efficiency of different grasses when cultivated with saline water

Species	Yield (t ha^{-1}) at Diw/CPE			Water use efficiency (kg ha^{-1} cm)		
	0.2	0.4	0.8	0.2	0.4	0.8
Brachiaria mutica	9.54	12.15	11.72	26.7	12.15	11.72
Cenchrus setigerus	4.64	4.57	4.38	12.9	4.57	4.38
Cynodon dactylon	8.91	9.23	10.20	25.0	9.23	10.20
Panicum antidotale	9.34	11.41	11.77	26.2	11.41	11.70
P. coloratum	6.95	10.29	8.93	19.5	10.29	8.93
P. laevifolium	13.49	16.85	16.88	37.8	16.85	16.88
P. maximum (C)	10.87	13.04	12.72	30.5	13.04	12.72
P.maximum (wild)	14.00	14.72	13.72	39.3	14.72	13.72
P. virgatum	9.95	12.10	11.36	27.9	12.10	11.36
Mean	9.74	11.60	11.30	27.3	11.60	11.30

Diw/CPE = irrigation water/cumulative pan evaporation
Source Tomar et al. (2003a)

Minhas 2004a). Different cultivars of vetiver could produce 72.6–78.7 t ha^{-1} shoot biomass and 1.12–1.71 t ha^{-1} root biomass. The roots are used to extract aromatic oil.

Aloe barbadensis was also equally tolerant and could produce 18 t ha^{-1} fresh leaves under partial shade. *Ocimum sanctum* could produce 910 kg ha^{-1} dry shoot biomass. In a separate trial, dill (*Anethum gravelens*), taramira (*Eruca sativa*), and castor (*Ricinus communis*) could produce 931, 965, and 3,535 kg seeds per ha, respectively, when provided with three irrigation of saline water of EC 10 dS m^{-1} (Dagar et al. 2008). *Cassia senna* and *Lepidium sativum* could also be cultivated successfully irrigating with saline water up to 8 dS m^{-1}. Ornamental and medicinal flowers such as *Chrysanthemum, Calendula,* and *Matricaria* were also found successful when cultivated irrigating with water of EC up to 5 dS m^{-1}. These species could yield 13.2, 4.7, and 3.5 t ha^{-1}, respectively, fresh flowers in a season when irrigated with good quality water available at site. A few irrigations with good quality water for establishment will increase the yield of flowers significantly. All these high value crops could successfully be grown as intercrops with forest and fruit trees at least during the initial years of establishment (Dagar 2009; Dagar et al. 2006a, b, 2008, 2009, 2013).

Afforestation of Coastal Saline Areas

Agroforestry systems including afforestation, biodrainage plantations on saline and waterlogged situations have been dealt in Chap. 7.

Other Management Practices

As stated earlier, saline and sodic soils are found in arid, semi-arid and hot and dry subhumid regions, where about 70–80 % of the total rainfall is usually received during the months of July–September (particularly in Indian subcontinent). Usually the rains are erratic and periods following them are dry. Though the transplanting of tree saplings is mostly completed during rainy season, the saplings may suffer for want of water during the post-monsoon period especially the summers. Young saplings of many species except a few may also suffer from frost injuries during winters in northern regions of India. Therefore, provision of supplemental irrigation for early establishment and growth and avoiding frost injuries of saplings is very crucial. Like crops, trees also need irrigations to meet their evapotranspiration demands. The experiments on irrigation requirements (Gupta et al. 1995, Tomar et al. 2003b, Singh and Dagar 2005) clearly indicated that plantations need regular irrigation after planting the saplings especially during summer (2 irrigations) and winter (1 irrigation) at least for the initial 3 years. Higher plant population may necessitate further extending the support period.

Irrigation practices for trees on saline and alkali soils should further ensure that there is no waterlogging and aeration problem, optimize the availability of moisture in the root zone, and minimize the secondary salinization of the root zone. Therefore, sub-furrow planting and furrow irrigation method has proved ideal. It may be pointed that when water table is within 50 cm during rainy season or within 2 m during later part of the year, irrigation may be avoided. This is because capillary rise of water toward surface will suffice irrigation needs of saplings. Irrigation under situations of high water table may preferably be applied for leaching the salts, when accumulated in excessive amounts.

Afforestation programs where good quality water is not sufficient can only succeed if the poor quality groundwater aquifers are developed and utilized judiciously for irrigating the saplings. Using furrow technique of irrigation, saline waters of ECiw up to 12 dS m^{-1} in sandy loam and loam soils can successfully be utilized. In finer-texture soils (clay loam), saline waters of ECiw up to 6–8 dS m^{-1} can be used with some reduction in tree growth. Use of water having residual alkalinity renders the soils alkali. The severity of problem depends mainly upon the quality and quantity of water used. Since smaller irrigation quantities suffice for the growth of tree saplings using furrow method of irrigation, alkali waters are unlikely to cause any serious problem unless residual sodium carbonate (RSC) is excessively high (>10 meq l^{-1}). Under such situations, a gypsum bag may be kept in irrigation channel to neutralize RSC in the water.

To give proper shape to the plants and to get clear boll, annual pruning preferably during winter is required. The trees like *Acacia nilotica* and *Prosopis juliflora*, which have more number of branches require regular annual pruning. The lower one-third part must be pruned but not more than that. The trees like *Eucalyptus* do not require intensive pruning. The pruned biomass may be used as fuelwood. Lopping of selected *Acacia* trees at 16 and 42 months of growth gave 2.5 and 7.2 t ha^{-1} fuelwood, respectively. The tree plantation program should also include measures for protection against wild or stray animals. The protection may be with barbed wire fencing or live fencing of spiny bushes or unpalatable hedges. Environmentally safe animal repellents like "Ro-Pel" are now available, which may be sprayed on saplings.

Environmental and Socioeconomic Benefits from Agroforestry

With ever-increasing human and cattle population, we require increased production from the nonproductive salt-affected lands which need to be used for producing food, forages, timber, fuelwood, oil seeds, medicine, and other minor products. In the scenario of scarcity of good quality water for irrigation, the use of poor quality waters, particularly in the arid and semiarid regions is unavoidable. The judicious use of saline waters for conventional and nonconventional salt-tolerant crops through sustainable agroforestry systems is a viable option. Many halophytes provide high biomass and high protein or mineral levels with outstanding ability to a wide range of environmental stresses. Aronson (1989) identified more than 1,600 salt-tolerant plants of coastal and inland desert environments to have an economic potential. More than 1,000 plant species of economic importance are found on Indian saline environment (Dagar and Singh 2007). Many of these species find utilization as food, firewood, timber, forage, medicine, and minor products. When grown on salty lands, many species act as bioameliorative and soil acts as sink for carbon sequestration. In agroforestry systems, these not only provide food security but also create employment and improve microclimate and general environment and help in biodiversity conservation.

Le Houe'rou (1986), Sankary (1986), Aronson (1989), NAS (1990), Dagar et al. (1991, 1993), Lieth and Al Masoom (1993), Jaradat (2003), Dagar (1995, 2003, 2005, 2006), Alsharhan et al. (2003) and Dagar and Singh (2007) have generated valuable information regarding the potential economic value of salt-tolerant plants as food, forage, edible oil, fuelwood, liquid fuel, pulp and fiber, bioactive derivatives, medicine, landscape, and ornamental. With the increasing world population and the need for increased crop production, the nonproductive salt-affected lands and saline water (for irrigation) have to be used for producing nonconventional crops of economic value. Many halophytes are already being used for a variety of purposes by traditional societies as well as through scientific technologies by different stakeholders for high economic yield. Some halophytes have agricultural or industrial potential and their cultivation is also considered as a biological method for soil desalination and reclamation. A brief account of potential salt-tolerant plants particularly as agroforestry crops is given here.

Contribution of Agroforestry Crops to Food, Fodder and Fuelwood Production

Food

Biosaline agroforestry provides food in many ways, especially in areas where traditional agriculture cannot be profitably practiced. Appropriate halophytes can be domesticated (NAS 1990) as agroforestry crops and their seeds, fruits, roots, tubers, or foliage can be used directly or indirectly as food. Dagar and Dagar (1999) and Dagar and Singh (1999) listed several food plants in wild being consumed by the aborigines of the Bay Islands any many of these such as fruits of *Pandanus*, radicles of mangroves, tubers of Dioscoreas, nuts of coconut are consumed as stable food. There is ample evidence (O'Leary 1993, Dagar 2003, Dagar and Singh 2007) that little-known seed-bearing halophytes are potential candidate for germplasm resources for the development of salt-tolerant agroforestry crops in the Middle East and Central Asia. It has been reported (Aronson 1989) that almost 50 species of seed-bearing halophytes are potential source of grains and oil. Pearl millet (*Pennisetum typhoides*) grows well on sand dunes and tolerates EC of 27–37 dS m^{-1} for irrigation (NAS 1990) and yields 1.6 and 6.5 t ha^{-1} grains and fodder, respectively, and can be grown successfully as intercrop with many fruit trees of dry region (Dagar et al. 2008).

Many species of *Acacia* produce seed that are rich in nutrients, with higher energy, protein and fat contents. For example, *A. aneura* is potential oil crop (37 % fat), whereas *A. dictyphleba* is considered potential grain crop with 26.8 % protein content (Turnbull 1986, Goodchild and McMeniman 1987). Wild water chestnut (*Eleocharis dulcis*) produces tubers that can be cooked or pounded to meal (Glenn and O' Leary 1985). Similarly, the roots and stems of saltwort (*Batis maritima*) can be used for food as green leaves and the plant produces up to 17 t ha^{-1} of dry biomass using seawater for irrigation (NAS 1990).

Dagar et al. (1993) and Dagar and Dagar (1991, 1999) have listed many wild coastal plants of tidal zone used in one or the other form by the aborigines of Andaman-Nicobar Islands as food items. Among conventional crops, beet root (*Beta vulgaris*) and date palm (*Phoenix dactylifera*) are well known for their food value and these can be grown successfully irrigating with saline water and salt-tolerant rice varieties (e.g., CSR10, CSR 27, CSR 30, CSR 36) can be cultivated on sodic soil of high pH (up to 10). Fruit bearing gooseberry (*Emblica officinalis*), Karonda (*Carissa carandas*), Ber (*Ziziphus mauritiana*), and Bael (*Aegle marmelos*) withstand drought as well as salinity. These can be cultivated with success irrigating with water up to 12 dS m^{-1}. These along with guava (*Psidium guajava*) and *Syzygium cuminii* could be grown on highly alkali soil (pH up to 9.8) with application of amendments (gypsum) in auger holes. *Ziziphus nummularia, Lycium* spp., *Santalum acuminatum,* and *Coccoloba uvifera* are other potential fruit genetic resources.

Salicornia bigelovii and *S. herbacea* have been evaluated as a source of vegetable oil and the cake as animal feed (Riley and Abdal 1993, Dagar 2003). Samphire (*Salicornia bigelovii*) yields about 28.2 % seed oil, 31.2 % protein, 5.3 % fiber, and 5.5 % ash from seeds. Its oil resembles to Saffola oil and also considered for cosmetic and pharmaceutical industries. Straw and cake are used as forage and considered suitable for paper pulp. It can be irrigated with water of sea salinity and has been successfully grown in some coastal areas of Gujarat. Under seawater irrigation, *Salicornia* has been reported to produce 20 t ha^{-1} plant biomass, out of which, 2 t ha^{-1} as oilseed (NAS 1990). It withstands high salinity both of soil and water. Raw fruits of Kair (*Capparis decidua*) tree are used for pickles and possess medicinal value. It grows naturally on both saline and sodic soils and can be domesticated using saline water after preparing nursery from its rootstocks, seeds, and also stem cuttings and then transplanting. The coastal badam (*Terminalia catappa*), salt bush *Salvadora persica* and species of *Pandanus* are known for their oils of industrial application. Fruits of *Pandanus* are staple food for coastal population of Bay Islands and many species are found natural growing in tidal zone which can be improved and domesticated successfully in coastal areas. Palmirah palm (*Borassus flabellifer*), widely used for toddy, jaggery, vinegar, beverage, juice for sugar, and edible radicles and fruits is found widely distributed all along Andhra coast. It needs to be genetically improved for wider cultivation. The use of *Suaeda maritima* in *papar* industry in Rajasthan & Gujarat is well known. The young leaves and shoots of *Chenopodium album*, species of *Amaranthus*, *Portulaca oleracea*, *Sesuvium portulacastrum* and many others are used as vegetable and salad in many parts of India and other countries. Many of these are even cultivated as agroforestry crops. Many seed spices such as coriander, fenugreek, dill, celery, cumin etc. are moderately tolerant to saline irrigation (up to EC 10 dS m^{-1}) and are cultivated as agroforestry crops in dry regions.

Forage

Halophytes have been used as forage in arid and semi-arid areas for millennia. The value of certain salt-tolerant shrubs and grasses has been recognized by their incorporation in pasture-improvement programmes in many salt-affected regions throughout the world. There have been recent advances in selecting species with high biomass and protein levels in combination with their ability to survive a wide range of environmental conditions, including salinity (NAS 1990; Ulery et al. 1998; Barrett-Lennard 2003; Jaradat 2003; Dagar 2003, 2005a, b, 2006a, b, 2009). Halophytes suitable for forage production either as native stands or established as agroforestry crops include the herbaceous species: *Elymus elongatus, Leptochloa fusca, Aeluropus lagopoides, Hedysarum carnosum, Cynodon dactylon* vars *hirsutissimum* and *villosum*, *Puccinellia ciliata*, species of *Panicum*, *Paspalum, Sporobolus, Chloris, Brachiaria, Eragrostis*, etc.; the forage shrubs: *Haloxylon persicum, H. aphyllum, H. salicornicum, Kochia indica, Maireana brievifolia* and many Atriplex species (*amnicola, atacamensis, barclayana, canescens, cinerea, glauca, halomus, isatidea,lentiformis, nummularia, paludosa, polycarpa, semibaccata, undulata*); and plenty of tree genera such as *Acacia, Prosopis, Ficus, Balanites, Ailanthus, Ziziphus, Cordia, Salvadora, Capparis, Azadirachta, Feronia, Albizia, Cassia*, etc. are traditional fodder resources.

In many coastal areas where mangroves occur sporadically and there is scarcity of fodder, the foliage of many mangroves (*Avicennia, Ceriops, Bruguiera, Rhizophora, Kandelia,* etc.) and their associated species such as species of *Terminalia, Pongamia, Salvadora, Ficus* and many others, are used as forage for cattle, goats, and camel. Among grasses *Distichlis spicata*, *Paspalum vaginatum, Sporobolus virginicus, Pennisetum clandestinum*, and *Chloris gayana* have tolerance to waterlogging and low to moderate salinity. Mixed stands of these and other halophytic grasses may be managed for production of silage.

Grazing lands of arid and semi-arid regions are poor in yield. One site in northwestern India with average yield of 0.85 t ha^{-1} when protected from grazing could produce 2.4 t ha^{-1} forage and the same site when brought under cultivated grasses and irrigated with saline water (ECiw 8–10 dS m^{-1}) could produce up to 22 t ha^{-1} dry forage. Even in the lean period when people are forced to lead nomadic life along with their herds of cattle, sufficient forage (30 % of total) was available from these perennial grasses. Species of *Salicornia, Chenopodium, Kochia, Atriplex*, *Salsola, Suaeda, Trianthema, Amaranthus, Portulaca, Tribulus*, and *Alhagi* along with several grasses such as *Leptochloa fusca, Aeluropus lagopoides, Cynodon dactylon, Dactyloctenium sindicum, Paspalum vaginatum, Sporobolus airoides, S. marginatus, Chloris gayana, Echinochloa crus-gali, E. colonum, Eragrostis tenella, Dichanthium annulatum, Brachiaria mutica, Bothriochloa pertusa* and many others are commonly used as forages from alkali and saline grazing areas (Dagar 2006). As described earlier, many of these forages can be cultivated successfully on degraded salt-affected soils or in drought prone areas irrigating with saline water, where other arable crops cannot be grown.

Kallar grass (*Leptochloa fusca*) has gained attention in India and Pakistan as fodder grass for saline and highly sodic soils (pH as high as 10.4) producing more than 45 t ha^{-1} green forage. Biomass production by several grasses has already been discussed in this Chapter. Species of *Sporobolus, Brachiaria, Panicum, Dactyloctenium*, and *Eragrostis* are tolerant to high salinity. *Aeluropus lagopoides* is a dominant grass in entire Rann of Kutchh and is used for grazing. The grazing lands of sodic soils are poor in forage production under open grazing but when brought under judicious management these can be explored successfully for sustainable forage production.

Production of Fuelwood

Often fuelwood is obtained from salt-tolerant trees and shrubs, which include species of *Prosopis, Acacia, Tamarix, Casuarina, Eucalyptus, Parkinsonia, Capparis, Sesbani*a, and *Salvadora*. In coastal areas, the mangroves and their associates are widely used for fuelwood and timber leading to deforestation of these habitats. Species of *Rhizophora, Bruguiera, Ceriops, Kandelia, Avicennia*, *Sonneratia, Xylocarpus, Heritiera,* and *Excoecaria* are excellent fuelwood and are also used for making charcoal. *Avicennia marina* is one of the most widely distributed species throughout the mangal stands of the world and tolerates biotic stress. Many species have been planted successfully in coastal regions of Goa and Tamil Nadu. *Casuarina equisetifolia* has been widely planted along Orissa coast. *Beta vulgaris* and *Nypa fruticans* have been identified as potential source of liquid fuels while species such as *Jatropha curcas, Pongamia pinnata*, and *Euphorbia antisyphilitica* are among potential diesel–fuel plants and these can be grown successfully on degraded lands with saline irrigation. The energy yield (in the form of biogas) from *Leptochloa fusca* has been estimated at 15×10^6 kcal ha^{-1} (Jaradat 2003). At present, every year about 1.2 million tons of tree-borne nonedible seed oil is produced in the country (GoI 2008) and there is huge potential to increase this figure by planting these perennial plants on degraded including salt-affected lands.

Among fuelwood trees and bushes, *Acacia (ampliceps, linarioides, tortilis, nilotica, senegal, africana, auriculaeformis, saligna, ligulata), Azadirachta indica, Casuarina equisetifolia, C. glauca, Cajanus cajan, Commiphora riparis, Cassia siamea, Eucalyptus camaldulensis, E. tereticornis, Haloxylon aphyllum, Parkinsonia aculeata, Prosopis (alba, juliflora, tamarugo, chilensis, pallida, stephanian), Tamarix articulata, Salvadora persica* and *Ziziphus* are important.

Aromatic, Medicinal, and Other Uses

The global demand for herbal products is not only large, but also growing. The largest markets for medicinal and aromatic plants besides India are China, France, Germany, Italy, Japan, Spain, UK, and USA. Due to ever-increasing population, we have an optimum pressure on arable lands for cultivation of foodcrops; therefore, utilization of degraded wastelands including salt-affected soils is a viable option for cultivation of medicinal & aromatic plants.

There are many reports on the medicinal uses of halophytes (CSIR 1986; Dagar 1995, 2003; Dagar and Dagar 1991, 1999; Dagar and Singh 1999; Dagar et al. 1991, 1993, 2004a, b, 2005, 2006a, b; Dagar and Singh 2007). Among mangroves and their associate species, leaves of *Acrostichum aureum* are applied on wounds and boils; *Acanthus ilicifolius* and *A. volubilis* are used in rheumatism, neuralgia, paralysis, asthma, as blood purifier and dressing boils and wounds; *Barringtonia acutangula* for diarrhea, toothache; *B. racemosa* in cough, asthma, diarrhea, jaundice; seed oil of *Calophyllum inophyllum* in rheumatism, skin diseases and leprosy; *Cerbera manghas* in rheumatism; *Cynometra ramiflora* in leprosy, scabies and cutaneous diseases; *Heritiera fomes* to cure piles; *H. littoralis* in diarrhea and dysentery; *Xylocarpus granatum* and *X. moluccensis* in dysentery and breast tumors; *Terminalia catappa* in cutaneous diseases; *Sonneratia caseolaris* as vermifuge; *Thespesia populnea* in stomach trouble; and *Suaeda fruticosa* is used as emetic and to cure sores on camel back (Dagar and Dagar 1991, 1999; Dagar and Singh 1999, 2007).

Among other important salt-tolerant plants found as wild or cultivated in agroforestry systems, *Achyranthes aspera* is used in asthma, renal dropsis; *Adhatoda vasica* in asthmatic problems; *Aloe barbadensis* in piles, rheumatism, boils, and stomach problems; *Azadirachta indica* in skin infections, eczema, and ulcers; *Balanites roxburghii* in whooping cough, skin troubles, source of diosgenin for synthesis of several steroidal drugs; *Calotropis procera* in skin diseases, tumors, piles, and as abortifacient and anticoagulant; *Capparis decidua* to cure cough, asthma, inflammations, cardiac troubles and biliousness; alkaloids of *Catharanthus roseus* are used for leukemia and blood pressure; *Citrullus colocynthis* in jaundice, rheumatism, and urinary diseases; *Clerodendrum inerme* in malarial fever as substitute to quinine; *Cressa cretica* as tonic, aphordisiac, and stomachic; *Jatropha curcas* in diarrhea, toothache, piles, rheumatism and skin diseases; *Kochia indica* as cardial stimulant; *Pandanus odoratissimus* in leprosy, scabies, diseases of heart, and oil as antispasmodic; *Pongamia pinnata* in diarrhea, cough, leprosy, gonorrhea, and rheumatic pains; *Ricinus communis* in boils, sores, and lumbago; *Salsola baryosma* posseses anthelmintic, emmenagogue, diuretic properties; ash for itch; *Salvadora persica* and *S. oleoides* in cough, rheumatism, suppositories, toothache, and piles; *Solanum surattense* in cough, asthma, sore throat, and rheumatism; *Tamarix articulata* and *T. troupii* in eczema, ulcers, piles, sore throat, diarrhea, liver disorders; *Trianthema portulacastrum* in asthma, amenorrhea, dropsy, rheumatism, liver problems, and as abortifacient; *Tribulus terrestris* as tonic, diuretic, and in painful micturition and calculous affections; grass *Vetiveria zizanioides* in rheumatism, fever, headache, toothache, and as tonic; *Withania somnifera* in asthma, cough; *Ziziphus nummularia* in skin diseases, cold, cough, biliousness; and the herb *Zygophyllum simplex* has cardiac properties and applied in eye diseases (CSIR 1986; Dagar 2003; Dagar and Singh 2007).

Among potential agroforestry salt-tolerant high value crops of medicinal importance include Isabgol (*Plantago ovata*), Periwinkle (*Catharanthus roseus*), Aloe (*Aloe barbadensis*), celery (*Apium graveolens*), chrysanthemum (*C. indicum*), calendula (*C. officinalis*), *Azadirachta indica, Cordia rothii, Salvadora persica, Ricinus communis, Jatropha curcas, J. gossypifolia,* and *Adhatoda vasica*.

The important plants yielding aromatic oil include vetiver (*Vetiveria zizanioides*), palmarosa (*Cymbopogon martini*), and lemon grass (*C. flexuosus*). German chamomile (*Matricaria chamomilla*) is a medicinal and flower-yielding salt-loving herbaceous crop of winter season.

Seed of *Salvadora oleoides* and *S. persica* contain 40–50 % fat and is good source of lauric acid. Purified fat is used for soap and candle making. Among other products of economic value such as medicinal oil from *Terminalia catappa, Calophyllum inophyllum;* perfume from male flowers of *Pandanus spp;* essential oil from *Mentha piperita, M. arvensis* (entire plants), *Anethum graveolens* (fruit), and species of *Ocimum* (entire plant); beverages from mangrove palm *Nypa fruticans*; aromatic resin from *Grindelia camporum, humilis, stricta, latifolia*, *integrifolia*, and *Larrea tridentata*; aromatic oil similar to sperm whale oil from *Simmondsia chinensis*; rubber from *Chrysothamnus nauseosus* and *Parthenium argentatum*; pulp and fiber from *Phragmites australis, P. karka, Juncus rigidus, J. acutus, Pandanus tectorius, Typha domingensis, T. australis, Hibiscus cannabinus, H. tiliaceous, Urochondra setulosa* and many others; bioactive compounds from *Calophyllum inophyllum, Balanites roxburghii, Salsola baryosma, Catharanthus roseus*, and liquid fuel from *Jatropha curcas, J. gossypifolia, Pongamia pinnata, Ricinus communis* and *Euphorbia antisyphilitica* are worth mentioning.

Many salt-tolerant species can also be used as landscape plants, especially in areas where fresh water is not available for irrigation. These may include trees, shrubs, succulents, ground covers, and lawn grasses. These observations show that there lie promising avenues of research and development on halophytes leading to biosaline agroforestry.

Bioamelioration and Carbon Sequestration

The biomass production and bioamelioration properties of several trees and grasses in system mode have already been discussed above in this Chapter. Reclaiming waterlogged, salt-affected lands which are low in organic carbon, through fast-growing plantations is a useful strategy for carbon sequestration. Increase in soil carbon through plantations may also act as an important carbon sink. The results discussed in biodrainage section show that by raising strip plantations of *Eucalyptus* (4 % of total agricultural area) in waterlogged areas of Haryana, 1.33 million tons additional C would be sequestered per annum. Therefore, apart from lowering the groundwater table, *Eucalyptus* plantation provides additional benefits in terms of carbon sequestration. Available estimates suggest that land use may mitigate additionally from 1 to 2 Gt C per year. Restoration of 1×10^9 ha of soil in the tropics has a potential to sequester C at the rate of 1.5 Pg year^{-1} (Lal and Kimble 2000). Achieving this full carbon mitigation potential will require that we use all land use-related options for carbon sequestration. The present stock of carbon in Indian soils is estimated to 63.19 Pg (Velayutham et al. 2000), which is just 4.2 % of the world and the C carrying capacity of Indian soils is estimated to 85.04 Pg (Dagar and Swarup 2003), therefore, there is a scope of additional C sequestration of 21.85 Pg. Earlier, Gupta and Rao (1994) advocated that grasses and trees when planted on the degraded lands have a potential of sequestering 1.9 Pg in 7 years as against emission of 2.27 Pg during the same period thus may help in slowing down the warming. The estimation proposed by them is toward conservative side. Analyzing the productive potential critically this figure may go higher.

Agroforestry has been recognized as having high potential for sequestering carbon and mitigating climate change (IPCC 2007; Lal 2011; Dagar et al. 2012). On an average, carbon storage by agroforestry land use system has been estimated to be around 9, 21, 50 and 63 t C ha^{-1} in semi-arid, sub-humid, humid, and temperate regions, respectively (Schroeder 1994). In India, agroforestry potential (mainly on degraded lands) carbon sequestration (on average basis) has been estimated to be 25 t ha^{-1} (Sathey and Ravindranath 1998). Singh and Lal (2000) have estimated that by bringing 40 Mha degraded land under forest with 5 t C ha^{-1}, the carbon mitigation of 3.32 Gt would be possible in next 50 years with annual reduction of about 0.072 Gt of carbon. Thus, optimization of biomass production through multispecies stands in agroforestry or sole forestry on degraded lands should be the priority for sustaining the system and continuously improving the environment. Wherever there is a scarcity of good quality water for establishment of tree plantation or silvopastoral system or growing medicinal plants, underground saline water can successfully be used for irrigation.

Control of Salinity and Waterlogging Through Vegetation

Tree planting should be considered in conjunction with other modified farming practices that minimize groundwater recharge, such as changing from bare ground fallowing to minimum tillage cultivation practices and the use of deeper rooted crops/trees or pasture species. Recharge areas are zones of high water infiltration. Trees have two major beneficial effects: (i) interception and evaporation of rainfall and (ii) transpiration of soil water. In waterlogged saline areas, salt-tolerant grasses such as *Leptochloa fusca*, *Brachiaria mutica*, *Thinopyrum ponticum,* and *Puccinellia ciliata* can be established. Once established, less-tolerant trees, shrubs, and grass species can be established as the water table falls and salt is leached as a result of recharge control. In some locations, high density tree planting on recharge areas could be in the form of commercial plantations. As discussed earlier under biodrainage that trees play very important role in controlling the waterlogging caused by seepage in canal command areas. Trees such as *Acacia ampleceps, Eucalyptus tereticornis, E. camaldulensis, Casuarina glauca, C. equisetifolia, Terminalia arjuna, Pongamia pinnata,* and *Syzygium cuminii* and grasses such as *Leptochloa fusca, Phragmites australis, Dichanthium annulatum, D. caricosum, Brachiaria mutica,* and *Paspalum* spp. have credibility for lowering down water table in waterlogged areas.

We can safely conclude that biodrainage can effectively contribute strongly in reducing the problems experienced from waterlogging in irrigated and nonirrigated agriculture. At least it is a safe remedy to control seepage all along canals. The problem of salinization associated with rise in water table can effectively be delayed using strips of plantations in semi-arid and arid regions. Undoubtedly, the added advantages of biodrainage and biodisposal systems, depending on the vegetation used, include production of timber, fuelwood, other products such as oil, honey, fruits, fiber etc., contribution to carbon sequestration, diminishing the effects of wind erosion, provision of shade and shelter, function as wind breaks, soil amelioration through litter fall, enhancement of biodiversity, and improvement in general environment.

Conservation of Biodiversity

Biodiversity consists of a hierarchy of definitions from the molecular level through taxa to the landscape level. The United Nations Convention on Biological Diversity (CBD) defines biodiversity as “the variability among living organisms from all sources including inter alia, terrestrial, marine and other aquatic ecosystems and ecological complexes of which they are a part; this included diversity with in species, between species and of ecosystems” (CBD 1992). The issues of biological and genetic diversity management in agroforestry are complex.

Atta-Krah et al. (2004) have assessed the diversity within and between tree species in traditional agroforestry systems. Their assessment shows that although the practice of agroforestry has been a diversity management and conservation system, research in agroforestry over time has emphasized the diversity element; nevertheless, farmers do value diversity and do manage agroforestry from that prospective. As discussed in detail (Chap. 7), homegardens are rich in biodiversity both of higher plants as well as microorganisms. Based on a profiling of various traditional agroforestry systems and research development technologies, a strong case is made for increased species and genetic diversity, at both inter- and intraspecific levels. It has been well recognized that agroforestry can serve to bridge the conflict that often exists between the need for conservation of biodiversity and provision of needs of human society. More attention needs to be given to the need to conserve biodiversity, through promotion of sustainable management and use of our genetic resources.

While dealing with biodiversity of saline habitats, Dagar (2000, 2003) mentioned that the inland highly salty lands are either devoid of any vegetation or support very meager cover and only some restricted species are found in highly inland saline regions. Contrary to inland saline habitats, the coastal tidal areas are rich in biodiversity. The mangrove ecosystems support several interesting animals such as saltwater crocodiles, turtles, water monitor lizards, snakes, wild pigs, monkeys, deer, even tigers (in Sunderbans), several indigenous and migratory birds, skippers, crabs, mollusks, insects, crustaceous, and microflora and fauna species. These are nursery and breeding ground and source of food for variety of animals and microorganisms. The aerial roots, pneumatophores and branches serve as shelter and food for large number of organisms including many beautiful orchids, ferns, lichens, mosses, jungermanniales, algae, fungi, bacteria, ciliates, nematodes, and amphipods which colonize and take part in complex food chain of this unique ecosystem. But unfortunately, all these habitats are now under tremendous anthropogenic pressure. Many species of this ecosystem are at the verge of extinction. As a result of the unsustainable exploitation of these habitats, many species are dwindling at a fast rate and the entire biodiversity is at stake. Certainly, the afforestation of these habitats will improve the biodiversity.

Afforestation of inland salty soils not only supports a variety of wild life such as hare, deer, blue bull, and birds but also improves the microbial status of soil. In a recent study it was found that in a silvopastoral system microbial biomass carbon increased tremendously. There was a significant relationship between microbial biomass carbon and plant biomass carbon ($r = 0.83$) as well as the flux of carbon ($r = 0.92$) in net primary productivity (Kaur et al. 2002b).

While reviewing biological amelioration of salt-affected soils, Rao (1998) concluded that due to litterfall and root decomposition, the microbial activities in soil improved a lot. Biological reclamation of salty lands is based on increasing soil carbon levels by addition of organic materials. By growing tolerant tree and grass/crop species, we also increase microbial activities. Growing of nitrogen-fixing trees and green manuring crops, we not only ameliorate soil but also improve the microbial biodiversity. Various species of *Rhizobium, Azotobacter*, and vesicular carbuncular mycorrhiza (VAM) fungi are found associated with nitrogen-fixing trees. In salty soils, organic matter application/addition or inoculation of crops and trees with tolerant *Rhizobium* strains or VAM helps plants in tolerating stress through their nutrition. Rao and Ghai (1995), Rao and Pathak (1996) and Rao (1998) reported several evidences where cultivation of nitrogen-fixing trees/crops helped in amelioration of salt-affected soils and microbial diversity conservation.

Improvement in Microclimate and General Environment

No doubt, the agroforestry systems ameliorate the salty lands by addition of organic matter in the form of litter and decomposition of fine roots in the soil. The water infiltration rates of soil also improve to a greater extent. The mean air temperature under canopy is lowered during summer and increased during winter. In a study, Gill et al. (1990) and Gill and Abrol (1993) found that under *Acacia nilotica* canopy, the mean air temperature was lowered by 2–5 °C during summer and increased by 2–4 °C during winter (Fig. 9.19). Similar results were found under *Eucalyptus* plantation but the magnitude of the modifying effect was less because of less spread of canopy. The influence of the two canopies on the thermal regime of the soil at 5 cm and 15 cm depth was also of the modifying type. Fluctuations were more marked for soil temperature recorded at 5 cm depth than at 20 cm depth in open. Effects of the plantations during summer were of blanketing type and of sheltering type during winter. Modification in thermal characteristics due to tree plantations, thus, owes to their sheltering effect by cutting insulation and by their blanketing effect in restricting outflow of heat thereby keeping the ground warmer during winter and cooler in the summer.

Plantations also improve water intake in soils and thereby aid in conservation of rainwater which otherwise is lost as runoff. Alkali soils, otherwise poorly permeable, when planted with trees, the infiltration rate increased and thus the runoff decreased (Gill et al. 1990, Gill and Abrol 1993). Trees because of their deeper roots can meet their water requirement from the deeper horizons helping themselves in overcoming drought. A tree plantation on ridge of alkali soils was found to conserve whole of the annual precipitation. Land use of alkali soils as silviculture to reduce runoff was also reported by Kamra et al. (1987). The percentage of runoff due to fallow, pastoral (*Leptochloa fusca* grass), and silvicultural (*Acacia nilotica*) land use was found to be 87, 62, and 44 of a rainfall event. The revegetation of alkali soils with tree and grass species helped in reducing the runoff volume and peak runoff rate significantly as compared to fallow alkali soils. As discussed earlier, the general root environment under plant canopy is congenial for microbial population. Thus, through agroforestry systems, we obtain not only food, timber, fuel, and forage from trees and crops and ameliorate soil but the systems also improve the microclimate and general environment.

Food Securities and Employment Generation

The global Hunger Index (GHI), worldwide improved from 19.8 % in 1990 to 15.1 % in 2010. With the GHI at 24.1 %, India ranks to

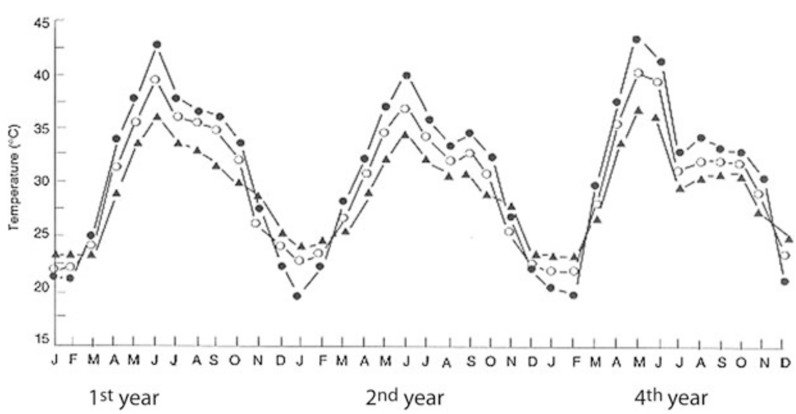

Fig. 9.19 Changes in atmospheric temperature in the bare fallow (●) and underneath canopies of *Eucalyptus tereticornis* (○) and *Acacia nilotica* (▲) *source* Gill and Abrol (1993)

67th position in the world, at an alarming high level. As per the UN report, India accounts for 42 % of world's underweight and about 40 % of the undernourished children (Rai 2013). Energy, iron, and vitamin A remain the major nutrient deficiencies in the semi-arid tropics. Due to population pressure, our forest and other natural resources including soil are dwindling at fast rate. Only nitrogen was deficient in our soil about 50 years ago. Now as many as 15 plant nutrients, both micro and macro, are deficient in major parts of the country. Some of the major nutrients like potash and phosphate are being imported. Therefore, focus on organic crop production, rejuvenation of old orchards, and high density plantations of fruit crops, rehabilitation of degraded (including salt-affected and waterlogged) lands, production and certification of quality planting material, popularization of tissue culture cultivation, establishment of improved storage facilities, value addition for enhanced income, establishment of suitable marketing chain, and farmer friendly agriculture policy ensuring food security and employment generation must get the outmost priority. In recent past, agroforestry practices have been paid more attention and hold a promising solution in the developing countries to help in securing food production, while protecting a safe environment and conserving biodiversity. Agroforestry will have close links with social forestry, particularly in degraded lands, to meet the needs of small holders and landless farmers.

In India, development of agroforestry-based technologies in harmony with biotechnological tools for rehabilitation of 121 Mha wastelands has the potential to enhance productivity, create additional employment avenues, and also provide resilience to 142 Mha of arable land through soil and water conservation and sequestering carbon in soil. Role of agroforestry in providing employment, particularly in the rural areas where there is often serious unemployment and poverty, is an important consideration. Abrol and Joshi (1984) estimated that roughly 216 mandays per ha are needed for initial establishment of forest plantation on alkali soils. For raising and managing *Acacia* and *Eucalyptus* for 7 years, approximately 1,092 and 940 mandays are needed, respectively.

Further, the watershed management technology (where agroforestry is major component), besides having the potential to reduce runoff from 42 to 14 % and soil loss from 11 to 2 t ha^{-1} is generating 215 mandays per ha per annum during implementation phase and 20 mandays per ha per annum in post-implementation phase (Rai 2005a, b). Thus, through implementation of improved agroforestry technology (including value addition to agroforest products), we stand a chance to capitalize on the natural resources on sustainable basis to eradicate poverty and nutrient imbalance. Agricultural produces in India including that from horticulture, dairy, fisheries, and animal husbandry amounting to more than 600 M tones in general is perishable. At present, post-harvest losses in India (so is true for many other developing countries) are estimated to be about 25 % and only 2 % is processed. The value addition is only 7 % of agro-produce as compared to 23 % in China, 30 % in Thailand, 70 % in Brazil, and 80 % in Malaysia.

Thus, the value addition and processing in the area of production is of paramount importance to convert the losses into earnings. The food and bioprocess engineers will always be needed to manage biological and food processes, improve process efficiency, food and worker safety, and reduce environmental degradation. Another important aspect is creation of suitable markets at the site of production. At present, the agricultural produce from production catchments is taken without any post-harvest processing to markets and processing industries located in urban areas. The farmer experiences the produce losses both qualitative and quantities during this transportation. In agroforestry, products presentation and packaging of fruit and vegetables-based products will not only generate many-fold income to rural population but also will generate employment. We need the production of fruit and vegetables, milk and meat, including poultry and fish products (with value addition) in accordance with the norms set for the consumers of the developed world. The developing countries like India will be able to diversify their agriculture and garner larger share in exports particularly in the scenario of a new global trade regime.

Gender Issues

There is increasing feminisation of agriculture in families with small and marginal holdings, particularly due to the out-migration of men. The problem is more acute in hilly areas of India like Uttranchal, Jharkhand, and North East States. In most of the developing countries (both in Africa and Asia), the women is deprived of property right. Besides sharing the labor in agriculture, she has responsibility of running the household, bringing the fuelwood from forest and cooking the food for the entire family. In many regions, they extract fruit juice, rear cattle, and prepare the country liquor. They have to earn for paying the fee for the school going children. Creating facilities of value addition to agroforestry products, employment can be generated for rural women. Garrity (2004) reviewed the role of agroforestry in the advancement of women. He stated that 60–80 % of the farmers in the developing world are women and in these countries rural women grow and harvest most of the staple crops that feed their families. In India, agriculture sector employs about 80 % of all economically active women and about 48 % of self-employed farmers are women. There are 75 million women engaged in dairying as against 15 million men and 20 million in animal husbandry as compared to 1.5 million men (Nagarajan et al. 2005). Women possess detailed knowledge of uses of plant and plant products for food, medicine, and animal feed. Women farmers possess a unique knowledge of plant products such as preparing pickles, milk products, fish processing and farming, cattle rearing, and handle most of the related works.

Women have trouble in diversifying their crops because they have difficulty obtaining the credit and land needed to shift to nontraditional exports. In India, out of nearly 44 million Kisan (farmer) Credit Cards issued till 2005, < 10 % were issued to women (Swaminathan 2005a, b). The proposed conferment of land rights to women will help to redress this distressing situation. Much more needs to be done to understand the kinds of traditional and nontraditional agroforestry products that are accessible to women, and to get research attention focused on them. This also applies to value-added processing activities and marketing. Trees are a medium for long-term investment on the farm. Thus, the propensity to cultivate them is particular sensitive to property rights. Policy research in agroforestry must continue to strengthen our understanding of these linkages. We need to assist in identifying the means by which womens' land rights can be made more secure to enhance the intensification of farming in general and the acceleration of tree cultivation in particular.

Efforts have been initiated in the recent past both by the governments and NGOs to incorporate gender issues in the development agenda to ensure womens' full and equitable participation agricultural (including agroforestry) development programmes. However, as stated above, statistics still indicate that these efforts have not been sufficient enough to bridge gender inequalities. Despite the key role of women in crop husbandry, live stock rearing, fisheries, forestry, and post-harvest technologies (particularly in value addition), those incharge of formulating packages of technologies, services, and public policies for rural areas have often tended to neglect the productive role of women. They have traditionally been discriminated in their access to productive resources and have been denied ownership of land, cattle, trees, harvest, and shelter and above all in access to credit and marketing facilities for their economic activities. It is thus, essential to develop strategies and mechanism to improve women's access to agricultural support services.

Other Social and Environmental Issues

Agroforesty is the major source of fuelwood, food, fodder, timber, tannin, gum, medicinal herbs, and a wide range of minor products. Biofuels are emerging as a renewable and eco-friendly source of energy which could help in enhancing the self-sufficiency in energy and minimizing dependence of a nation on imported fossil fuels. The feedstocks identified are molasses for the production of ethanol and tree-born nonedible oil-seed crops like *Jatropha* and *Pongamia* for the production of biodiesel. These plants have advantage as these can be grown on degraded lands. The National Policy on Biofuels, released in 2009, foresees biofuels as a potential means to stimulate rural development and generate employment opportunities, as well as aspires to reap environmental and economic benefits arising out of their large-scale use (GoI 2009). Every year around 1.2 million tons of tree-born nonedible seed oil is produced in the country (GoI 2008). Raju et al. (2012) have given insight to the potential, policy, and emerging paradigms to biofuels in India.

From adopting agroforestry especially on degraded lands, not only the individual farmer is benefited but the entire community around the area is benefited in many ways. The soil and water conservation measures by creating the bunds cross the nalas, fields, and ripping along the contour result in checking the soil erosion and harvesting rain water in situ. Creating the ponds for fish culture helps in meeting the water requirement of cattle and wild life population in surrounding areas. The grass harvested by local people from the afforested areas helps many families especially landless farmers to rear cattle and sustain their families. The trees influence the temperature extremes and help in percolation of rainwater into loose and porous soils (recharging of sub-soil water). The livefencing helps in protection of crop fields. Several medicinal herbs are collected by the local practitioners who sustain their families by subscribing plant-based drugs. Recently, the attention is being paid toward commercial forestry, raising block plantation of commercial trees, and also trees yielding biodiesel such as *Jatropha curcas, Pongamia pinnata, Ricinus communis*, etc. This approach will change the economical scenario by reducing the import of fossil fuels. As discussed in earlier sections, trees play a vital role both in lowering down water table (in waterlogged areas) and also recharging the groundwater in dry regions where water table is falling drastically. By adopting agroforestry practices, we shall be able to diversify the cropping pattern when more production will be obtained per unit of water available. Adopting biosaline agroforestry, the nomadic behavior of large population will be checked in dry regions. We need change in our policies tilting toward agroforestry.

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