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Sustainable Land-use Systems for Rehabilitation of Highly Sodic Lands in the Indo-Gangetic Plains of North-western India: Synthesis of Long-term Field Experiments

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Abstract

Land degradation is among the major challenges to meet the food requirement of ever-increasing global population. About 1 billion hectares of degraded lands are salt-affected, 54% being sodic soils. The traditional methods of applying chemical amendments for reclamation of sodic lands are costly enough and beyond the reach of small and marginal farmers and need government-support. Research efforts have shown that bio-amelioration through increasing organic carbon through re-vegetation is a viable option to restore these sodic lands. To find out the suitable agroforestry systems and affordable technologies involving salt-tolerant trees, grasses, arable and under-explored crops including high-value crops which besides having quick soil reclamation capability can also produce forages for livestock, wood biomass for fuel-wood and timber, food products and medicine to sustain the livelihood security. A series of long-term field experiments were conducted during last three decades by the authors and other associate workers on highly sodic (pH >10) soils of semi-arid region using alkali water found at the site for irrigation. This paper aims to synthesize the results of long-term studies on the ecological restoration of highly degraded sodic lands by using agroforestry practices. A synthesis of successful agroforestry interventions and results obtained from these studies are highlighted in this paper. The results of these studies established the fact that by integrating salt-tolerant trees including fruit trees, forage grasses, arable crops and under-explored crops (including high-value aromatic and medicinal crops) and using appropriate technologies are practicable for increasing agricultural production on these degraded lands. Agroforestry systems can support reclamation of these soils without applying costly amendments and drainage materials and sustain the livelihood security of resource-poor farmers dependent on these marginal lands. The fertilizer salt-tolerant multi-purpose trees, nitrogen-fixing grass (Kallar grass) are suitable for reclamation, whereas high-value halophytes, and commercial crops are suitable for semi-arid region.

Key words: Degraded sodic lands, Fertilizer trees, Nitrogen-fixing Kallar grass, Reclamation, Technologies

Introduction

Land degradation and climate change are the major constraints for producing sufficient food for ever-increasing population (Dagar *et al*., 2020a, b). Most assessments indicate that 20 to 40% of the world's lands are either highly degraded or subject to varying degrees of degradation (Gibbs and Salmon, 2015; FAO and ITPS, 2015; UNCCD, 2022). Therefore, it is a global priority to restore degraded lands and poverty alleviation besides attaining sustainable development goals (UNCCD, 2022). As per FAO/UNESCO Soil Map of the World, 831 million ha (Mha) area is salt-affected, out of which 434 Mha (54%) is sodic and rest saline soils (FAO, 2000). In India, out of 6.75 Mha salt-affected lands, 3.8 Mha are sodic lands, while rest are saline soils (Mandal *et al.,* 2010).

Reclamation of degraded sodic lands has involved a wide range of approaches and technologies. The farmers of Indo-Gangetic plains have put their efforts in using amendments, mostly gypsum (to replace sodium with calcium) through government-supported subsidy, and following the traditional rice-wheat cropping system. Now, the subsidy is no more available to the farmers, consequently the farming in sodic soils has become costly. Moreover, a large part of sodic lands are the community lands owned by *Panchayats* and also by marginal farmers who cannot afford the use of amendments. Many studies have indicated that bio-amelioration of barren sodic lands through protection from grazing, revegetation, afforestation and agroforestry has been possible, affordable and profitable using appropriate technologies (Singh *et al.,* 1993, 1995, 1997; Dagar *et al.,* 2001a, b; Singh and Dagar, 2005; Singh *et al.,* 2014, 2022). These approaches have the potential to add organic carbon in soil, hence, ameliorate degraded sodic lands to support livelihoods, improve food security, and help the resource-poor farmers, who cannot afford using costly amendments (Dagar and Gupta, 2020). Thus, with judicious use of planting technologies, these lands can be utilized successfully for providing fuel wood, timber, fodder, food and other essential products besides carbon sequestration, improving biodiversity and saving water. This study aims to synthesize the results of long-term studies on the carbon storage and ecological restoration of highly sodic land by using different land-use systems.

Materials and Methods

Study site

Several long-term studies were conducted on a highly sodic soil located in the Saraswati Reserve Forest, being maintained by the Haryana State Forest Department. The experiments were conducted at the Bichhian site (30°03′N and 76°18′E) in the Kurukshetra district of Haryana State in north-western Indo-Gangetic plains at an elevation of 240 m (Fig. 1). This site remained long-abandoned because of the severe alkalinity problem. The efforts to produce a viable forest

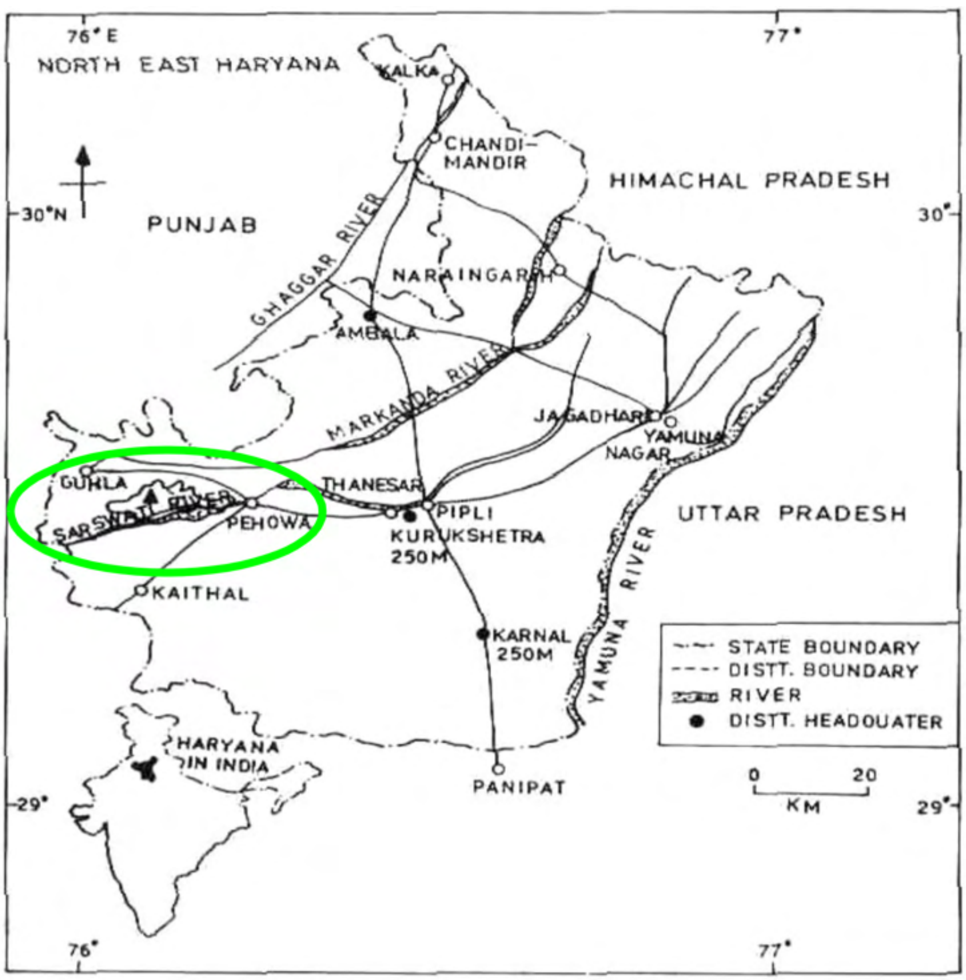

Fig. 1 Location of the experimental site at Bichian, Pehowa (Kurukshetra), in north-western India

cover by the Forest Department failed because of lack of appropriate technologies. The area is surrounded by a network of canals and is located in a relatively slight topographic depression. To conduct different experiments, an area of about 30 ha was cleared of bushes, levelled and fenced with barbed wires to provide protection from wild animals such as blue bull, deer, and stray cattle.

The climate of the study area is semiarid, monsoonic with little or no water surplus, megathermic with an aridity index of 63.38 and a moisture index of -38:03 as calculated by Sehgal *et al.* (1987) following Thornthwaite and Mather (1955). Mean annual rainfall and annual potential evapotranspiration (PET) of the area are 516 mm and 1407 mm, respectively producing an annual water deficit of 891 mm. Months with mean summer temperature >20 °C are eight. Mean annual temperature remains 24.6 °C, the mean summer and winter temperatures are 32.4 °C and 15.1 °C, respectively. During the experimental period, the actual annual rainfall ranged from 490 to 1216 mm during 7 years. The climatic features of the area during study period showed that the majority of the rainfall occurred during the months of July, August and September.

Experimental details

Protection of Native vegetation from grazing

The natural vegetation of the study site was sparse consisting of some trees, bushes and grasses represented by *Acacia nilotica, A. leucophloea, Capparis decidua, C. sepiaria, Prosopis juliflora* (exotic), *P. cineraria, Maytenus emerginatus, Clerodendron phlomidis, Butea monosperma, Ziziphus nummularia, Adhatoda vasica, Calotropis procera, Desmostachya bipinnata, Sporobolus marginatus, S. diandra* and *Cynodon dactylon.* Some other salt-tolerant plants associated with grasses were *Kochia indica, Suaeda fruticose, Pluchea lanceoleta,* and *Trianthema portulacastrum.* Some sparsely growing climbers of medicinal value growing during the rainy season included *Asparagus racemosus, Mukia maderaspatana, Cayratia trifolia, Cocculus pendulus, C. hirsutus* and *Momordica dioica.* A part of the fenced area was kept undisturbed to monitor the vegetation succession over the years and some communities were identified for biomass studies.

Afforestation with tree plantations

To study the performance of different tree species on highly alkali soil (profile pH > 10), a three-times replicated field experiment in split plot design was conducted planting 30 common multi-purpose trees used in agroforestry in shallow (20 cm diameter and 60-75 cm deep) and deep (20 cm diameter and 120-140 cm deep) auger-holes made by tractor-mounted augers (Fig. 2) keeping distance of 2 m from plant to plant and 4 m between rows. The total area of plantation was about 2.5 ha. The species included *Acacia auriculiformis, A. leucophloea, A. nilotica, Albizia lebbeck, Anthocephalus cadamba, Azadirachta indica, Bambusa arundinacea, Bombax ceiba, Butea monosperma, Cassia siamea, Casuarina equisetifolia, Cedrela serrata, Cordia rothii, Dalbergia sissoo, Eucalyptus tereticornis, Ficus rumphii, Kigelia pinnata, Leucaena leucocephala, Melia azedarach, Moringa oleifera, Parkinsonia aculeata, Pithecellobium dulce, Pongamia pinnata, Prosopis juliflora, Sesbania sesban, Tamarindus indica, Tamarix articulata, Tectona grandis, Terminalia arjuna*, and *Thespesia populnea*. For detailed planting methods see Dagar et al. (2001b) and Singh and Dagar (2005). Growth parameters such as survival, height and stump diameter were measured at six months interval. Roots of selected (successful) species (5 representative plants in each treatment of a species) were excavated after 2 and 7 years of planting by digging piths around the tree and cleaning the soil with jet-water pump at the experimental site. The fresh and dry root and shoot biomass were determined.

Fig. 2 Digging auger holes in highly alkali soil to pierce *kankar* pan ($CaCO_3$ layer) for planting tree sapling

Growing of fruit trees

There was a perception among the local people that most of the fruit tree species are senstive to salt stress in general and sodicity in particular. Therefore, to standardize the planting techniques and amendment dose to be used these experiments were conducted. One experiment of about 2 ha sodic land was designed to evaluate the response of different fruit tree species [Sapota (*Achras zapota*), Bael (*Aegle marmelos*), Karaunda (*Carissa carandas*), Goose berry (*Emblica officinalis*), Mulberry (*Morus alba*), Date (*Phoenix dactylifera*), Guava *(Psidium guajava*), Pomegranate (*Punica granatum*), Jamun (*Syzygium cuminii*), Tamarind (*Tamarindus indica*), and Ber (*Ziziphus mauritiana*)] to site preparation methods and quantity of gypsum amendment. Three-times replicated experiment in double-split design was conducted. In main plot, two methods of planting [pit-auger method (after making 45 cm × 45 cm × 45 cm pits manually and then piercing 1.6-1.8 m deep auger-holes of 25 cm diameter) and pit method (pits of 0.9 m × 0.9 m × 0.9 m were dug manually); and in sub-plots filling mixture was (i) in auger-holes, original soil + 5 kg gypsum + 10 kg FYM + 15 kg river silt + 20 g zinc sulphate and 20 g insecticide-hydrated benzene hexachloride powder; and in 2[nd] treatment all similar mixture except gypsum 10 kg] and in sub-plot 10 tree species were planted having 12 trees of each species in two-rows in row-to-row and plant-to-plant 4 m and 3 m space in two rows. Growth performance was observed at regular interval of 3 months and data were computed.

Silvopastoral systems

One three times replicated field experiment involving four tree species (*Acacia nilotica, Prosopis juliflora, Dalbergia sissoo* and *Casuarina equisetifolia*) in the main plot and three inter-crop-treatments in the sub-plots was initiated in August-September during rainy season. As the soils were highly sodic in nature having pH more than 10 and ESP more than 60 in all the soil depths (Table 1) and calcareous layer (*Kankar pan*) of precipitated $CaCO_3$ was present at various depths, auger-holes (25 cm diameter and 1.2 m deep) were dug with the help of tractor-mounted augers to plant trees before the rainy season. After planting of trees, four number of irrigations were provided with the help of bucket after making rings of 1 m diameter, which later connected with water channels for tube well irrigation.

The four tree species were planted with auger-hole technique (described above) accommodating 36 plants in each sub-plot in a 4 m × 2 m planting geometry. The inter-crop treatments included sole trees (without any grass), Kallar grass (*Leptochloa fusca*), and *Sporobolus marginatus* grass. In established plantations (3-months old), the root-stocks of grasses were planted at 50 cm (row-to-row) × 20 cm (plant-to-plant) spacings in August. No amendment was used for growing grasses except 100 and 20 kg ha^{-1} of nitrogen and zinc sulphate, respectively were applied after planting. The irrigation was applied on need basis.

The height of trees was measured with meter road and the girth using vernier-calliper. The biomass of grasses was measured after harvesting the entire plot when grasses got matured. To get the biomass of trees, 3 number of representing trees of different heights and girth from each treatment were harvested after 4 and half years of growth, air dried and biomass of different parts was measured with spring-balance. After termination of experiment soil samples were collected from 0-20 cm depth from each treatment to measure pH and organic carbon as described earlier. To measure the root biomass the monoliths of 3 plants of each species from each treatment were dug around trees up to 1.2 m depth (the roots of plants usually stay in auger-holes for initial 4-5 years) and taken near tube-well and washed carefully with jet-water-pump and air-dried and weighed.

Growing of grass species

Performance of 20 grass species was evaluated in a 3-time replicated experiment in 4 m × 4 m plots in highly alkali soil (pH 10.4) applying 3 treatments of gypsum, viz, 0, 25 and 50% of gypsum requirement (GR). Observations recorded after 4 months showed that grasses such as *Saccharum benghalensis, Cymbopogon martini, C. flexuosus, C. nardus, Eulaliopsis binata*, *Sorghum halepense, Pennisetum purpureum, Cenchrus ciliaris, C. setigerus*, and *Setaria glauca* could not survive

Fig. 3 Typical sodic soil at the Bichian experimental site (left) and soil profile (right) showing *kankar* -calcic ($CaCO_3$) layer

even in gypsum treated plots. Therefore, only successful grasses such as *Leptochloa fusca, Brachiaria mutica, Sporobolus marginatus, Panicum laevifolium, P. virgatum, P. antidotale, P. maximum, Chloris gayana, Saccharum spontaneum* and *Chloris gayana* were taken under further observations regarding survival and biomass production. The root biomass was determined by excavating soil monoliths, washing the roots under a fine jet of water, air-drying and consequently oven-drying and weighing in the laboratory.

Soil analysis

Before starting the experiment, four soil profiles were dug at representative sites. Soil samples were collected at an interval of 15 cm, air- dried and subsequently oven-dried. After grinding, the samples were passed through a 2-mm sieve and analysed for physico-chemical parameters. Mechanical analysis for sand, silt and clay contents was done following Pipett method (Piper, 1966). The pH and electrolytic conductivity of the soil were determined in 1:2 soil-water suspension using digital pH-meter and conductivity meter (Jackson, 1973); organic C was quantified using Walkley and Black rapid titration method as modified by Walkley (1947); available P was determined by the Olsen's sodium bicarbonate extraction method (Olsen and Dean, 1965); exchangeable Na^+ was determined by flame Photometer; Ca^{2+} and Mg^{2+} content were determined through titration method as described by Jackson (1973). Values of $CaCO_3$, CO_3^{2-}, HCO_3^-, and Cl^- contents were analysed following standard method described by Jackson (1973).

Irrigation water analysis

The irrigation water was also analysed for pH and EC (using digital pH and electrical conductivity meters, and for Ca^{2+}, Mg^{2+}, CO_3^{2-} and HCO_3^- using methods as described by Richards (1954) and Jackson (1973). Residual sodium carbonate (RSC) was determined as:

$$RSC\ (me\ L^{-1}) = (CO_3^{2-} + HCO_3^-) - (Ca^{2+} + Mg^{2+}).$$

Results and Discussion

Initial soil properties and water quality

The soils of study site were extremely sodic in entire field (Fig. 3). The pH values throughout the profiles were almost more than 10, at times reaching up to 10.8. Electrical conductivity also varied and was high especially in upper layers. Organic carbon was low. The most peculiar feature of the soil profiles was the presence of precipitated $CaCO_3$ layers (*kankar pans*) at various depths (Fig. 3) necessitating the need of deeper auger-holes to pierce these for planting trees. The $CaCO_3$ contents varied from negligible amounts at the surface to about 24% nearer to 1m depth. It varied to great extent more so in middle layers and similarly carbonate and bicarbonate contents were very high making the soils typical sodic. The phosphorus and potash contents were sufficient. The amount of Ca + Mg, Na, CO_3, HCO_3 and Cl in the surface varied from 3-6, 194-369, 72-232, 16-160 and 22-540 me L^{-1}, respectively (Table 1).

The groundwater used for irrigation was also sodic with pH 8.3 and the Residual Sodium

Table 1. Initial soil properties of the experimental site (Average of 4 profiles)

Soil depth (cm)	pH (1:2)		EC_2 (1:2)		OC (g kg^{-1})		$CaCO_3$ (%)		Available P (kg ha^{-1})	
	Range	Mean	Range	Mean	Range	Mean	Range	Mean	Range	Mean
0-15	10.4-10.8	10.6	2.2-5.4	3.4	0.4-0.9	0.6	0-11.4	3.0	65-83	71
15-30	10.5-10.7	10.6	1.3-5.2	3.1	0.2-0.5	0.4	0-14.8	4.0	39-80	58
30-45	10.3-10.7	10.4	1.0-3.6	1.9	0.1-0.6	0.3	1.0-23.4	8.1	22-65	45
45-60	9.9-10.4	10.2	0.5-7.4	2.4	0.2-0.6	0.4	5.6-36.1	23.2	15-43	37
60-90	9.6-10.3	10.1	0.4-1.6	0.9	0.3-0.5	0.4	3.9-36.1	17.1	12-55	27
90-120	9.4-10.2	9.9	0.5-1.1	0.7	0.3-0.5	0.4	2.7-20.0	9.7	15-28	23
	Na (me L^{-1})		Ca + Mg (me L^{-1})		CO_3 (me L^{-1})		HCO_3 (me L^{-1})		Cl (me L^{-1})	
	Range	Mean	Range	Mean	Range	Mean	Range	Mean	Range	Mean
0-15	194-369	256	3-6	4	72-212	147	16-160	66	22-540	178
15-30	90-312	191	2-4	3	40-216	112	12-100	47	44-220	105
30-45	50-218	120	2-4	4	28-128	59	12-104	39	8-48	37
45-60	13-369	120	2-4	3	12-200	65	8-188	62	6-124	39
60-90	20-81	40	1-3	2	8-48	23	8-20	11	6-30	16
90-120	15-33	23	1-3	2	16-28	19	8-16	10	4-22	12

Carbonate (RAC) ranged from 7.2 to 10.8 me L^{-1} and bicarbonate contents were 8.0 to 10.9 me L^{-1} and. electrical conductivity was low about 1 dS m^{-1}.

Effect of protection from grazing on natural vegetation

During the very first year of protection from grazing, grasses such as *Chloris barbata, C. variegata, C. gayana, (Cynodon dactylon, Cenchrus ciliaris, C. setigerus* in pockets), *Eragrostis* spp., *Dichanthium annulatum, Panicum antidotale, Dactyloctenium aegyptium*, *Echinochloa crusgalli, E. colona* and *Paspalum* spp with many annual herbs appeared as colonizers. *Desmostachya bipinnata* and *Sporobolus marginatus* retained their dominance. During rainy season, plant species such as *Cassia tora, C. occidentalis, Abutilon indicum, Croton bonplandianum, Trianthema triquetra, Eclipta prostata, Amaranthus virdis, Achyranthus aspera, Veronia cinerea, Oldenlandia diffusa, Commelina* spp., *Sida* spp, species of *Cyperus, Corchorus, Euphorbia (*mainly *hirta* and *thymifolia),* and many annuals appeared uniformly. In the third year, the number of these species increased whereas density of *Suaeda fruticose* and *Kochia indica* declined to the minimum. After fourth year of protection, the standing dry biomass of all species ranged from 1.7 to 2.7 kg m^{-2}. Even after 4 years, *Desmostachya bipinnata* and *Sporobolus marginatus* were the dominant communities (Fig. 4a), the later on higher pH soil. However, the density of the palatable species like *Cynodon dactylon, Dichanthium annulatum, Cenchrus setigerus, Digitaria ciliaris, Eleucine indica, Panicum antidotale, Paspalum* spp., and *Echinocloa colona* increased considerably. In the protected stand, five grass communities were identified (Table 2), which when harvested at maturity could provide 17.0 to 26.8 Mg ha^{-1} dry forage biomass and 5.6 to 11.2 Mg ha^{-1} dry

Table 2. Harvested dry biomass at maturity of 5 grass communities and pH and organic carbon in upper 20 cm soil depth.

Grass community	Harvested dry biomass (Mg ha^{-1})		Soil pH		Soil organic C (g kg^{-1})	
	Forage	Roots	I	F	I	F
Desmostachya bipinnata	26.8	11.2	10.2	9.9	0.42	0.93
Sporobolus marginatus	18.2	7.5	10.4	10.1	0.39	0.85
Dactyloctenium aegyptium-Chloris virgata	16.8	5.6	10.2	10.0	0.43	1.32
Chloris virgata-Sporobolus marginatus	24.4	8.2	10.3	10.0	0.41	1.02
Dichanthium annulatum-Cynodon dactylon	17.0	6.0	10.2	9.8	0.45	1.43

I= initial, F= after 4 years

root biomass. The grasses also helped in improving the organic carbon through litter and root decomposition, consequently reducing the soil pH (Table 2).

Performance of multi-purpose tree species

After one year of plantation, there was no significant difference in survival of species in two auger depths because the roots were still in the auger-holes and most of the species showed 80 to 100% survival except *Cassia fistula, Cedrela serrata, Bombax ceiba, Tectona grandis* and *Thespesia populnea,* which were too sensitive to sodicity and high temperature. Dagar *et al*. (2001b) and Singh and Dagar (2005) have given details of performance of all trees every year. After 7 years of plantation, the plants which had more than 50% survival in both deep and shallow auger depths included *Tamarix articulata, Acacia nilotica, Prosopis juliflora, Eucalyptus tereticornis, Pithecellobium dulce, Terminalia arjuna, Dalbergia sissoo, Cordia rothii, Kigelia pinnata,* and *Parkinsonia aculeata*. The pruned biomass in these species varied from 2.64 to 73.31 kg ha^{-1} in deep auger-holes and 1.47 to 31.75 kg ha^{-1} in shallow auger-holes. Their carbon storage both in shoot and roots is shown in Table 3. *Tamarix articulata* stored maximum carbon (53.35 Mg ha^{-1}) followed by *Acacia nilotica* (34.25 Mg ha^{-1}), *Prosopis juliflora* (26.98 Mg ha^{-1}) and *Eucalyptus tereticornis* (8.41 Mg ha^{-1}) in deep augers and 16.89, 18.37, 11.45 and 2.90 Mg ha^{-1}, respectively in shallow auger-holes. The growth could not take place in shallow auger-holes and plants remained stunted; therefore, deep auger-holes are essential in these soils. Besides fruit trees the biomass from local grasses harvested from interspaces was 8 to 10 Mg C annually with about 1.8-2.4 Mg C from standing root biomass.

Another interesting feature was that despite of the fact that all trees of a species were from the same source, there were huge variation in growth among trees of the same species. To find out reasons for such a variation in tree growth, extensive soil sampling was done at 0-30 cm depths at a grid of 4 m × 4 m along transects in East-West and North-South directions. The data were analysed for pH, EC_2, organic carbon and $CaCO_3$ contents (as described under soil analysis). Data on pH showed least standard deviation 0.8 (CV 9%), whereas $CaCO_3$ content showed highest variation (CV 83%) as shown in Table 4.

The change in soil properties were significant under four most successful trees on the sodic soils (Table 5). *Tamarix articulata* ameliorated the soil by inducing the maximum reduction in soil ESP and pH values in 7 years of growth. It was followed by *Prosopis juliflora, Acacia nilotica* and *Eucalyptus tereticornis.* The organic carbon content in 0-15 cm layer under *T. articulata* increased from 0.5 to 2.8 g C kg^{-1}; under *P. juliflora* from 0.4 to 3.0 g C kg^{-1} and under *A. nilotica* from 0.2 to 1.4 g C kg^{-1}; and under *E. tereticornis* from 0.4 to 1.2 g C kg^{-1}.

Table 3. Plant biomass carbon (Mg ha^{-1}) in different tree species after 7 years of growth in highly sodic soil at Bichian , Kurukshetra, North-western India

Tree species	Deep augers			Shallow augers		
	Shoot	Root	Total	Shoot	Root	Total
Tamarix articulata	38.93	14.42	53.35	12.68	4.21	16.89
Acacia nilotica	27.91	6.34	34.25	15.64	2.73	18.37
Prosopis juliflora	20.51	6.47	26.98	8.82	2.63	11.45
Eucalyptus tereticornis	5.78	2.63	8.41	2.08	0.82	2.90
Pithecellobium dulce	2.59	1.39	3.98	0.89	0.75	1.64
Terminalia arjuna	1.07	0.60	1.67	0.71	0.47	1.18
Dalbergia sissoo	0.70	0.42	1.12	0.50	0.30	0.80
Cordia rothii	0.73	0.59	1.32	0.38	0.23	0.61
Kigelia pinnata	0.66	0.47	1.13	0.30	0.20	0.50
Parkinsonia aculeata	0.56	0.34	0.90	0.36	0.21	0.57

LSD ($p<0.05$): Between species=2.38; between auger depths= 0.47; auger depth × species 1.48

Table 4. Summary of statistical analysis of data (mean lateral surface variability)

Soil parameters	Range	Mean	SD	CV (%)
pH (1:2)	9.0-10.5	9.8	0.8	9
EC_2 (dS m^{-1})	0.2-3.6	1.6	0.63	52
OC (g $kg^{-1)}$	0.1-0.6	0.2	0.16	61
$CaCO_3$ (g kg^{-1})	0.2-7.8	4.5	3.68	83

Table 5. Change in soil properties under the four most successful trees after 7 years of plantation

Species	pH_2				EC_2 (dS m^{-1})				OC (g kg^{-1})				ESP			
	I		F		I		F		I		F		I		F	
	A	B	A	B	A	B	A	B	A	B	A	B	A	B	A	B
T. articulata	10.4	10.5	9.2	9.9	3.05	1.13	0.36	0.50	0.5	0.3	2.8	0.9	85	92	35	62
P. juliflora	10.4	10.5	9.7	10.1	3.15	1.20	0.67	1.02	0.4	0.2	3.0	1.4	87	93	54	69
A. nilotica	10.5	10.6	10.1	10.3	3.20	1.36	0.88	1.23	0.4	0.2	1.4	0.8	91	93	71	79
E. tereticornis	10.4	10.5	10.1	10.3	3.20	1.42	1.32	1.00	0.4	0.2	1.2	0.6	89	94	78	82
LSD ($p<0.05$)	NS	NS	0.36	0.14	NS	NS	0.32	0.16	NS	NS	1.4	0.3	NS	NS	4.71	3.43

I=initial value, F=after 7 years; A=soil layer 0-15 cm, B= 15-30 cm; NS=not significant

In similar situations, Singh *et al*. (2008, 2014) reported biomass production and soil amelioration by growing ten multi-purpose species in Indo-Gangetic plains of Uttar Pradesh near Lucknow. The growth performance and ameliorative process was comparatively faster as compared to those reported in these studies because of higher rainfall, low mean temperature in summer and good quality underground water used for establishment of trees.

Growth performance and biomass carbon of fruit trees

Growth observations recorded after 2 years of planting showed that survival, height and stump diameter of all species remained unaffected owing to site preparation methods and amendment levels. Irrespective of planting techniques and amendment (gypsum) used, Jamun, guava, Ber, and pomegranate gave best performance. Singh *et al.* (1997) and Dagar *et al*. (2001b) gave more details on these parameters. Some of the fruit tree species such as pomegranate and Bael were sensitive to water stagnation hence raised and sunken bed technique was developed (Dagar *et al*., 2001a) in which the trees could be raised on bunds and crops like rice and Egyptian clover in sunken beds. Aboveground and belowground carbon storage indicated that pit-cum auger hole technique with higher dose of gypsum was perfect for fruit cultivation followed by pit methods with higher dose of gypsum (Table 6) but the digging of pits in these soils is highly cumbersome and costly affair, hence pit-cum auger hole technique with higher dose of amendment is most appropriate way of growing fruit trees and species sensitive to water stagnation may be grown on raised bunds. After 7 years, Ber, Jamun, guava and goose berry performed very good and produced good biomass when 10 kg gypsum per auger-hole was applied per auger-hole (Table 6) and the same may be recommended for these soils. Besides fruit trees the biomass from local grasses harvested from interspaces was 12 to 15 Mg C annually with about 2-3 Mg C from standing root biomass.

Silvopastoral systems

Irrespective of the treatment, after four years of planting, the maximum survival (96%) was in the case of *Prosopis juliflora* followed by *Acacia nilotica* (90%), *Dalbergia sissoo* (82%) and minimum (32%) in the case of *Casuarina equesitifolia*. When integrated with *Leptochloa fusca* and *Sporobolus marginatus*, the survival of trees was better with *Leptochloa fusca*. The high mortality in *Casuarin*a was due to two reasons, one, occurrence of frequent frost during winter (*Casuarina* being a semi-tropical plant is sensitive to frost); secondly,

Table 6. Plant biomass C (Mg ha^{-1}) of 7 years old fruit trees grown in pit-cum-auger hole and pit methods with application of different amount of gypsum in these methods

Species	Auger hole (5 kg G)			Auger hole (10 kg G)			Pit (10 kg G)			Pit 20 kg G		
	AG	Roots	Total	AG	Roots	Total	AG	Roots	Total	AG	Roots	Total
Emblica officinalis	2.64	0.90	3.54	3.39	1.15	4.54	3.40	1,41	4.81	6.80	1.49	**8.29**
Psidium guajava	1.79	0.71	2.50	2.22	3.10	**5.32**	2.38	0.82	3.20	3.57	1.05	4.62
Syzygium cuminii	3.62	0.94	4.56	4.18	5.23	**9.41**	3.05	1.25	4.30	6.81	1.54	8.35
Ziziphus mauritiana	3.53	0.92	4.45	4.14	5.51	**9.65**	4.31	6.18	10.49	5.35	1.69	7.04
Carissa carandas	0.89	0.76	1.15	1.16	0.42	1.58	1.70	0.57	2.27	2.14	0.80	2.94
Tamarindus indica	2.75	1.30	4.05	2.70	1.35	4.05	2.92	1.30	4.22	3.30	1.60	4.90
Phoenix dactylifera	0.58	0.46	1.04	1.96	0.48	1.44	1.32	0.65	1.97	3.10	0.75	3.85
Morus alba	0.73	0.66	1.39	1.02	0.77	1.79	1.30	0.82	2.12	2.00	1.03	3.03
LSD ($p \leq 0.05$)			AG			Root			Total			
Between planting techniques (A)			0.24			0.10			0.21			
Between amendment dose (B)			0.29			0.07			0.17			
Between species (C)			0.21			0.12			0.27			
Interaction A × B			0.20			NS			0.24			
Interaction A × C			0.50			0.17			0.38			
Interaction B × C			0.30			NS			0.38			
Interaction A × B × C			0.41			NS			0.54			

AG=Above ground; G=gypsum, NS= not significant

due to less tolerance to moisture stress as irrigation was stopped after two years of growth. On the contrary, the other three tree species could withstand the stress and adapt well to the arid environment. The *Sporobolus* exhibited greater adverse effect on growth of trees as compared to that of *Leptochloa*, because roots of *Leptochloa* grass have the capacity of fixing nitrogen in soil due to an association of its roots with nitrogen-fixing bacterium *Azoarcus* and *Klebsiella pneumoniea* (Malik *et al*., 1986; Qureshi *et al*., 1989). It has been estimated that nearly half of the plant N (90-120 kg ha^{-1}) is derived from associative fixation (Malik and Zafar, 1984; Malik *et al*., 1986) and helps the plant to survival in adverse habitats such as sodicity, salinity and waterlogging.

Trees were pruned of side branches up to one-third of the total stem-length, at 16 months, 30 and 45 months after planting to assess fuel wood production. The total air-dried biomass (used as fuelwood) in different species ranged from 3-4 Mg ha^{-1} in *Acacia,* 8-10 Mg ha^{-1} in *Prosopis*, 2-3 Mg ha^{-1} in *Dalbergia* and 2-2.5 Mg ha^{-1} in *Casuarina. P. juliflora* is much branched, hence could substantially yield fuelwood biomass. Total aboveground and belowground (root) C biomass after $4^{1/2}$ years was maximum in *P. juliflora* in all treatments followed by *A. nilotica* and *D. sissoo* (Table 7).

In one experiment comprised of *Acacia nilotica* + *Desmostachya bipinnata*, *Dalbergia sissoo* + *Desmostachya bipinnata* and *Prosopis juliflora* + *Desmostachya bipinnata* the bole wood (that can be used as small timber) was found to be 4.62–9.78 Mg ha^{-1}, and branch wood biomass (that can be used as fuelwood) production ranged from 4.16 to 20.82 Mg ha^{-1} year^{-1} (Kaur *et al*., 2002a). A view of the silvopastoral system of *Prosopis juliflora* with *Desmostachya bipinnata* is shown in Figure 4b. The system was found quite effective in improving soil fertility and sequestering carbon. Organic carbon increased by 24-62% in soils under different silvopastoral systems mentioned above as compared to sole grass system.

The C biomass of trees indicated that *Prosopis juliflora* produced maximum above and below-ground C biomass (7.96 to 12.74 Mg C ha^{-1} and 1.36 to 2.14 Mg C ha^{-1}, respectively) followed by *Acacia nilotica* (3.84 to 6.28 Mg C ha^{-1} and 1.62 to 32.14 Mg C ha^{-1}, respectively) and lowest by *Dalbergia sissoo* (3.48 to 4.86 Mg C ha^{-1} and 1.16 to 1.98 Mg C ha^{-1}, respectively). As *Casuarina* was not successful in these situations and most of the plants died, hence not reported. Another

Fig.4 (a) Growth of native grasses comprised of *Desmostachya bipinnata* and *Sporobolus marginatus* on sodic soils during the rainy season; (b) silvopastoral system of *Prosopis juliflora* with *Desmostachya bipinnata*

Table 7. Above and belowground C biomass (Mg ha^{-1}) of trees (n=3) in the sole plantation and the trees integrated with *Leptochloa fusca* and *Sporobolus marginatus* after four and half-years growth

Treatment	*Acacia nilotica*		*Prosopis juliflora*		*Dalbergia sissoo*	
	AG	BG	AG	BG	AG	BG
Sole trees	4.96 ± 1.04	1.64± .42	10.04± 1.72	1.62 ±0.64	4.32± 0.88	1.42 ± 0.94
T + Lf	6.28 ± 0.72	1.96±0.62	12.74± 2.01	2.14± 0.74	4.86± 1.16	1.98 ± 1.06
T + Sm	3.84 ± 0.84	1.16± 0.30	7.96 ± 0.86	1.36± 0.37	3.48± 0.84	1.16 ± 0.64
LSD (p≤0.05)	1.42	0.83	1.62	0.85	1.08	0.62

Depictions: AG=Aboveground, BG=belowground, T=tree, Lf= *Leptochloa fusca*, Sm= *Sporobolus marginatus*

interesting feature was that trees in association with Kallar grass (*L. fusca*) got advantage and gained better growth and biomass as compared to sole trees and in association with *Sporobolus* the growth and biomass was reduced. As stated earlier, Kallar grass fixes atmospheric nitrogen in the roots, hence associated trees got advantage while *Sporobolus marginatus* is a bunch forming grass which could have retarded the growth of associated trees. Besides these studies, Dagar *et al.* (2001b), Singh *et al*. (1993), Singh and Dagar (2005) and Singh *et al.* (2008, 2012, 2022) have found *P. juliflora* and *A. nilotica* along with *Tamarix articulata* and *Eucalyptus tereticornis* as suitable tree species for growing in sodic soils. Now, germ plasm of improved bole-forming thornless trees of *Prosopis juliflora* and *P. alba* is also available with CSSRI and CAZRI, Jodhpur, which may be preferred as agroforestry trees for highly sodic soils.

Tree-based systems for forage production

The forage yield of Kallar grass (*Leptochloa fusca*), irrespective of plantations was 2-3 times more than *Sporobolus marginatus*. During first two years the impact of plantations on yield was lesser as compared to 3rd and 4th year when canopy development was taken place. The canopy of *P. juliflora* and *A. nilotica* was denser due to maximum survival of plants, hence the yield reduction of grasses was also more. As there was higher mortality of *Casuarina* hence lower competition with grasses, therefore, the grass yield was higher as compared to other tree species but lesser than the sole grasses. The yield and C biomass of grasses in association with *Dalbergia sissoo* was higher as compared to *Acacia* and *Prosopis* because of lesser canopy cover and density of the plants (Table 8). More cuts and biomass were obtained during rainy season (data not reported).

Table 8. Forage biomass C (Mg ha^{-1}) of *Leptochloa fusca* (Lf) and *Sporobolus marginatus* (Sm) grasses when cultivated along with different tree species

Associate trees	Average standing biomass C (Mg ha^{-1} yr^{-1})		Standing root C harvested after 4 years (Mg ha^{-1})	
	Lf	Sm	Lf	Sm
A. nilotica	6.48	2.12	2.38	1.04
P. juliflora	6.24	1.88	2.18	1.23
D. sissoo	6.80	2.16	2.50	1.47
C. equisetifolia	6.96	2.28	2.86	1.82
Sole grasses	7.24	2.56	3.32	2.13
LSD (p£0.05)	0.56	0.32	0.24	0.21

Lf=*Leptochloa fusca,* Sm= *Sporobolus marginatus*

Leptochloa fusca proved more productive under sodic conditions as compared to that of *S. marginatus* when grown in association with trees. It has been reported that the leaf-sheath of *L. fusca* helps in regulating the Na^+ contents of its lamina by retaining the major portion of Na^+ (Malik *et al.*, 1986). Its tolerance to salt stress and water stagnation for longer period and nitrogen-fixing capacity makes it most suitable species for reclamation of high pH soils and forage production. Singh *et al.* (2022) in one well-conducted study on highly sodic soils reported that fodder grasses such as *Chloris gayana, Panicum maximum* and *Pennisetum purpurium* when cultivated under 10 years old trees of *Acacia nilotica, Casuarina equesitifolia* and *Eucalyptus tereticornis* produced significant amount of forage and helped in reducing soil pH and ESP values significantly.

The performance of ten grasses at the same site was evaluated and found that *Leptochloa fusca, Brachiaria mutica, Sporobolus marginatus* (not a preferable forage), *Panicum virgatum* and *Vetiveria zizanioides* (tolerates stagnation of water and roots also yield an aromatic oil) were most successful species (Fig. 5) for highly sodic soils.

Carbon sequestration in the soil - plant system

The trees on salt-affected soils have the potential for carbon sequestration by increasing soil carbon and plant biomass production (Singh *et al.*, 1995; Bhojvaid and Timmer, 1998; Garg, 1998; Kaur *et al.,* 2002 a, b). In an age sequence of *Prosopis* plantations, trees have been found to ameliorate highly sodic soils by alleviating sodium toxicity and improving the build-up of soil fertility (Bhojvaid and Timmer, 1998). These workers showed the average annual rate of increase of 1.4 Mg C ha^{-1} yr^{-1} over a 30-years period of *Prosopis* plantation.

Carbon pools in *Prosopis juliflora* + *Desmostachya bipinnata* and *Prosopis juliflora* +

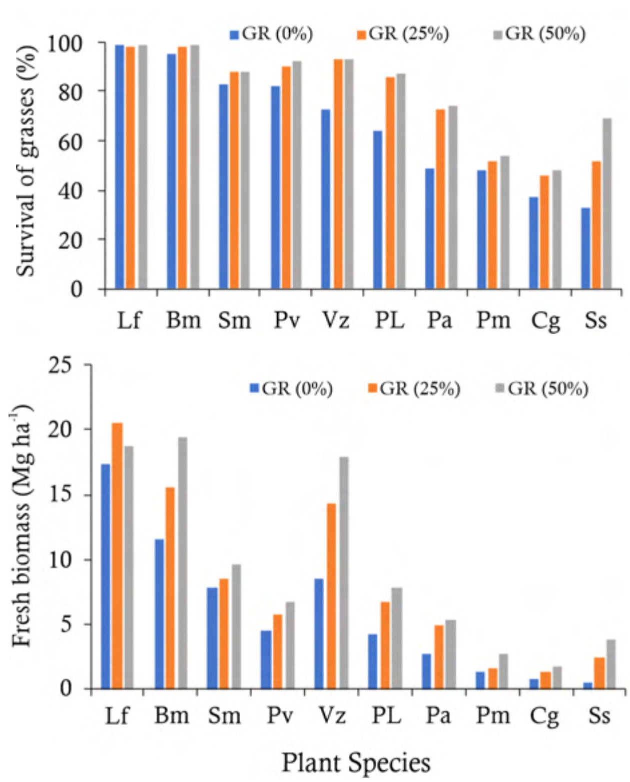

Fig. 5 Performance of some grasses on highly alkali soil (pH >10) with and without gypsum application [Depictions: Grasses Lf= *Leptochloa fusca*, Bm= *Brachiaria mutica,* Sm= *Sporobolus marginatus* Pv=*Panicum virgatum* Vz= *Vetiveria zizanioides Pl=Panicum laevifolium Pa=Panicum antidotale* Pm= *Panicum maximum* Cg=*Chloris gayana* Ss=*Saccharum spontaneum* GR stands for gypsum requirement]

Sporobolus marginatus silvopastoral systems on a highly sodic soil at Bichhian (study site) the total carbon storage was 1.18-18.55 Mg C ha^{-1} and carbon input in net primary production ranged from 0.98 and 6.50 Mg C ha^{-1} $year^{-1}$ (Kaur *et al.,* 2002 a). The aboveground woody biomass carbon in *Prosopis juliflora* + *Desmostachya bipinnata* silvopastral systems, bole and branches comprised 82% of the total biomass carbon in six-year-old systems (Kaur *et al.,* 2002a). Total carbon storage was 18.54 to 12.17 Mg C ha^{-1}, and carbon input in net primary production varied from 6.50 to 3.24 Mg C $ha^{-1}year^{-1}$. In the *Prosopis juliflora* + *Desmostachya bipinnata* and *Prosopis juliflora* + *Sporobolus marginatus* silvopastoral systems on sodic soils at Bichhian, the soil carbon pool ranged from 13.431 Mg C ha^{-1} to 9.621 Mg C ha^{-1} (Kaur *et al.,* 2002a).

Soil enrichment and bioamelioration

There are no two opinions that trees and grasses improve the soil properties in terms of increase in organic carbon and reducing the soil pH and ESP values to a greater extent. More is the tree growth more will be its ameliorating capacity. For example, *Tamarix articulata, Prosopis juliflora, Acacia nilotica* and *Eucalyptus tereticornis* being most successful trees could also improve the soil fertility. Dagar *et al.* (2001a, b), Singh and Dagar (2005) and Singh *et al.* (2008, 2014, 2022) have reported results of long-term experiments showing the ameliorating capacity of various tree species successful in sodic soils. *Leptochloa fusca* grass when grown with any tree could ameliorate the soil to a greater extent due to its nitrogen-fixing capacity. In these experiments the decrease in pH under sole *L. fusca* and *S. marginatus* was from 10.2 to 9.8 and 9.9, respectively, while increase in OC was from 1.2 g kg^{-1} to 2.2 and 1.8 g kg^{-1}, respectively. Because of better growth performance of *P. juliflora* in sodic soils, more litter-fall and improved soil microbial status as reported earlier by Kaur *et al.* (2002a) the organic carbon accumulation was more. The total litter-fall from 5-7 years old trees ranged from 0.34 (*Casuarina*) to 3.41 (*P. juliflora*) Mg ha^{-1} yr^{-1} and was 2.05 Mg ha^{-1} yr^{-1} in *Dalbergia sissoo* and 1.81 Mg ha^{-1} yr^{-1} in *A. nilotica*. The soil amelioration was more when the grasses were cultivated in association with trees as compared to sole trees or sole grasses. *L. fusca* was more effective than *S. marginatus*. It is reported that pH of alkaline soils is highly sensitive to changes in the partial pressure of CO_2 and the release of CO_2 from roots facilitates the replacement of adsorbed Na^+ in calcareous soils by solubilizing the native $CaCO_3$ and thus enhances the process of soil reclamation (Abrol and Gupta, 1990). Marked increase in organic carbon content in tree + *L. fusca* grass may be attributed to an increase in biological activity in the previously barren soil as a result of grass root development, litter fall, fine root decomposition, and nitrogen fixation by trees and grasses. *L. fusca,* besides having nitrogen-fixing bacterium association has quite high lignin content which may serve as a good substrate for the synthesis of humus (Malik *et al.*, 1986). Therefore, by cultivating *L. fusca*, it is possible to improve the stable organic matter in alkali/sodic soils, which are characterised by a very low level of soil organic matter.

Soil microbial biomass is a labile fraction of soil organic matter comprising 1 to 3% of total soil organic matter (Jenkinson and Ladd, 1981) and plays a key role in soil nutrients cycling. In salt-affected soils, the size and dynamics of soil microbial biomass carbon pool have been found to vary with land use type (Kaur *et al.*, 2000) and tree species (Kaur *et al.*, 2002 b). The soil microbial biomass at two soil depths in different silvopastoral agroforestry systems on highly sodic soils was: 71.0 to 140.02 kg C ha^{-1} 0 to 7.5 cm; 36.00 to 54.35 kg C ha^{-1} in 7.5 to 15.0 cm soil depth.

According to Kaur *et al.* (2002b), there was 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. Nitrogen mineralization rates were found greater in silvopastoral systems as compared to that of the sole grass system. Soil organic matter was also positively correlated with microbial biomass carbon, soil nitrogen, and nitrogen mineralization rates ($r = 0.95$–0.98, $p<0.01$) (Kaur *et al.*, 2002 b).

Desmostachya bipinnata and *Sporobolus marginatus* are salt adapted grasses, which showed moderately high diversity of arbuscular mycorrhizal (AM) fungi in their rhizosphere growing on sodic soils (Jangra *et al.*, 2011). The arbuscular mycorrhizal species belonging to G*lomus* and *Acaulospora* have been found to dominate the AM fungal species occurring in the rhizosphere of these salt adapted grasses. The density of arbuscular mycorrhizal (AM) fungal spores in soil of the sodic grassland systems was: 0-15 cm soil depth, 22.8 to 60.8 g^{-1} soil; 15-30 cm soil depth, 9.6 to 18.4 g^{-1} soil. The AM fungi associated with salt adapted grasses could play an important role in bioamelioration and soil carbon storage. Mycorrhizal fungi are reported to sequester large amounts of C in living, dead and residual hyphal biomass in the soil, and may be mediating soil carbon sequestration (Treseder and Allen, 2000).

Conclusions

To rehabilitate highly alkali soils, besides proper planting techniques such as pit-cum-auger-hole and raised and sunken beds (for stagnant water), suitable species tolerant to sodic salts, stagnation of water and also frost is very important. For common property lands species such as *Acacia nilotica, Prosopis juliflora, Eucalyptus tereticornis, Tamarix articulata, Dalbergia sissoo* and *Casuarina equisitifolia* (areas not having frequent frost) are most suitable species to prefer. Silvopastoral system involving forage grasses such as *Leptochloa fusca, Brachiaria mutica, Panicum laevifolium* and *P varigata* is most appropriate system for such lands. On farmers' fields many fruit trees such as guava, goose berry, sapota (areas without frost), Karonda, and Jamun are most suitable species. Bael (*Aegle marmelos*) and pomegranate are sensitive to water stagnation, hence may be cultivated on raised bunds. These species not only sustain livelihood but will also sequester significant amount of carbon and ameliorate the soil to the extent that later we may grow any crop on these soils.

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