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Bio-amelioration of alkali soils through agroforestry systems in central Indo-Gangetic plains of India

Y.P. Singh • Gurbachan Singh • D.K. Sharma

Abstract: A long-term field study was initiated during 1995 at Central Soil Salinity Research Institute, Regional Research Station, Lucknow (26°47′58″ N and 80°46′24″ E) to analyze the effect of agroforestry systems on amelioration of alkali soils. Three agroforestry systems (pastoral, silvipastoral and silvicultural) were compared with the control where no agroforestry system was introduced. Tree-based silvicultural and silvipastoral systems were characterized by tree species *Prosopis juliflora* and *Acacia nilotica* along with grass species *Leptochloa fusca*, *Panicum maximum*, *Trifolium alexandrium* and *Chloris gayana*. Growth of ten-year-old *Prosopis juliflora* and *Acacia nilotica* planted in combination with grasses was significantly higher over the silviculture system with the same species. Tree biomass yields of *P. juliflora* (77.20 t·ha^{-1}) and *A. nilotica* (63.20 t·ha^{-1}) planted under silvipastoral system were significantly higher than the sole plantation of (64.50 t·ha^{-1} and 52.75 t·ha^{-1}). Fodder yield under the pastoral system was significantly higher than the silvipastoral system during initial years but it was at par with that of silvipastoral systems after eight years of plantation. The microbial biomass carbon in the soils of silvipastoral systems was significantly higher than in soils under sole plantation of trees and control systems. The *Prosopis*-based silvipastoral system proved more effective in reducing soil pH, displacing Na$^+$ from the exchange complex, increasing organic carbon and available N, P and K. Improvement in soil physical properties such as bulk density, porosity, soil moisture and infiltration rate was higher in the *Prosopis*-based silvipastoral system than in the silviculture system or control. On the basis of biomass production and improvement in soil health due to tree + grass systems, silvipastoral agroforestry system could be adopted for sustainable reclamation of highly alkali soils.

Keywords: agroforestry systems, alkali soils, biomass production, microbial biomass, soil amelioration

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Introduction

Amelioration of alkali soils is essential for sustaining food, fuel, fodder, fiber, and timber production for an ever increasing human population (Garg and Jain 1992; Gill and Abrol 1991; Jain and Garg 1996; Singh, 1975). Geographically, the Indo-gangetic plains lies between 21° 55′ to 32° 39′ N and 73° 45′ to 88° 25′ E and is comprised of the states of Punjab, Haryana, U.P. and part of Bihar (North), West Bengal (south), and Rajsthan (north). Salt-affected soils of Indo-gangetic alluvium (2.7 million ha) constitute centuries old barren alkali soils without any land use system (NRSA & Associates 1996). A large tract of common lands (either government lands or village panchayat lands) are not in any productive use (Singh 2009). Alkali soils belonging to small and marginal farmers is unproductive because of high pH and exchangeable Na$^+$ percentage, which adversely affect physico-chemical and biological properties of these soils (Oster et al. 1996; Oster et al. 1999; Qadir et al. 1996; Qadir et al. 1997; Qadir et al. 2001). Presence of hard kankar (calcite) pan at a depth of about 90 cm of the soil profile is a major problem for planting of deep rooted plants (Garg 1998; Jain and Singh 1998; Singh 1989a). Tree growth in alkali soils is constrained mainly by the inability of roots to penetrate this calcite pan. Judicious use of these lands can substantially contribute to increasing demand for food, fodder, fuel and timber in India. Planting of trees and grasses on alkali soils provides an alternative to control further deterioration of these soils and to maintain soil health (Thorrold et al. 1997; Singh et al. 2008). Several studies have been conducted to measure the increase in N status of the soil under varying N$_2$- fixing tree species (*Acacia* spp.). Because alkali soils are poor in organic carbon, the rates of organic carbon and N accumulation tend to be greatest in the first five years of plantation (Luken and Fonda 1983). Karnal grass (*Leptochloa fusca*) is suitable for pasture because it can tolerate extremely

alkaline conditions (Kumar 1996). Rhodes grass (*Chloris gayana*) and Gatton panic (*Panicum maximum*) are highly succulent, palatable and quick-growing grasses that have proven highly salt tolerant and produce abundant biomass in salt affected soils (Kumar and Abrol 1986; Bogdan 1977). Growing of these fodder species in combination with *Prosopis juliflora* and *Acacia nilotica* improved the soil health to such an extent that less tolerant but more palatable fodder species such as *Trifolium alexandrium* and *Melilotus parviflora* could be grown. Our study was initiated in 1995 to examine the potential of different agroforestry systems and to quantify their ameliorative effect on alkali soils. We focused on the evaluation of agroforestry systems for biomass production and soil ameliorating properties to meet the increasing demand for fuel wood and fodder due to lack of good quality arable land (Chaturvedi and Behl 1996; Hellden 1992; Swaminathan 1980; Toth 1981).

Materials and methods

Experimental site

Our field experiment was initiated during 1995 at the research farm of Central Soil Salinity Research Institute, Regional Research Station, Lucknow, Uttar Pradesh (26°47′58″ N and 80°46′24″ E), on the Indo-Gangetic alluvial plains of India. The study site was representative of large areas of abandoned alkali soils of the Indo-Gangetic plains that have been classified as

typical Natrustalfs with sandy loam on the surface, silty loam and clay loam in middle horizons, and sandy loam in lower horizons (Sharma et al. 2006). These soils displayed physical and nutritional problems due to poor soil water cover and soil-air relations caused by high bulk density (> 1.5 $g \cdot cm^{-3}$) and very poor infiltration. Soils were strongly alkaline (pH of 10.2) with electrolytic conductivity (EC) of 1.55 $dS \cdot m^{-1}$ and exchangeable sodium percentage (ESP) of 89% in the upper 0–15 cm soil layer with a predominance of carbonate and bicarbonate of Na^+ (Table 1). The climate is semi-arid, subtropical and monsoonal with average annual rainfall of 817 mm. Mean climatological data for the study area covering 1995–2005 are given in Fig. 1.
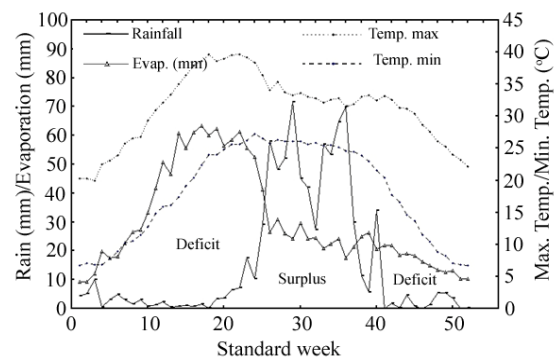
Fig. 1: Annual variations in rainfall, temperature and evaporation averaged during the period of 1995–2005.

Table 1: Initial soil physico-chemical properties of the experimental site

Soil depth (cm)	Sand (%)	Silt (%)	Clay (%)	Textural class	Bulk density ($g \cdot cm^{-3}$)	Porosity (%)	pH (1:2)	EC (1:2) ($dS \cdot m^{-1}$)	ESP	O.C. ($g \cdot kg^{-1}$)
0–15	63.4±1.45	18.8±0.61	17.8±0.60	l	1.66±0.01	42.4±0.60	10.5±0.10	1.43±0.10	89.0±2.50	0.8±0.02
15–30	48.0±2.10	25.2±0.75	26.8±0.80	Sil	1.59±0.02	44.2±0.50	10.6±0.20	2.42±0.10	82.6±4.00	0.8±0.03
30–45	48.6±0.80	38.0±2.40	35.0±1.10	Sil	1.60±0.01	44.4±0.30	10.6±0.10	2.02±0.08	82.0±5.00	0.6±0.02
45–60	42.0±1.20	23.0±0.70	35.0±2.10	Cl	1.66±0.04	42.2±1.00	10.4±0.10	0.86±0.09	80.2±2.60	0.6±0.02
90–120	52.5±0.90	25.0±1.20	32.5±1.00	Cl	1.74±0.02	33.2±0.70	9.7±0.20	0.44±0.20	60.4±3.20	0.6±0.02

Soil depth (cm)	$CaCO_3$ ($g \cdot kg^{-1}$)	Available N ($kg \cdot ha^{-1}$)	Olsen's P ($kg \cdot ha^{-1}$)	Available K ($kg \cdot ha^{-1}$)	$Ca^{++}+Mg^{++}$ ($mEq \cdot L^{-1}$)	Na ($mEq \cdot L^{-1}$)	K ($mEq \cdot L^{-1}$)	CO_3 ($mEq \cdot L^{-1}$)	HCO_3 ($mEq \cdot L^{-1}$)	Cl ($mEq \cdot L^{-1}$)
0–15	14.1±2.10	94.00±1.20	19.5±0.40	388±22.50	1.60±0.21	141.0±0.70	0.11±0.01	118.0±0.50	24.0±0.50	12.0±0.30
15–30	12.6±1.20	62.72±2.00	18.6±0.50	388±21.20	2.10±0.12	129.0±1.10	0.10±0.01	84.00±0.30	21.00±0.60	9.0±0.21
30–45	23.2±2.00	54.60±1.50	17.5±0.20	321±12.40	2.20±0.20	110.0±1.20	0.10±0.02	54.5±0.45	21.0±0.20	7.0±0.14
45–60	23.2±4.00	47.04±1.50	17.7±0.40	404±21.20	1.60±0.40	52.7±0.80	0.06±0.01	26.00±0.19	18.0±0.10	7.0±0.15
90–120	124.6±0.90	37.63±1.25	16.6±0.20	169±11.20	2.10±0.40	5.00±1.25	0.01±0.02	1.00±0.30	3.50±0.19	3.0±0.20

l= loam; sil= silty loam; sicl= silty clay loam; cl=clay loam; ESP: Exchangeable sodium percent

Soil analysis

To characterize the physico-chemical properties of the experimental site, composite soil samples were taken to 120 cm depth from three soil profiles. These samples were mixed and homogenized. The samples were air dried, ground in a Willey mill and passed through a 2.0-mm sieve. The pH and EC of the soil were determined in 1:2 soil-water suspension using a digital pH meter

and a digital conductivity meter following the procedure outlined by Singh et al. (1999). Organic carbon was quantified using the Walkley and Black rapid titration method as modified by Walkley (1947). Available N was determined by distillation of soil with $KMnO_4$ and NaOH (Subbiah and Asija 1956). ESP was calculated by the formula ESP = [exchangeable Na^+ ($cmolc \cdot kg^{-1}$) × 100/CEC ($cmolc \cdot kg^{-1}$)] (Richards 1954). The concentrations of Ca^{2+} and Mg^{2+} were estimated by an Inductivity Coupled Plasma

Analyzer (Perkin Elmer), and Na^+ and K^+ were measured by Flame Photometer. Soil bulk density (BD) was determined by weighing a known volume of a core sample of 5.3 cm internal diameter (Wilde et al. 1964). Soil porosity was determined using the procedure described by Brady (1990). Soil samples for moisture analysis were taken at monthly interval from 50 cm away from tree trunks at 0, 0.15, 0.30, 0.60, 0.90 and 1.20 m soil depth and dried at 105°C for 24 hours. Double concentric infil-trometer cylinders with 60 cm outer and 30 cm inner diameters were used (Brechtel 1976; Yadav and Vasistha 1989) to measure the infiltration rate.

Experiment

Five treatments comprised of T_1 - control (barren) where no agroforestry system was initiated and the plot was kept undisturbed; T_2 - pastoral system (Karnal grass (*Leptochloa fusca* (*L.*) for four years followed by Gatton panic grass (*Panicum maximum)* for six years (without amendments); T_3 - Only tree plantation (*Prosopis juliflora* (Swartz D.C.); T_4 - Only tree plantation (*Acacia nilotica*); T_5 - silvipastoral system (*Prosopis juliflora + L. fusca* for four years followed by Berseem (*Trifolium alexandrium*) for six years (without amendments) and T_6 - silvipastoral system (*Acacia nilotica + L. fusca*) for four years followed by Rhodes grass (*Chloris gayana*) Kunth (L.) (T. Mannetie & Kertsen S.M.M. 1992) for six years without amendments. Natural grasses were allowed to grow in T_1, T_2 and T_3. The natural grasses such as *Sporobolus marginatus*, *Cynodon dactylon*, *Aristida abscendens*, *Launnacea procumbens*, *Verimonia cineria* and *Cyprus difformis* that regenerated under the trees and control treatments were harvested annually. *L. fusca* planted under pastoral and silvipastoral systems for four years was harvested quarterly and used as fodder for cattle. Similarly, *P. maximum* and *C. gayana* planted after four years as sole and in combination with trees respectively were harvested quarterly. *T. alexandrium* a seasonal fodder grass was harvested five times during the cropping season (October–April) after which the plot was allowed to grow natural grasses. All these grass species were used as fodder for cattle.

Planting methodology

Nine month old saplings of tree species *viz. P. juliflora* and *A. nilotica (L)* of almost uniform height, collar diameter and phenotype raised in the state government forest department nursery in normal soil were planted during September 1995 in auger holes of 45 cm diameter at the surface, 20 cm at the base and 120 cm deep in a Randomized Block Design (RBD). Three rows of twelve plants each (36 plants) were replicated four times, keeping a distance of 5 m and 4 m between the rows and plants, respectively. Each augerhole was filled with a uniform mixture of original soil + 4 kg gypsum + 10 kg FYM+ 20 kg river sand before planting. The amount of amendment was determined by volume of soil extracted from the augerhole and the alkalinity of the soil. No fertilizer was applied to the plants during the study period. For establishment of saplings, three irrigations with 10

cm depth of water were applied monthly during the first year after planting and thereafter once annually in June.

Root slips of Karnal grass (*L. fusca*) were planted under pastoral and silvipastoral systems at 50 cm × 30 cm plant to plant and row to row spacing without application of any amendment for four years. After four years, *L. fusca* was replaced with *P. maximum* a perennial and shade tolerant grass, *T. alexandrium and C. gayana.* Root slips of *P. maximum* and *C. gayana* were planted in 1999 during the rainy season at 50 cm × 30 cm plant to plant and row to row spacing. However, *T. alexandrium*, an annual grass, was sown every year during October at a seeding rate of 25 kg·ha^{-1}.

Tree growth and biomass

Tree growth parameters including plant height, diameter at breast height (DBH, at 1.30 m above ground level), diameter at stump height (DSH, at 0.65 m above ground level), crown diameter and pruned biomass were measured five and ten years after planting. To measure the pruned biomass and to stimulate growth of trees and inter-planted grasses (Singh et al. 1989), side branches up to one third of the total stem length were pruned during the dormant period. The pruned biomass of the trees was used as fuel. Four randomly selected trees representing the range of size variations were harvested ten years after planting by cutting at the ground surface and each plant component was weighed separately on air dry basis for biomass estimation using a stratified sampling procedure. Stump root and lateral roots of the sample plants were excavated and cleaned by applying a gentle jet of water at the site. Four trees of each diameter class were marked for the annual increments. In this study, we used the Gompertz non-linear growth model using curve expert version 1:3 for calculating the annual increment (Draper and Smith 1998):

$$Y = ae^{-eb^{-cx}} \tag{1}$$

where, Y is the biomass yield (t·ha^{-1}), a, b and c are the regression constants, x is the age of the plant, and e is the constant.

The biomass yield of natural grasses regenerated under control, silvicultural and silvipastoral systems was estimated at the termination of the growing season and measured on annual dry weight basis. The data were analyzed statistically using standard analysis of variance in M STAT-C software. The treatment comparisons were made using a *t*-test at 5% level of significance.

Microbial biomass

The microbial biomass carbon was estimated by the fumigation extraction method (Vance et al. 1987). Sieved soil samples at 40% water holding capacity were fumigated with alcohol free chloroform in vacuum dessicators and stored in the dark for 24 hours. After removing the fumigant the soil samples were extracted with 0.5 M K_2SO_4 for 30 min on a shaker. The extracts of fumigated and unfumigated samples were analyzed for determining the organic carbon using the acid dichromate method.

Results and discussion

Tree growth

Survival percentage and growth of plants ten years after planting did not differ significantly (Table 2). Higher values were, however, recorded in T_5 and T_6. The highest survival rate was recorded in T_5 followed by T_6, T_3 and T_4. Similarly, plant height at ten years in T_5 and T_6 was higher than in T_3 and T_4. This was because of improvement in soil fertility, higher nutrient and water availability and suitable hydrothermal conditions that developed in the soil and stimulated plant growth (Singh et al. 1987). DBH, DSH and crown diameter in T_5 and T_6 were higher than in T_3 and T_4.

Table 2: Performance of trees under different agroforestry systems 10 years after planting

Treat-ments	Survival (%)	Average Height (m)	Mean diameter of DBH (cm)	DSH (cm)	Crown diameter (m)
T_1	-	-	-	-	-
T_2	-	-	-	-	-
T_3	90	4.83	6.82	12.84	8.63
T_4	81	4.53	7.51	12.21	7.2
T_5	95	5.21	10.1	15.57	8.87
T_6	93	5.16	8.22	13.49	7.73
LSD ($p<0.05$)	NS	NS	NS	NS	0.71

LSD: Least significant difference.

Tree biomass production

We estimated average pruned biomass production during the ten-year period (Table 3). Maximum pruned biomass (3.35 t·ha⁻¹) was recorded in T_4 and minimum pruned biomass (2.56 t·ha⁻¹) was recorded in T_6. The *P. juliflora* silvipastoral system (T_5) produced significantly greater pruned biomass than the *Acacia* silvipastoral system (T_3). Singh et al. (1989a) reported that the plant height of *P. juliflora* increased significantly with pruning of trees in highly alkali soils. Pruning of side branches of trees helps the trees grow better and also improve the forage yield of inter-planted grasses (Singh et al. 1989). The dry biomass production was estimated by uprooting the trees ten years after planting (Table 3). Biomass was greatest in T_5 and least in T4 (Table 3). The *P. juloflora* based silvipastoral system (T_5) produced significantly drier biomass than T_3, T_4 and T_6. This was because of higher availability of moisture, nutrients and fixation of N through N_2 fixing grass species planted in the treatment. Malik et al. (1986) and Singh et al. (1987) reported higher tree growth and biomass yields with nitrogen fixing leguminous intercrops. Annual increments in biomass yield in T_6 (6.83 t·ha⁻¹) and T_5 (6.73 t·ha⁻¹) during years 0–5 of tree growth were similar both were greater than in T_3 and T_4. However, during years 5–10 of tree growth, annual increments in T_5 and T_3 were significantly

greater than in T_6 and T_4 (Table 4). The greater annual increment under silvipastoral systems was due to improvement in soil fertility (Singh et al. 2010).

Table 3: Total dry biomass production and allocation in to stem, branch and root components ten years of plantation in alkali soils

Treatments	Harvested biomass under different plant parts (Mg·ha⁻¹)				Total harvested biomass	Average pruned biomass (Mg·ha⁻¹)
	Leaf	Branch	Stem	Root		
T_1	-	-	-	-	-	-
T_2	-	-	-	-	-	-
T_3	2.58	33.66	14.5	13.75	64.5	2.94
T_4	2.35	14.3	25	11.05	52.75	3.2
T_5	3.1	37.1	20	17	77.2	3.35
T_6	2.6	16.5	30.45	13.65	63.2	2.56
LSD ($p<0.05$)	1.21	4.63	2.43	2.12	11.24	0.22

LSD: Least significant difference.

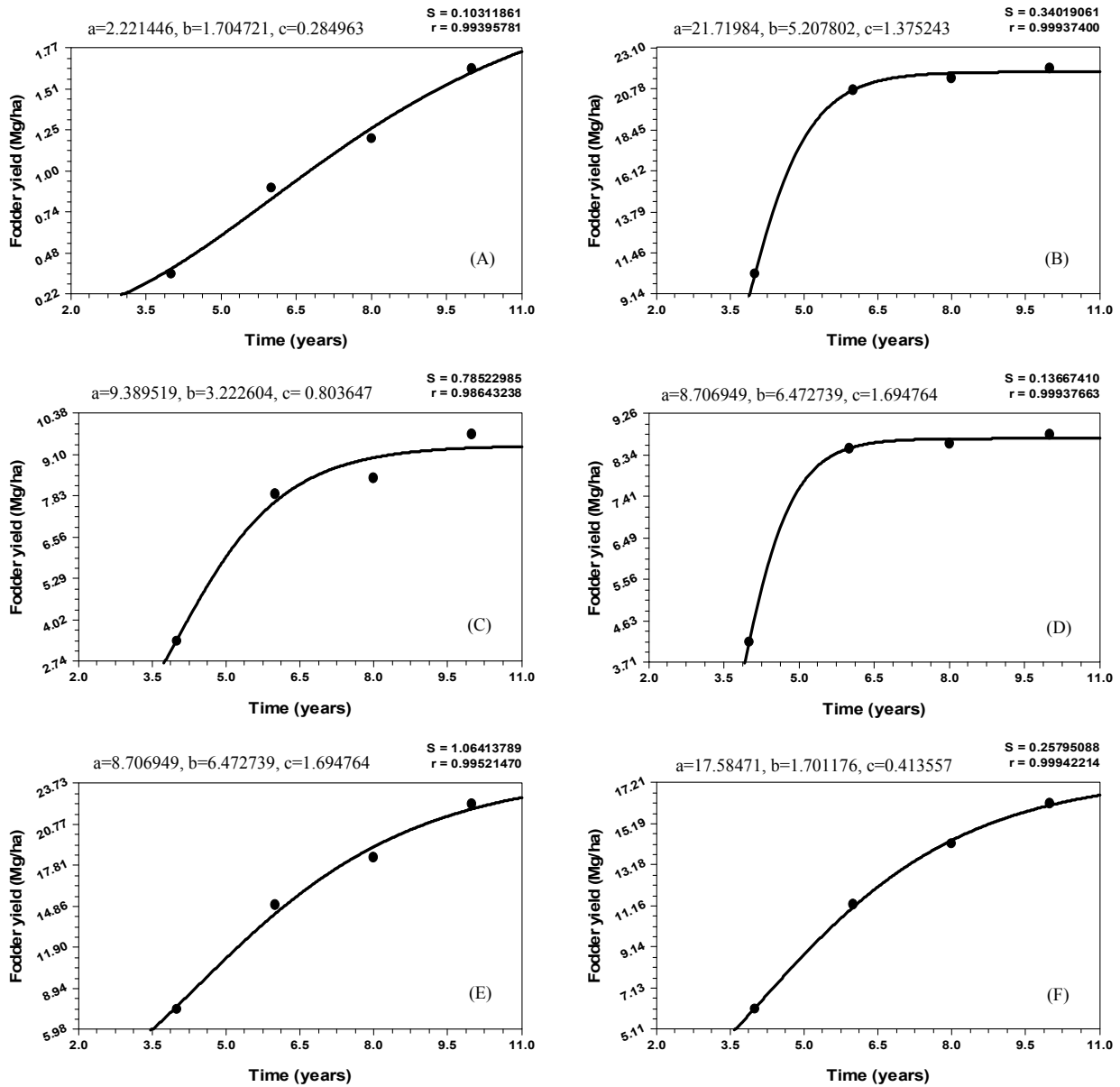**Table 4:** Annual increment and r2 values for tree biomass under different agroforestry systems

Treatments	Annual biomass increment (Mg·ha⁻¹)		R^2	Regression constants		
	0–5 years	5–10 years		a	b	c
T_1	-	-	-	-	-	-
T_2	-	-	-	-	-	-
T_3	6.52	6.38	0.996	64.5	58.33	1.74
T_4	5.8	4.75	0.996	53.1	3.77	0.85
T_5	6.73	8.67	0.997	77.21	8.52	1.74
T_6	6.83	5.81	0.986	13.98	1.39	0.82

Productivity of fodder grasses

The fodder productivity of naturally regenerated grasses under all treatments increased with increasing age of plants. Four years after planting, the productivity of fodder grass under T_2 was significantly greater than in T_1, T_3, T4, T_5 and T_6 (Fig. 2). A similar trend was observed six and eight years after planting because of high tolerance of *L. fusca* to alkalinity as reported from Australia (Lazarides 1970), India (Ashok 1988a; Singh and Dagar 2005), Pakistan (Sandhu et al. 1981; Qureshi et al. 1982; Kumar 1996), and Zambia (Verboon and Brunt 1970). Ten years after planting, T_5 produced significantly more fodder than T_1, T_3, T_4 and T_6. This might have been because of improvement in soil health due to the combined effect of *P. juliflora* and *T. alexandrium* nitrogen fixing grass species. Kumar et al. (1990–1991) found that *T. alexandrium* yield in salt-affected soils was less affected by tree canopy species than were other fodder crops. Pruning of side branches of trees during dormant period helps to improve the forage yield of inter-planted grasses. When large canopy-forming trees such as *Prosopis* and *Acacia* are pruned of side branches, light penetrates through the openings and increases the productivity of understory vegetation. Maximum annual increment in fodder yield under all treatments was recorded at stand ages of four to six years (Table 5). This was probably because the yield of *L. fusca* declined from the third year onwards when soil con-

ditions improved (Kumar and Abrol 1983; Kumar 1988b). After six years, annual increments in fodder yields were significantly

higher in T_5 and T_6 than in T_1, T_2, T_3 and T_4 because of more soil amelioration and improvement in fertility of alkali soils.

Fig. 2: Fodder yield over the years under (A) control (B) pastoral (C and D) *Prosopis* and *Acacia* based silvicultural and (E and F) *Prosopis* and *Acacia* based silvipastoral systems.

Table 5: Annual increments, R^2 and regression constants for fodder yields under different agroforestry systems

Treatments	Annual increment (Mg·ha⁻¹)				R^2	Regression constants		
	0–4 years	6–8 years	8–10 years	10–12 years		a	b	c
T_1	0.08	0.25	0.17	0.22	0.996	2.335	1.673	0.26
T_2	2.57	5.22	0.33	0.27	0.999	2.719	5.207	1.375
T_3	0.84	2.26	0.25	0.67	0.986	9.389	3.222	0.803
T_4	1.04	2.16	0.05	0.1	0.999	8.706	6.472	1.694
T_5	1.86	3.75	1.71	1.92	0.995	24.332	1.7	0.387
T_6	1.55	2.57	1.47	1	0.999	17.584	1.701	0.413

Microbial biomass

Microbial biomass carbon in alkali soils was greater in agroforestry systems (Table 6). Microbial biomass carbon in surface (0–7.5 cm) and sub-surface (7.5–15 cm) soils in T_1 measured 43 and 23 $\mu g \cdot g^{-1}$, respectively, ten years after planting. In T_2 where grasses were planted, microbial biomass carbon was 76 and 32 $\mu g \cdot g^{-1}$, respectively. In T_3 (plantation of *P. juliflora* only), the microbial biomass carbon in surface and sub-surface soil layers was 81 and 43 $\mu g \cdot g^{-1}$, respectively, which was higher than in the pastoral system. In T_4 (*Acacia* tree plantation), microbial biomass carbon was 63 and 26 $\mu g \cdot g^{-1}$, respectively, lower than in T_3

and T_2. In T_5 and T_4, microbial biomass carbon at 0–7.5 and 7.5–15 cm soil depths was 132 and 61 μg·g^{-1}, respectively, and 123 to 51 μg·g^{-1}, respectively, which was significantly higher than in other treatments. This was due to the ameliorative effects of trees and grasses on soil conditions, and the increase in organic carbon content in the soil. Microbial biomass carbon was significantly affected by soil depth. Significantly higher amounts of biomass carbon in surface soils might have been due to higher amounts of readily available organic compounds such as sugars, amino acids and organic acids from the roots that play important roles in the maintenance energy of microbial populations (Bowen and Rovira 1991).

Table 6: Soil microbial biomass carbon under different agroforestry systems in alkali soils

Treatments	Microbial biomass carbon (μg·g^{-1})	
	0–7.5 cm	7.5–15 cm
T_1	43	23
T_2	76	32
T_3	81	43
T_4	63	26
T_5	132	61
T_6	123	51

Soil amelioration

After ten years of experimentation, the maximum reduction in soil pH was in T_5 (Table 7). This confirms earlier studies (Abrol and Prasad 1985; Singh et al. 1993; Singh 1995). This resulted from larger root surface area (Jain and Garg 1996) and high replacement of exchangeable Na$^+$ by Ca^{2+} and subsequent leaching

of Na$^+$. In soil containing plant roots, the presence of CO_2 enhances $CaCO_3$ dissolution, resulting in measurable replacement of adsorbed Na$^+$ (ibid.). EC and ESP declined significantly over their initial levels of 1.43 dS·m^{-1} and 89%. The influence of trees, grasses and a combination of both was more pronounced in the surface layer and it followed an increasing trend with soil depth. The significant effect of agroforestry systems on ESP was recorded up to 120 cm of soil depth in comparison with the control (T_1) where there was no significant change in ESP throughout the soil profile. This might have been due to increasing CO_2 concentration in the soil, which, on dissolution in water, produces carbonic acid (H_2CO_3), which reduces soil pH and dissolves Ca (HCO_3)$_2$ by increasing the solubility of $CaCO_3$ (Garg and Jain 1996). A fourfold increase in organic carbon content was recorded in T_5 and T_6, and about a threefold increase in T_3 and T_4 ten years after plantation (Fig. 3). However, in T_1, the organic carbon content was similar to levels recorded at the time of initial plantation. Similar trends were recorded for available N and P and K. This might have been due to production of certain allelo-chemicals/mixture of acids released from tree biomass as well as from root and shoot biomass of grasses. Gill et al. (1987) and Lal (1998) reported threefold and twofold increases in organic carbon in surface (0–15 cm) soil over a span of five years under *A. nilotica* and *E. teriticornis*, respectively. Garg (1999) reported greater accumulation of organic carbon by *P. juliflora* as compared to other tree species due to differences in root distribution in the soil profile. Tidemann and Klemmedson (1986), Kaur et al. (2000) and Kaur et al. (2001) also reported that soils under *Prosopis* species contained 2–3 times as much organic matter as soils without any plantation. The increment in available K$^+$ content might have been due to release of K$^+$ from the K$^+$ bearing minerals following reclamation and recycling of K$^+$ from litter decomposition (Mishra et al. 2002; Mongia et al. 1998).

Table 7: Changes in nutrient levels up to 120cm soil depth under different agroforestry systems ten years after plantation

Treatment	Ca^{2+}+ Mg^{2+} (me·L^{-1})					Na$^+$ (me·L^{-1})					K$^+$ (me·L^{-1})				
	Depth (cm)					Depth (cm)					Depth (cm)				
	0–15	15–30	30–60	60–90	90–120	0–15	15–30	30–60	60–90	90–120	0–15	15–30	30–60	60–90	90–120
T_1	1.72	2.12	2.1	2.1	1.6	136	128.6	52.7	21.5	9.6	0.11	0.1	0.08	0.08	0.05
T_2	2.75	2.43	2.35	2.12	1.84	11.6	17.4	25.6	19.3	6.54	0.16	0.16	0.15	0.15	0.13
T_3	3.1	2.85	2.63	2.2	2.2	7.72	8.1	11.4	9.4	8.2	0.17	0.17	0.16	0.14	0.13
T_4	3.15	2.76	2.54	2.2	2.15	9.6	11.2	16.5	11	9.4	0.16	0.16	0.15	0.15	0.14
T_5	3.5	3.1	2.86	2.4	2.4	6.96	8.1	11.2	9.6	8.5	0.18	0.18	0.17	0.16	0.14
T_6	3.43	2.89	2.75	2.25	2.1	8.6	9.1	12.1	10.12	9.1	0.17	0.17	0.16	0.15	0.13

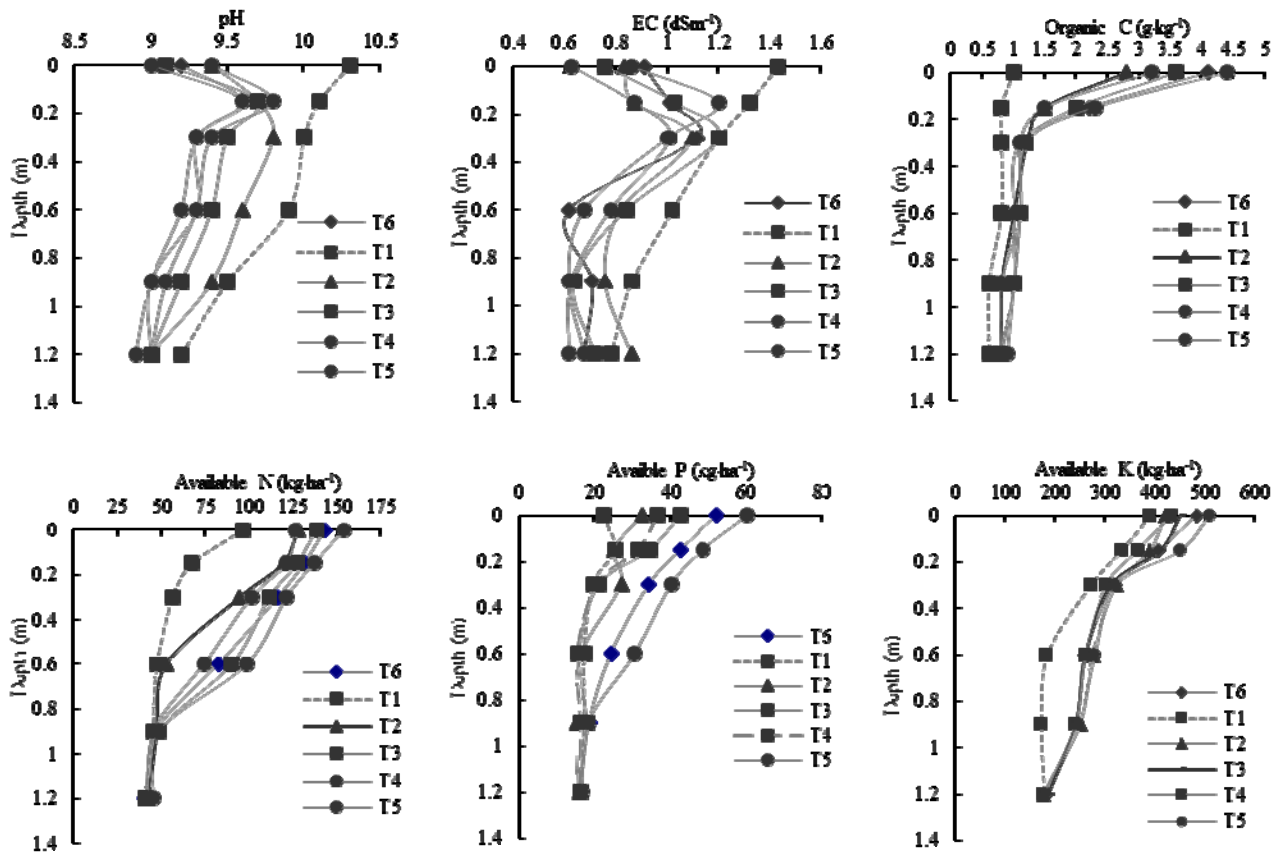| Treatment	Cl (me·L^{-1})					ESP				
	Depth (cm)					Depth (cm)				
	0–15	15–30	30–60	60–90	90–120	0–15	15–30	30–60	60–90	90–120
T_1	7	7	4	2.5	4	76	80	82	82	64
T_2	5.2	6	4	2.2	3.5	32	36	42	40	32
T_3	5.5	6	4.2	2.5	4	34	36	40	42	34
T_4	5	5.5	4	2.4	3.5	36	38	40	42	28
T_5	5	5.2	4.5	2.25	3.5	30	32	36	40	26
T_6	4.5	5	5	3	4	34	36	38	42	30

ESP: Exchangeable sodium percent

Fig. 3: Changes in pH, EC, organic carbon, available N, available P and available K under different agroforestry systems compared with control

Maximum $Ca^{2+} + Mg^{2+}$ and K^+ contents were recorded in T_5 and T_6. $Ca^{2+} + Mg^{2+}$ contents in the surface soils of silvipastoral systems (T_5 and T_6) increased to double over the control (T_1) and initial values over a period of ten years. The increases in these cations resulted from the combined root action of trees and grasses that reclaimed the soil. Khanduja et al. (1986) reported a reduction in Na^+ and improvement in Ca^{2+} content of soil under *P. juliflora* and other fruit tree cover. A similar trend was observed in Na^+ content. The Na^+ content was lowest in the surface layer and increased with increasing depth in all treatments. Exchangeable Na^+ was replaced by Ca^{2+} as a result of growing *C. dactylon* for two years followed by barley and alfalfa. The reduction in Cl^- content was more pronounced in the surface layer in all agroforestry systems (Table 6).

Reduction in bulk density was greatest in T_5 and least in T_2 but enhancement in porosity was greatest in T_5 and T_6 and least in T_1 (Fig. 4). Soil moisture retention in the surface layer in T_5 and T_6 was significantly greater than in T_3, T_4 and T_2. Moisture retention under silvipastoral systems was about five times that in the control where the soil was completely barren. Similarly, infiltration rate in T_5 and T_6 was higher than in T_3, T_4 and T_2. This was due to better tree growth, improved soil physico-chemical properties, enhanced biological activities of the soil due to greater root growth of trees and decomposition of grass residues. Singh et al.

(1989) compared the effects of several tree species on sodic soils and found the largest improvement in infiltration rate under *P. juliflora*.

Conclusion

The amelioration of alkali soils is feasible using silvipastoral systems. Establishment of a *P. juliflora* silvipastoral system with planting of *L. fusca* for four years followed by *T. alexandrium* for six years might be a more remunerative land use system than pure pastoral or silvicultural systems because of its capacity to produce more biomass and improve physico-chemical properties of alkali soil. It is thus inferred that the alkali soils rehabilitated with silvipastoral systems for ten years can be put under cultivation of highly remunerative crops to harness the productivity potential of these soils. Our results can be applied to the utilization of salt-affected soils for biomass and bio-energy production and their rehabilitation for productive uses.

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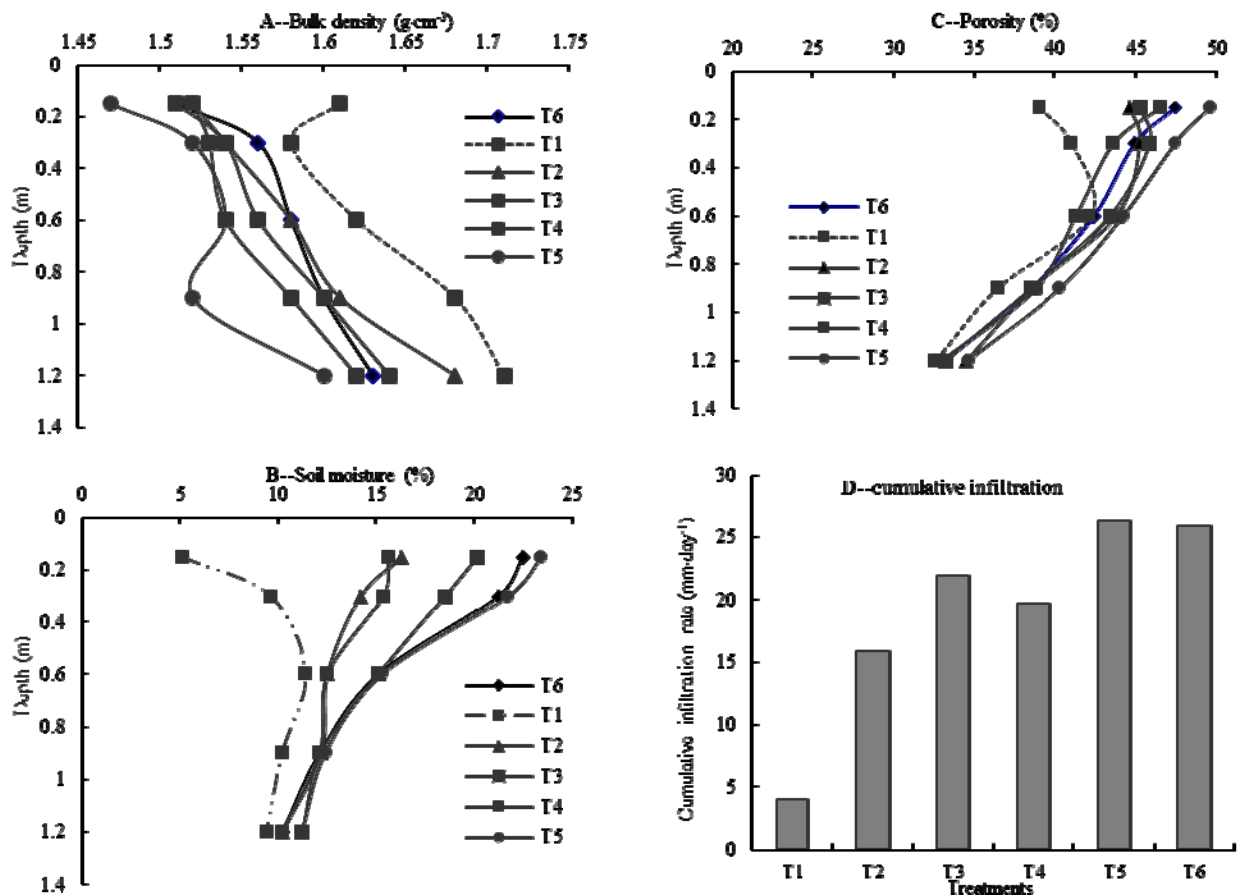
Fig. 4: Changes in (A) soil bulk density, (B) soil moisture, (C) porosity, and (D) cumulative infiltration ten years after plantation under different agro forestry systems and control

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