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Ameliorative Effect of Multipurpose Tree Species Grown on Sodic Soils of Indo-Gangetic Alluvial Plains of India

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A Long-term field study was carried out to compare the impact of ten-year old plantation of ten multipurpose tree species, viz., Terminalia arjuna, Azadirachta indica, Prosopis juliflora, Pongamia pinnata, Casuarina equisetifolia, Prosopis alba, Acacia nilotica, Eucalyptus tereticornis, Pithecellobium dulce, *and* Cassia siamea *on tree growth, biomass yield, and physico-chemical properties of sodic soils representing major tract of salt-affected soils of the Indo-Gangetic Alluvial Plains of India. Maximum (100%) survival was recorded with* Terminalia arjuna, Prosopis juliflora, Pongamia pinnata, *and* Pithecellobium dulce *whereas minimum (50%) in* Prosopis alba. *Maximum plant height (9.3 m) was recorded with* Eucalyptus tereticornis *followed by* Casuarina equisetifolia *(8.2 m) whereas; minimum plant stature was attained by* Cassia siamea. Prosopis juliflora *reported maximum diameter at stump height, crown diameter, lopped biomass, and litter fall at all the growth stages.* Prosopis juliflora *also produced highest aerial biomass (70.27 Mg ha^{-1}) followed by* Acacia nilotica *(63.09 Mg ha^{-1}) and* Casuarina equisetifolia *(53.11 Mg ha^{-1}). Significant improvement in soil pH and electrical conductivity; exchangeable sodium percentage; organic carbon; and available N, P, and K was recorded under tree plantation than natural fallow. Significant reduction in soil bulk density (from 1.57 to 1.21 mg m^{-3}) and increase in porosity (40.7 to 54.3%) and infiltration rate (2.10 mm day^{-1} to 26.30 mm day^{-1}) was recorded under tree plantations. It is concluded that tree species like* Prosopis juliflora, Acacia nilotica, *and* Casuarina equisetifolia *have a significant impact on soil properties, which could help to rehabilitate the sodic wastelands in the region.*

Keywords biomass production, multipurpose tree species, physico-chemical properties, sodic soil, soil improvement, tree growth

Worldwide, salt – affected areas are estimated to range from 340 million ha to 1.2 billion ha (FAO 2007). Millions of hectares of these salt affected soils are suited for agricultural production but are unexploited because of salinity/sodicity and other soil and water related problems (Abrol et al. 1988). According to FAO, salinization of arable land will result in 30% to 50% land loss in the next 25 years to the year 2050 if remedial actions are not taken. In India, salt affected soils occupy about 6.73 million hectare; 3.60 million hectare are sodic soils (NRSA and Associates 1996). Indo-Gangetic plains

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lies between 21° 55′ to 32° 39′N and 73° 45′ to 88°25′E comprising of the states of Punjab, Haryana, Uttar Pradesh and part of Bihar (North), West Bengal (south), and Rajasthan (north) is having about 2.7 million hectare salt affected soils (NRSA & Associates 1996). This area is progressively expanding because of improper soil and water management and development of water logging and soil salinization upon introduction of irrigation in arid, semi-arid, and sub-humid regions. Rise in the water table is inevitable upon introduction of irrigation network without provision of adequate drainage. Excessive exchangeable Na^+ associated with high pH (>8.5) impairs the physical condition of the soils and adversely affects water and air movement, nutritional, and hydrological properties of the soils (Suarez et al., 1984; Gupta & Abrol, 1990; Sumner, 1993; Garg, 1998). The presence of $CaCO_3$ concretions at various depths (caliche bed) causes physical impedance for root proliferation, therefore, making it difficult for tree establishment. Sizable area of sodic soils in the Indo-Gangetic plains has been reclaimed through chemical amelioration techniques and is now supporting rice-wheat cropping system. However, a large tract of alkali soils is constituted by village panchayat lands (lands having common property rights), government lands reserved for specific purposes, and the lands lying abandoned near roads, canals, and railway tracks. Reclamation of such lands for crop production through chemical amendments is posing social problems owing to common property rights. During last three decades the management of these soils has been done largely for crop production, and there were only a few attempts to afforest (Yadav, 1980). Reclamation of sodic soils may be achieved by growing tree species, which ameliorates the soil to various degrees through the addition of large amount of organic matter and nutrients from litter and fine roots (Singh 1996, 1998) and improve the physical and chemical properties as well as biological activity in the soil (Garg, 1998). Studies conducted at various locations in India have shown that sodic soils can be improved by afforestation and related to reclamation (Yadav, 1980; Bhumbla & Chhabra 1982). Some indigenous species established on these soils suffer with stunted growth and poor yield (Chaturvedi & Behl, 1996; Singh, 1989). There is an urgent need to prevent soil degradation and restore already degraded areas. Establishment of permanent tree cover of suitable tree species on sodic soils is an option for providing fuel, fodder, and timber, as well as being environmentally important (Gill & Abrol 1991; Mishra et al. 2002). Essentially, there are two approaches for the rehabilitation of sodic lands. The first is by improving soil properties through suitable chemical amendments, and the second is biological amelioration through plantation of suitable tree species. For the first approach, about 12–14 tones ha^{-1} gypsum ($CaSO_4 \cdot 2H_2O$) is required. However, in the second approach, only 3.30 tones ha^{-1} of gypsum is required. Although there are certain other approaches like sub-surface drainage, they are expensive and beyond the reach of small and marginal farmers. Therefore, the present study was carried out through plantation of ten multipurpose tree species to find out tree species suited to plantation under sodic soils and to asses the impact of tree plantations on growth, productivity, and ameliorating properties of the sodic soils.

Materials and Methods

Location and Climatic Parameters

The study was conducted at Central Soil Salinity Research Institute (CSSRI), Regional Research Station, Research Farm, Shivri, Lucknow, in north India

(26° 47′ 45″ – 26° 48′ 13″ N, 80° 46′ 7″ – 80° 46′ 32″ E). Geographically, this region is classified as Gangetic alluvial plains. A vast tract of this alluvium constitutes abandoned sodic soils without any significant vegetation cover. The experiment was initiated in 1995 on a virgin soil represents a typical sodic soil in subtropical region of central Indo-Gangetic plains in India. The annual precipitation of the site varied from 700–1000 mm (Long-term average 800 mm). More than 80% of the precipitation generally occurs during the monsoon season (July–September). The rainfall exceeds evapotranspiration in the months of July, August, and September but internal drainage of the soil remains restricted due to highly dispersing nature. The mean monthly temperature recorded for 10 study years varied from 21°C in January to 40.5°C in June. Mean annual soil temperature recorded at single depth (10 cm) during study period varies from 18.6°C during winter and 32°C during summer. The annual rainfall and mean minimum and maximum air temperatures are shown in Figure 1. The water table ranged between 5–7 m was measured for ten years at weekly interval using piezometers open at the bottom installed at 20 and 50 m away from the experimental site (Figure 2).

Soil and Water Analysis

To diagnose the severity and extent of the sodicity problem in the experimental field, soil samples were collected by exposing profile to 120 cm depth at three randomly selected places before initiation of the experiment. We exposed the profile up to 120 cm depth because we had dugout a 120 cm deep auger hole for planting the tree seedlings. The soil samples were collected at eight depths of 0–15, 15–30, 30–45, 45–60, 60–75, 75–90, 90–105, and 105–120 cm from these profiles. The soil samples were air dried and ground to pass a 2.0 mm sieve. Soil pH and electrical conductivity (EC) were determined in a 1:2 soil water suspension. The soil of the study site was characterized by loam in texture on the surface and silty loam and silty clay loam

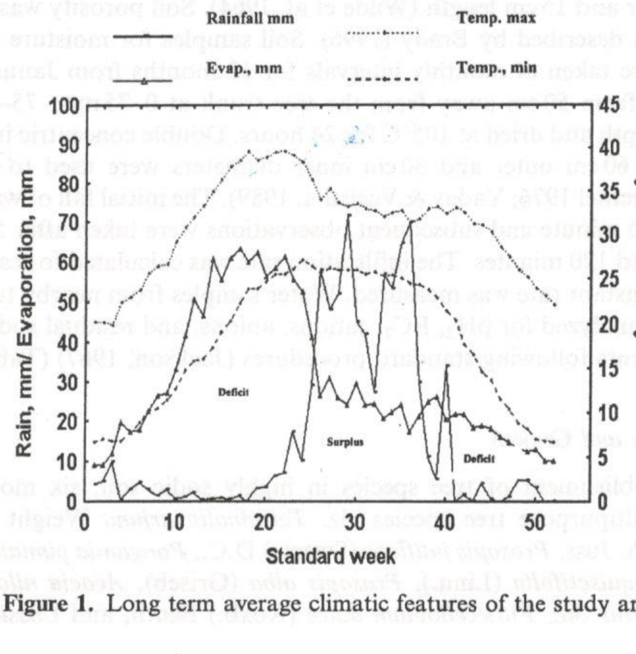


Figure 1. Long term average climatic features of the study area.

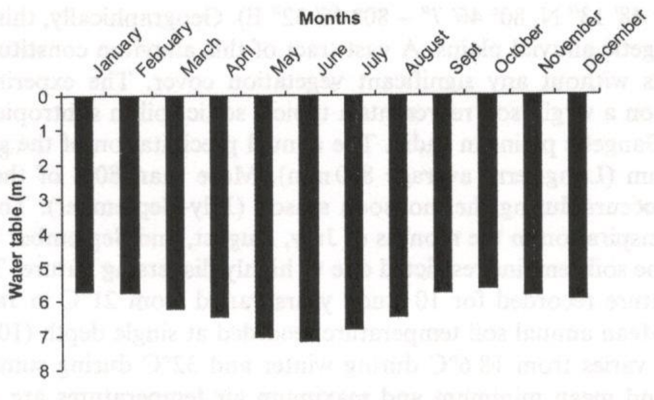


Figure 2. Water table fluctuation pattern at experimental site (10 years average).

in middle and clay loam in lower layers. Soil structure at the surface was sub-angular blocky, angular blocky in middle, and massive to sub-angular blocky in the lower layers. The soil was sodic, fine loamy, mixed, hyperthermic, and classified as Typic Natrustalfs having physical and nutritional problems. The soil contained about 40 cm thick $CaCO_3$ concretion layer in the substratum (at about 1.0 m soil depth), inhibiting water and root penetration. The soil reaction was strongly alkaline in surface 0–15 cm (pH_2 10.5), subsurface horizons (pH_2 8.8–10.0), EC_2 (<3.0 dSm^{-1}), and ESP ranges from 85–92 (Table 1). The organic carbon was measured by ignition (Wang et al. 1996) where approximately 2 g of dry soil (sieved to <2.0 mm) was placed in ceramic crucibles in a muffle furnace at 375°C for 16 hours. Available N was estimated by distillation of soil with $KMnO_4$ and NaOH (Subbiah & Asija 1956). Available P and K were determined by the Olson sodium bicarbonate extraction (Olsen & Dean 1965) and sodium acetate extraction, respectively. The bulk density of different soil layers was determined from intact cores extracted with a core sampler of 10 cm in diameter and 15 cm length (Wilde et al. 1964). Soil porosity was determined by the method described by Brady (1996). Soil samples for moisture analysis, gravimetrically, were taken at monthly intervals for 12 months from January 2005 to December 2005 from 50 cm away from the tree trunk at 0–75 mm, 75–150 mm, and 150–300 mm depth and dried at 105°C for 24 hours. Double concentric infiltrometer cylinders with 60 cm outer and 30 cm inner diameters were used to measure infiltration rate (Brechtel 1976; Yadav & Vasistha, 1989). The initial fall of water level was recorded after 5 minute and subsequent observations were taken after 5, 10, 20, 30, 40, 50, 60, 90, and 120 minutes. The infiltration rate was calculated for each interval and the final constant rate was measured. Water samples from nearby tube wells were collected and analyzed for pH_2, EC_2, cations, anions, and residual sodium carbonate (RSC) contents following standard procedures (Jackson, 1967) (Table 2).

Planting Techniques and Growth

For successful establishment of tree species in highly sodic soil, six months old saplings of ten multipurpose tree species viz. *Terminalia arjuna* Weight & Arn., *Azadirechta indica* A. Juss, *Prosopis juliflora* (Swartz) D.C., *Pongamia pinnata* (Linn.) Pierre, *Casuarina equisetifolia* (Linn.), *Prosopis alba* (Griseb), *Acacia nilotica* (L), *Eucalyptus tereticornis* Sm, *Pithecellobium dulce* (Roxb.) Benth, and *Cassia siamea*

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

Soil parameters	Soil depth (cm)							
	0–15	15–30	30–45	45–60	60–75	75–90	90–105	105–120
Sand (%)	63.4	48.0	48.6	42.0	54.0	57.4	46.5	52.5
Silt (%)	18.8	25.2	38.0	23.0	28.7	25.0	22.4	25.0
Clay (%)	17.8	26.8	35.0	35.0	34.2	43.6	33.9	32.5
Textural class	1	sil	sil	cl	sicl	cl	cl	cl
Bulk density (g/cm^{-3})	1.64	1.57	1.55	1.51	1.50	1.48	1.48	1.46
pH (1:2)	10.5	10.6	10.6	10.4	10.2	9.8	9.8	9.7
EC (1:2) $d Sm^{-1}$	1.43	2.42	2.02	0.86	0.64	0.64	0.26	0.44
ESP	89.0	82.6	82.0	80.2	80.0	66.0	63.4	60.4
O.C. ($g kg^{-1}$)	0.8	0.8	0.6	0.6	0.8	0.8	0.6	0.6
$CaCO_3$ ($g kg^{-1}$)	14.1	12.6	23.2	23.2	37.7	89.4	116.9	124.6
Available N ($kg ha^{-1}$)	94.00	62.72	54.60	47.04	45.10	45.04	40.60	37.63
Available P ($kg ha^{-1}$)	19.5	18.6	17.5	17.7	18.2	17.0	16.1	16.6
Available K ($kg ha^{-1}$)	388	388	321	404	290	278	199	169
$Ca^{++} + Mg^{++}$ ($meq l^{-1}$)	2.60	2.10	2.20	1.60	1.60	1.60	1.75	2.10
Na ($meq l^{-1}$)	242.0	119.0	110.0	52.7	21.4	9.00	7.5	5.00
K ($meq l^{-1}$)	0.22	0.12	0.06	0.04	0.04	0.03	0.02	0.01
CO_3 ($meq l^{-1}$)	188.0	84.00	54.5	26.00	8.2	2.00	2.0	1.00
HCO_3 ($meq l^{-1}$)	18.0	21.00	21.0	21.00	11.5	5.50	4.5	3.50
Cl ($meq l^{-1}$)	33.0	12.0	11.0	11.0	7.0	3.0	3.0	3.0

1 = loam; sil = silty loam; sicl = silty clay loam; cl = clay loam.
pH_2 and EC_2: Refers to soil: water suspension ratio of 1:2.
ESP: Exchangeable sodium percent.

Table 2. Water quality of tube well water used for irrigation

Parameters	Composition
pH	8.2
EC ($d\,Sm^{-1}$)	0.6
Ca + Mg ($me\,l^{-1}$)	3.5
CO_3 ($me\,l^{-1}$)	1.6
HCO_3 ($me\,l^{-1}$)	4.7
Cl ($me\,l^{-1}$)	1.5
SO_4 ($me\,l^{-1}$)	0.0
Na ($me\,l^{-1}$)	3.2
K ($me\,l^{-1}$)	0.1
RSC ($me\,l^{-1}$)	2.8

RSC: Residual sodium carbonate.

Lam. raised in the state government forest department nursery in a normal soil were transplanted in randomized block design with 4 replications on September 26, 1995. The selection of species was based on its different uses such as *P. juliflora, P. pinnata, A. nilotica,* and *P. alba* are nitrogen fixing tree species; *T. arjuna, A. indica, P. dulce,* and *E. tereticornis* have medicinal and timber values; however, *C. siamea* is used for fodder and fuel purposes. The experimental plot measuring 20 × 12 m contained 18 trees of each species in each replication. These species were planted in auger holes (45 cm diameter at the surface 20 cm at the bottom and 120 cm deep) filled with a uniform mixture of original soil + 4 kg gypsum + 10 kg FYM + 20 kg silt keeping row to row and plant to plant spacing of 4 m and 3 m, respectively. For proper establishment of the saplings, three irrigations with 10 cm depth of water were applied at monthly intervals during the first year of planting; after that, only one of the irrigations that had good water quality in a summer (June) month was applied. No fertilizer was applied to the plants during the study period. The observations on survival percentage, plant height, diameter at stump height (DSH), diameter at breast height (DBH) 1.33 m from the ground, crown diameter, and number of stems and branches at 1/3rd plant height were taken and reported on an average basis.

Biomass Production

To estimate tree biomass production, three trees with different heights and diameters, representing each of the ten tree species were harvested ten years after plantation and their air dry biomass in the form of shoot and root was weighted separately. Trees were partially lopped every year during the month of October to get lopped biomass yield. The roots were exposed to measure the root length and root biomass at the ten-year growth stage. Natural grasses regenerated under these tree species were harvested from a 4 × 3 m area from each species every year at the termination of the growing season in the month of October and oven dried to measure the annual understory natural grass biomass yield. Forty litter collectors of 1 × 1 m sizes, with 0.5 mm mesh steel net attached at the base, were placed randomly in each replicated plot to measure litterfall yield. To monitor the ameliorative effect of trees over natural fallow (control), a control plot of 600 m^2 (12 m × 50 m) adjacent to the tree plantation was kept as the natural fallow.

Nutrient Analysis

Approximately 50 g of air dry soil samples ground in a Willey mill and passed through a 0.1 mm mesh sieve were processed for nutrient analysis. Nitrogen was estimated by Kjeldahl digestion and distillation unit, and carbon content was estimated following standard methods (Jackson, 1973).

Statistical Analysis

The data were analyzed as per the standard analysis of variance technique using MSTAT-C software. The treatment comparisons were made using a *t*-test at 5% level of significance.

Results

Survival and Growth Parameters

The survival of all the tree species except *P. alba* was quite satisfactory during the initial years. At five years growth stage 2–7% mortality was recorded in *A. indica, C. equisetifolia, A. nilotica, E. tereticornis,* and *C. siamea.* At this stage only 50% *P. alba* plants survived. However, in *P. alba* only 60% survival was recorded three years after planting and it increased to 50% at seven and ten years growth stages. *P. juliflora, T. arjuna, P. pinnata, A. nilotica, C. equisetifolia,* and *P. dulce* were found to be highly tolerant under sodic conditions and showed >95% survival even after ten years of planting (Table 3). Yadav and Singh (1970), Gill and Abrol (1986), Gill et al. (1990), and Singh et al. (1993) also reported similar results. Maximum plant height at three, five, seven, and ten years of planting was attained by *E. tereticornis* followed by *C. equisetifolia* and *P. juliflora* (Figure 3). Among all the species tried, the growth in *C. siamea* and *A. indica* was quite slow. Maximum diameter at breast height (DBH) at three and five years of age was in *E. tereticornis* (7.86 and 10.84 cm) followed by *P. juliflora* (7.20 and 9.21 cm), *C. equisetifolia* (7.14 and 8.80 cm), and *A. nilotica* (6.10 and 9.03 cm). The stem thickness attained by *T. arjuna, A. indica, P. pinnata,*

Table 3. Growth parameters at 10 years growth stage

Tree species	Survival (%)	Crown diameter (cm)	Root length (m)	Number of stems	Number of branches
T. arjuna	100.0	2.40	2.13	3	24
A. indica	93.5	7.53	1.54	5	14
P. juliflora	100.0	8.87	2.14	2	38
P. pinnata	100.0	5.42	1.74	12	27
C. equisetifolia	97.4	8.75	2.10	2	28
P. alba	50.0	3.00	1.72	2	26
A. nilotica	95.4	7.20	2.25	5	30
E. tereticornis	99.0	4.80	1.86	7	12
P. dulce	100.0	5.80	2.36	4	26
C. siamea	98.0	4.18	1.32	6	11
LSD (P=0.05)	–	1.12	0.24	–	–

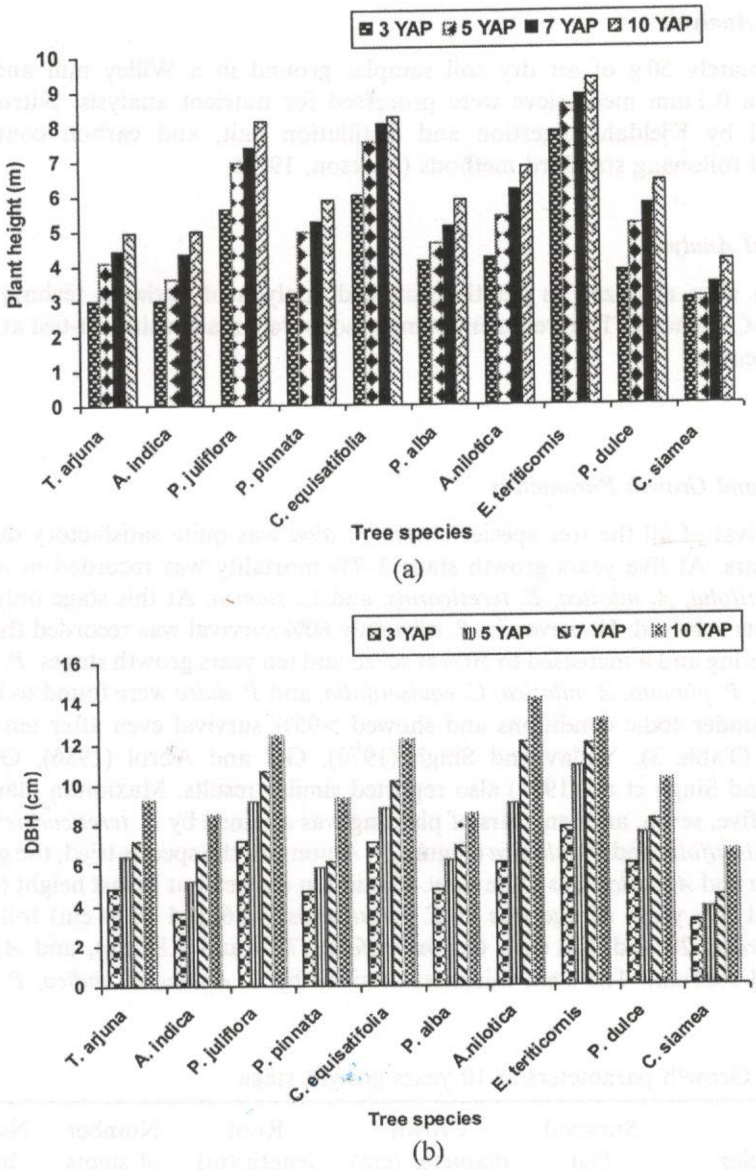


Figure 3. (a) Plant height (m) and (b) diameter at breast height (cm) at 3, 5, 7, and 10 years after plantation (YAP). (Significant difference in plant height and diameter at breast height at 5% level of significance is 0.96 and 6.50, respectively.)

P. alba, P. dulce, and *C. siamea* was in the range of 3–5 cm. However, at seven years of age, maximum DBH was attained by *A. nilotica* followed by *E. tereticornis* and *P. juliflora*. Similarly, a trend was also observed at the ten-year growth stage (Figure 3). Maximum crown diameter at three, five, seven, and ten years of growth stage were in *P. Juliflora* followed by *A. nilotica.* On the other hand *C. siamea, A. indica*, and *T. arjuna* gained minimum crown spread (Table 3). At the early growth stage, maximum DSH was determined in *E. tereticornis* (9.42 m) followed by

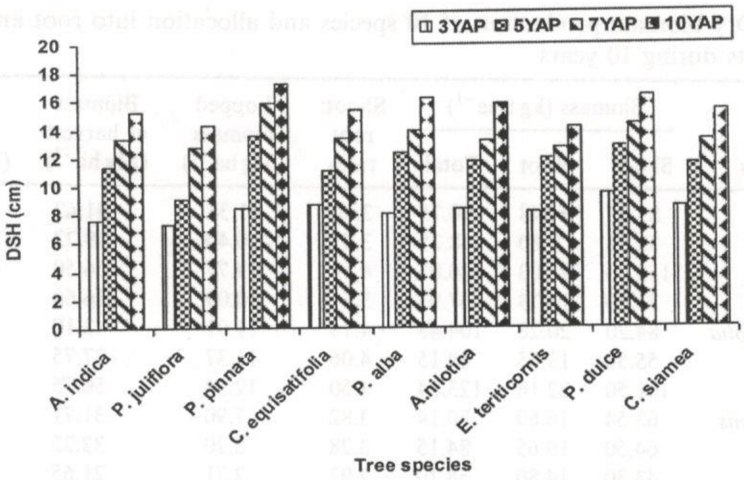


Figure 4. Diameter at stump height at 3, 5, 7, and 10 years growth stages. (Significant difference in diameter at stump height at 3, 5, 7, and 10 years growth stages at 5% level of significance is 0.36, 0.72, 0.48, and 0.43, respectively.)

P. pinnata (8.60 cm) and *P. juliflora* (8.43 cm). After five years and onwards *P. juliflora* attained maximum DSH followed by *E. tereticornis* and *C. equisetifolia* (Figure 4). The maximum number of stems at the ten-year growth stage was recorded with *P. pinnata;* however, the maximum number of branches were found in *P. juliflora, because P. pinnata* produced more branches from the initial stage, which became a thick stem at a later stage, whereas *P. juliflora* had less stems and more branches, being bushy in nature (Table 3).

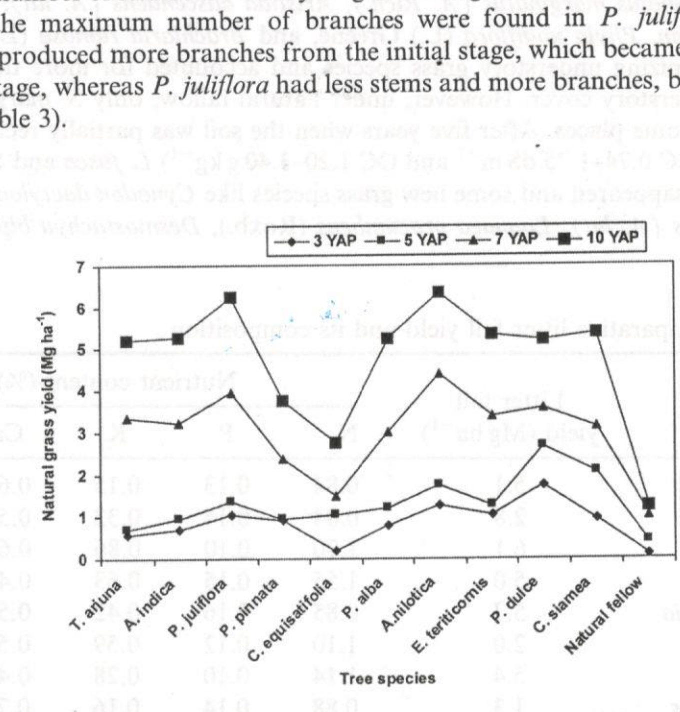


Figure 5. Natural grass yield under trees and natural fallow at 3, 5, 7, and 10 years after plantation (YAP). (Significant difference in natural grass yield at 3, 5, 7,and 10 years growth stages at 5% level of significance is 0.46, 0.63, 1.04, and 0.76, respectively.)

Table 4. Dry biomass production of 10 species and allocation into root and shoot components during 10 years

Tree species	Biomass (kg tree^{-1})			Shoot: root ratio	Lopped biomass (Mg ha^{-1})	Biomass at harvest (Mg ha^{-1})	Total biomass (Mg ha^{-1})
	Shoot	Root	Total				
T. arjuna	83.25	24.48	90.75	3.40	11.33	41.62	52.95
A. indica	38.45	9.80	48.25	3.51	6.40	19.22	26.62
P. juliflora	113.00	27.03	140.03	4.18	13.77	56.50	70.27
P. pinnata	53.20	14.73	67.93	3.61	10.09	26.60	36.69
C. equisetifolia	84.20	20.28	104.48	4.15	11.01	42.10	53.11
P. alba	55.50	13.65	69.15	4.06	11.37	27.75	39.12
A. nilotica	101.50	22.14	123.64	4.50	12.34	50.75	63.09
E. tereticornis	63.54	16.60	80.14	3.82	7.90	31.77	39.67
P. dulce	64.50	19.65	84.15	3.28	8.20	32.25	40.45
C. siamea	43.30	14.80	58.10	2.92	2.71	21.65	24.36
LSD (P = 0.05)	6.34	2.36	–	0.54	1.12	5.42	7.52

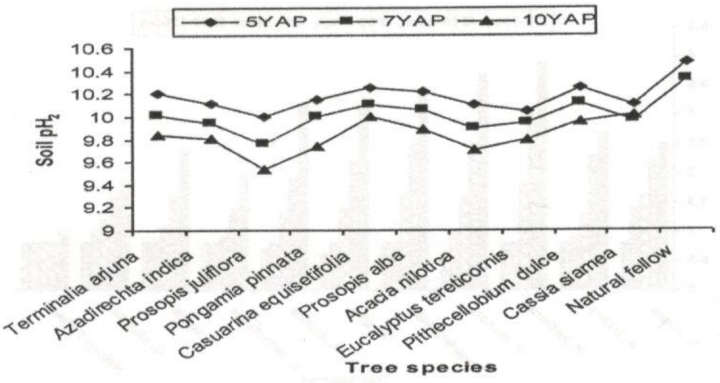
LSD = least significant difference.

Biomass Production

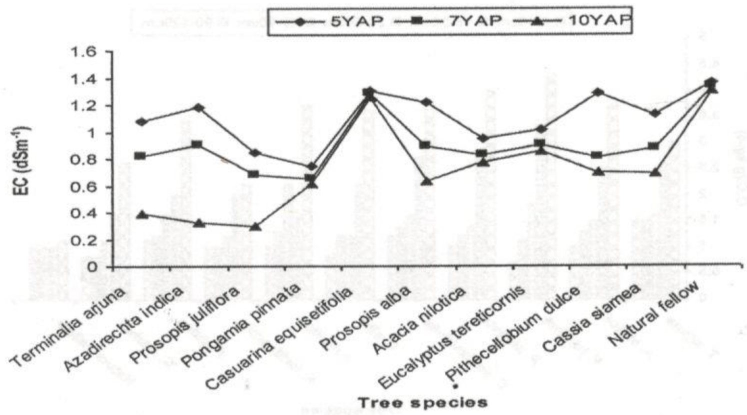
During the initial years of the study, when the soil was highly sodic, the germination of natural grasses was scarce. After three years of plantation, *Leptochloa fusca* (L.) Kunth, *Sporobolus marginatus (A. Rich.), Aristida adscendens (A. lat), Euphorbia prostrata Aiton, Phyla nodiflora* (L.) Greene, and *Brachiaria ramosa* (L.) were the primary colonizing understory grass species and accounted for more than 70% of the total understory cover. However, under natural fallow, only *S. marginatus* was observed at some places. After five years when the soil was partially reclaimed (pH 10.0–10.25, EC 0.74–1.75 dS m^{-1} and OC 1.20–3.40 g kg^{-1}) *L. fusca* and *S. marginatus* almost disappeared and some new grass species like *Cynodon dactylon* (L.) Pers., *A. adscendens (A. lat), Launaea procumbens* (Roxb.), *Desmostachya bipinnata* (L.)

Table 5. Comparative litter fall yield and its composition

Tree species	Litter fall yield (Mg ha^{-1})	Nutrient content (%)				
		N	P	K	Ca	Mg
T. arjuna	5.1	0.84	0.13	0.15	0.67	0.52
A. indica	2.8	0.84	0.14	0.32	0.54	0.28
P. juliflora	6.1	1.70	0.10	0.86	0.62	0.36
P. pinnata	5.0	1.55	0.15	0.63	0.46	0.32
C. equisetifolia	5.7	0.85	0.16	0.42	0.51	0.30
P. alba	2.0	1.10	0.12	0.59	0.53	0.32
A. nilotica	5.4	1.14	0.10	0.28	0.43	0.26
E. tereticornis	1.3	0.88	0.14	0.16	0.73	0.36
P. dulce	2.4	0.86	0.16	0.43	0.52	0.36
C. siamea	1.3	0.78	0.14	0.40	0.86	0.84



(a)



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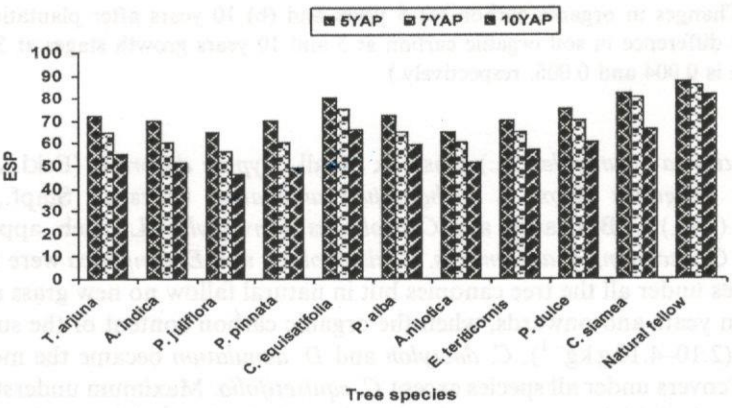

(c)

Figure 6. Changes in (a) soil pH (b) electrical conductivity, and (c) ESP of sodic soil after 5, 7, and 10 years of plantation at 0–15 cm depth.(Significant difference in soil pH at 5, 7, and 10 years growth stages at 5% level of significance is 0.16, 0.18, and 0.21, respectively.) (Significant difference in soil EC at 5, 7, and 10 years growth stages at 5% level of significance is 0.06, 0.04, and 0.04, respectively.) (Significant difference in soil ESP at 5, 7, and 10 years growth stages at 5% level of significance is 4.63, 3.68, and 7.32, respectively.)

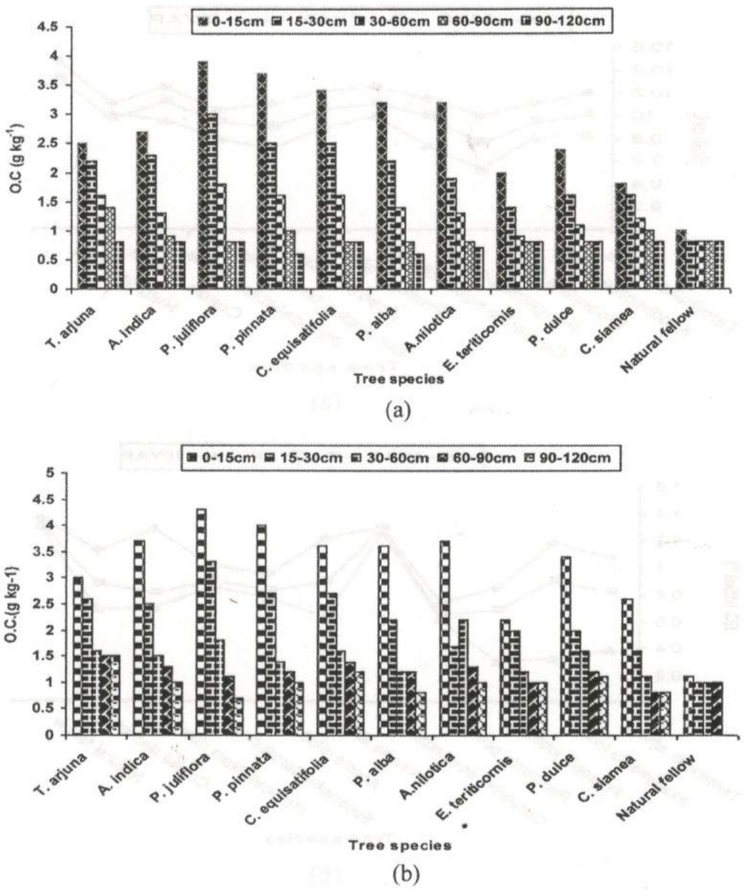

Figure 7. Changes in organic carbon (a) 5 years and (b) 10 years after plantation (YAP). (Significant difference in soil organic carbon at 5 and 10 years growth stages at 5% level of significance is 0.004 and 0.006, respectively.)

Stapf., *Vetiveria zizanioides* (L.) Nash ex Small, *Cyprus difformis* (Eckl. & Zeyh.), *Eragrostis gangetica* (Roxb.), *Dichanthium annulatum* (Forssk.) Stapf., *Pluchea lanceolata* (DC.) C. B. Clarke, and *Convolvulus microphylus* (L.) Sieb. appeared. At this stage, *C. dactylon, A. adscendens, V. zizanioides,* and *E. gangetica* were the dominant grasses under all the tree canopies but in natural fallow no new grass appeared. After seven years and onwards, when the organic carbon content of the surface soil improved (2.10–4.10 $g\,kg^{-1}$), *C. dactylon* and *D. annulatum* became the most dominant grass covers under all species except *C. equisetifolia.* Maximum understory grass yield during the initial years was under *P. dulce* (1.74 $Mg\,ha^{-1}$) followed by *A. nilotica* (1.25 $Mg\,ha^{-1}$) and minimum under *C. equisetifolia* (0.2 $Mg\,ha^{-1}$). A similar trend was observed at five years after plantation. However, at seven and ten years of age, *A. nilotica* and *P. juliflora* recorded significantly higher understory grass yield, although the difference between the two species was not significant (Figure 5). Notably, the natural grass yield in the control plot was significantly low (1.24 Mg ha^{-1}). Diaz et al. (1984) also reported higher natural grass yields under *P. juliflora* in understory situations than in the open.

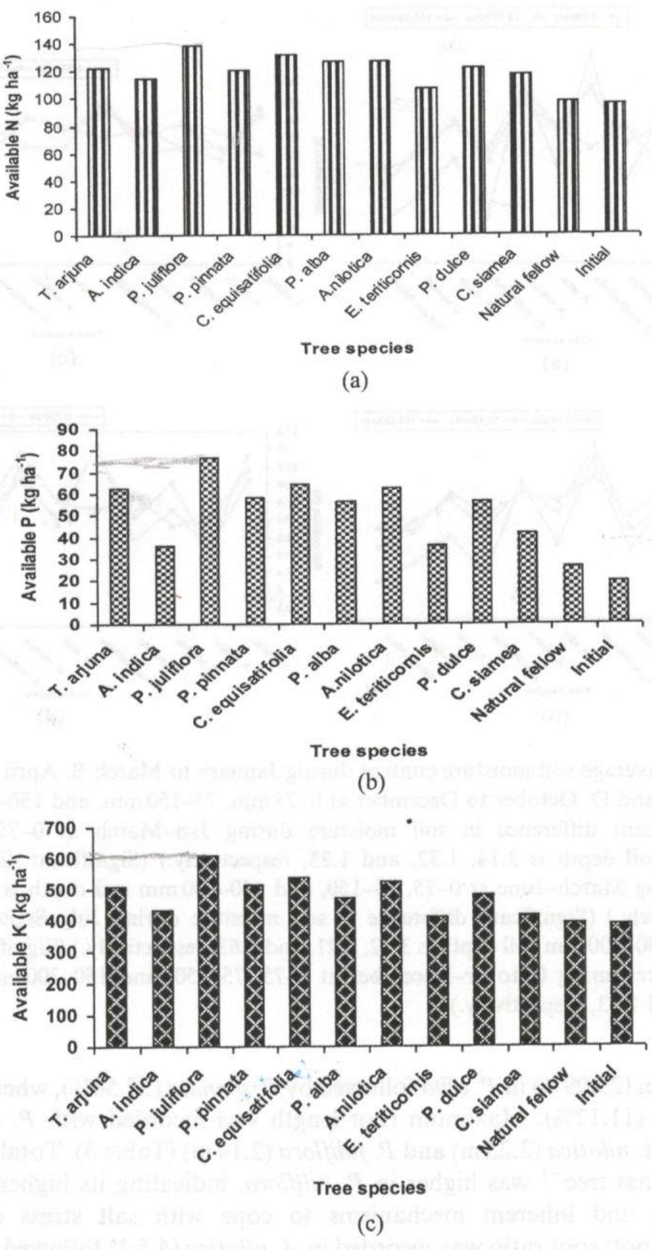

Figure 8. Available N, P, and K status in the sodic soil 10 years after plantation (YAP) at 0–15 cm soil depth. (Significant difference in available N, P, and K after 10 years of plantation at 5% level of significance is 7.68, 6.32, and 16.42, respectively.)

The data given in Table 4 indicated that *P. juliflora* recorded the maximum (140.0 kg tree^{-1}) biomass followed by *A. nilotica* (123.6 kg tree^{-1}) and *C. equisetifolia* (105.6 kg tree^{-1}) harvested at ten years age. G. Singh et al. (1993) also reported similar results. Lopped biomass partially removed in different years was significantly higher in *P. juliflora* over the remaining species. The share of lopped biomass to total biomass

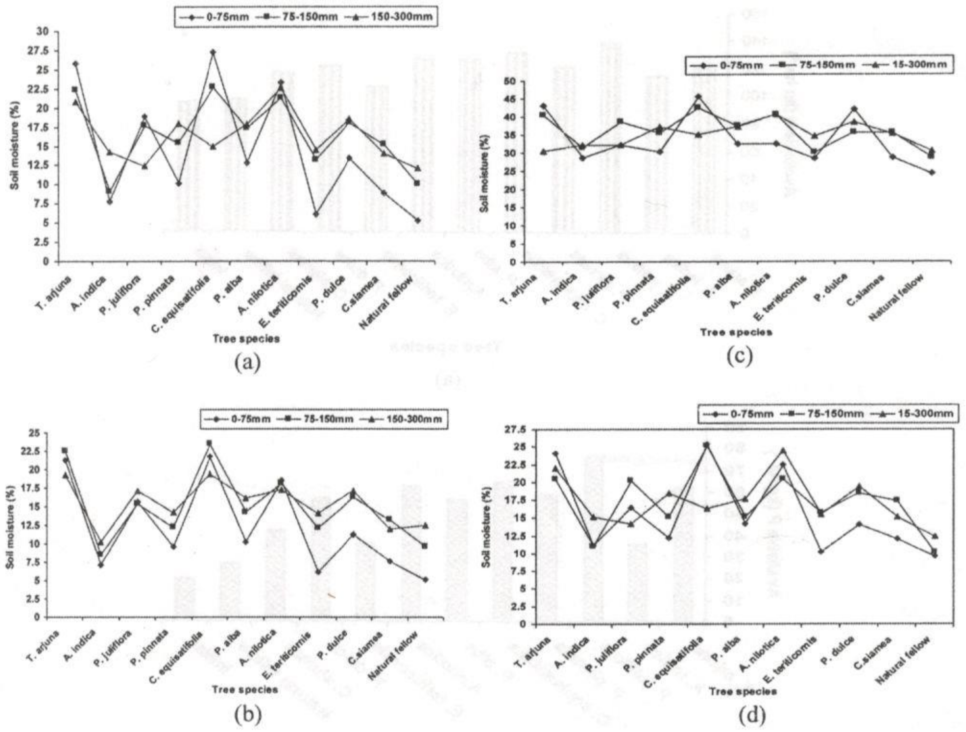

Figure 9. A. Average soil moisture content during January to March B. April to June C. July to September and D. October to December at 0–75 mm, 75–150 mm, and 150–300 mm during 2005. (Significant difference in soil moisture during Jan–March at 0–75, 75–150, and 150–300 mm soil depth is 3.14, 1.32, and 1.23, respectively.) (Significant difference in soil moisture during March–June at 0–75, 75–150, and 150–300 mm soil depth is 2.21, 4.32, and 1.14, respectively.) (Significant difference in soil moisture during July–September at 0–75, 75–150, and 150–300 mm soil depth is 3.12, 2.21, and 1.63, respectively.) (Significant difference in soil moisture during October–December at 0–75, 75–150, and 150–300 mm soil depth is 0.86, 1.01, and 1.23, respectively.)

was maximum (29.09%) in *P. alba* followed by *P. pinnata* (27.50%), whereas minimum in *C. siamea* (11.12%). Maximum root length was recorded with *P. dulce* (2.36 m) followed by *A. nilotica* (2.25 m) and *P. juliflora* (2.14 m) (Table 3). Total shoot, as well as root biomass tree^{-1} was higher in *P. juliflora*, indicating its highest tolerance to sodium salts and inherent mechanisms to cope with salt stress environments. Maximum shoot: root ratio was recorded in *A. nilotica* (4.5:1) followed by *P. juliflora* (4.2:1) and *C. equisetifolia* (4.1:1) indicating that root development in general in sodic soils was impeded because of hard concretion layer at the lower level (Table 4).

Soil Amelioration

Chemical Properties of Soil

Tree plantations on sodic soils improved the soil properties in terms of pH, EC, ESP, and organic carbon. The degree of improvement was linked to the total biomass production, annual litterfall and its quality, root spread and weight, and the level

Table 6. Ameliorative effect of different tree species on physical properties of soil 10 years after plantation

Tree species	Bulk density ($Mg\,m^{-3}$) 0–75 mm	75–150 mm	Soil porosity (%) 0–75 mm	75–150 mm	Cumulative infiltration rate ($mm\,day^{-1}$)
T. arjuna	1.47	1.52	44.5	42.6	21.20
A. indica	1.48	1.56	44.1	41.1	21.70
P. juliflora	1.32	1.46	50.2	44.9	26.30
P. pinnata	1.36	1.57	48.6	40.7	24.30
C. equisetifolia	1.21	1.42	54.3	46.4	25.80
P. alba	1.37	1.61	48.3	39.2	20.00
A. nilotica	1.29	1.58	51.3	40.4	21.90
E. tereticornis	1.38	1.51	48.0	43.0	19.70
P. dulce	1.25	1.58	52.8	40.4	23.10
C. siamea	1.46	1.48	45.0	44.1	15.80
Natural fallow	1.50	1.57	43.4	40.7	11.80
Initial	1.57	1.64	40.7	39.6	2.10
LSD (P = 0.05)	0.08	0.11	3.26	0.76	6.34

of management practices. The highest litterfall at ten years tree growth stage was recorded under *P. juliflora* (6.1 $Mg\,ha^{-1}$) followed by *C. equisetifolia* (5.7 $Mg\,ha^{-1}$), *A. nilotica* (5.4 $Mg\,ha^{-1}$), *T. arjuna* (5.1 $Mg\,ha^{-1}$), and *P. pinnata* (5.0 $Mg\,ha^{-1}$) (Table 5). Gill et al. (1987) have also observed similar trend in plantations raised in sodic soils. The winter months accounted for 40–55% of total litterfall that was composed of about 75–80% foliage. Results indicated that after ten years of plantation, highest improvement in terms of soil pH, electrical conductivity, and exchangeable sodium percentage in 0–15 cm soil depth was recorded under *P. juliflora*, followed by *A. nilotica* and *P. pinnata*. (Figure 6). Singh and Gill (1990), Singh and Gill (1992), and Mishra et al. (2004) have also reported higher soil amelioration in terms of decreased soil pH with *P. juliflora*. The increase in organic carbon content of the surface soil (0–15 cm) in a span of ten years was about four-fold under *P. juliflora* and *P. pinnata* and about three-folds in other species. Tripathi and Singh (2005) also reported the overall higher improvement in the soil organic matter under *P. juliflora*. The increase in organic carbon was significant at 60 cm soil depth for all species over the control (Figure 7). A significant improvement in available N, P, and K content in surface soil under tree plantation over control was observed. The highest improvement in these characters was recorded under *P. juliflora* and minimum under *P. dulce* because of the highest litterfall yield under *P. juliflora* (Figure 8).

Physical Properties of Soil

There was significant improvement in the physical properties of the sodic soil due to tree plantation (Table 4). Bulk density in 0–75 mm soil layer decreased significantly over the control, whereas porosity and infiltration rate increased. Maximum reduction in bulk density was recorded under *C. equisetifolia* (1.21 Mg m^{-3}) followed by *P. dulce* (1.25 Mg m^{-3}), *A. nilotica* (1.29 Mg m^{-3}), and *P. juliflora* (1.32 Mg m^{-3}); minimum reduction was recorded under *A. indica* (1.48 Mg m^{-3}) over the initial value of 1.57 Mg m^{-3}. The bulk density of the surface soil (0–75 mm) under control remained unchanged; whereas, under 75–150 mm soil layer, it was slightly improved. Soil porosity under ten-year old plantation at 0–75 mm soil layer increased from 40.7% to 54.3%. However, under the control plot, soil porosity was almost unchanged. Highest soil porosity at 0–75 mm soil layer was recorded under *C. equisetifolia* (54.3%) and minimum under *A. indica* (44.1%). Maximum moisture content at 0–75 mm soil layer was under *C. equisetifolia* followed by *T. arjuna, A. nilotica,* and *P. juliflora* and minimum under *E. tereticornis* (Figure 9). There was significant improvement in the infiltration rate under tree plantation over the control and initial values. Highest infiltration rate after ten years of tree plantation was recorded under *P. juliflora* followed by *C. equisetifolia, P. pinnata, P. dulce, A. nilotica, A. indica, T. arjuna, P. alba, E. tereticornis, and C. siamea.*

Discussion

Tree establishment and growth on sodic soils is influenced by a number of factors including genotypes, agro-climatic conditions, and plantation methodologies. In addition to biomass and bio-energy production, growing of trees on sodic soils resulted in their amelioration by improving physical and chemical properties of the soil. Sodic soil can support certain tree species that are salt tolerant and capable of growing, both under flooded and moisture stressed conditions and having low nutrient requirements. The degree of amelioration varies with the kind of species and habit of its growth, N_2–fixing ability, age of plantations, and management practices (Garg & Jain, 1992; Mishra et al., 2003; Singh et al., 1989). Long term field studies at several locations indicated that the ameliorative effect of tree species on sodic soils depends on the enrichment of the soil with the addition of organic matter, thereby recycling of important nutrients (Singh & Gill, 1992; et al., Garg, 1999; Jain & Garg, 1996). The species raised under sodic soils generally suffer higher mortality (Singh, 1989). Of the tree species, *P. juliflora, T. arjuna, P. pinnata, A. nilotica, C. equisetifolia, E. tereticornis, and P. dulce* showed >95% survival and were found to be highly tolerant to sodic soils (Yadav & Singh, 1970; Gill & Abrol, 1982; Gill et al., 1990; Singh et al., 1993). Some of the species, such as *P. alba,* showed 50% mortality. *E. tereticornis* attained maximum plant height but minimum crown diameter, whereas maximum diameter of the stem at breast (DBH) was recorded with *A. nilotica*. *P. juliflora,* being highly tolerant to sodicity, attained maximum diameter at stump height (DSH), crown diameter, and number of branches at 1/3 plant height. Understory biomass in the form of natural grasses produced under *A. nilotica* (6.35 Mg ha^{-1}) and *P. juliflora* (6.25 Mg ha^{-1}) was significantly higher compared with other species such as *C. equisetifolia* (2.73 Mg ha^{-1}), *T. arjuna* (5.20 Mg ha^{-1}), and *P. pinnata* (3.75 Mg ha^{-1}). Diaz et al. (1984) also reported higher natural grass yield under *P. juliflora* over story than in the open. Air dry biomass of different tree species predicted by Felker et al. (1983) under green house conditions found that *P. alba* produced the highest biomass. The data recorded from the experiment on tree biomass indicated that *P. juliflora* recorded the maximum biomass (56.50 Mg ha^{-1}) followed by *A. nilotica* (50.75 Mg ha^{-1}) and *C. equisetifolia* (42.10 Mg ha^{-1}) in ten years. In another study, Singh et al. (1993) and Singh et al. (2008) have also reported maximum biomass production from *P. juliflora* and *A. nilotica*. B. Singh (1989) estimated the above ground biomass of *P. juliflora* to be 1.06Mg ha^{-1} after three and one-half years when planted on sodic soils through a pit planting method. In our experiment, *P. juliflora* planted with an auger-hole method produced 3.26 Mg ha^{-1} after three years due to increased root development and plant growth. Soil pH and ESP are the important parameters that determine the severity of the sodicity in the soils. These values declined more at the surface than at lower depths for each species, because of replacement of exchangeable Na^+ by Ca^{2+} due to the root exudates, decomposition of litter, and subsequent leaching of the Na^+. Azevedo (1982) reported that leaf litter and root nodules of *P. juliflora* contributed to increasing nitrogen content and of other minerals in the soil. In addition to recycling of N, the decomposition of litter leads to evolution of CO_2 which helps mobilize the inherent Ca^{2+}. The released Ca^{2+} can hasten the reclamation by replacing the exchangeable Na^+ from the soil, thus reduced the soil sodicity and pH levels (Yadav & Singh, 1970). This was reflected more in *P. juliflora* and *A. nilotica,* which proved more efficient in reducing pH and ESP because of the presence of a higher content of organic matter, soluble calcium, and lower content of $CaCO_3$. Ponnamperuma (1972) reported that pH of alkaline soils was highly sensitive to changes in the partial pressure of CO_2. The CO_2 released from the roots of growing plants facilitates the replacement of adsorbed Na^+ by solubilizing the native $CaCO_3$ (Goertzen & Bowers, 1958) and, thus, enhances the process of reclamation. This improvement may change the overall land use by converting degraded land into agricultural land. Changes in other chemical properties due to tree plantation were evaluated after ten years of tree growth, and it was found that the percentage of increase in organic carbon content was higher near the surface soil and declined with depth (Figure 7). The highly significant increase in organic carbon content in soil was recorded, and its highest percent increase was in *P. juliflora,* followed by *P. pinnata* and *A. nilotica*. Highest organic carbon content in *P. juliflora* may be due to larger crown diameter, higher litterfall, and nutrient content. Rao and Ghai (1985) also recorded a reduction in soil pH and improvement in organic carbon of the under tree cover. These results are in agreement with the observations, under different tree covers on sodic soils, of many workers (Garg & Jain, 1992; Mishra et al., 2002; Shukla & Mishra, 1993). Organic matter plays an important role in the transformation and mineralization of nutrients in the soil. The increase in N content could be due to the addition of leaf litter and improved biological activities by the tree root system. Garg (1999) reported larger accumulation of organic carbon and nitrogen by *P. juliflora* compared to *E. tereticornis* and *Dalbergia sissoo* were due to differences in root distribution in the soil profile. Other field studies (Rundel et al. 1982; Tiedemann & Klemmedson, 1986) showed that soils under *Prosopis spp*. contained two to three times as much organic matter and nitrogen content as soils outside the tree canopy. The increment in available P and K content was due to increase in organic carbon content. The other constraint of sodic soil is dominance of Na^+ content in the soil. Na^+ content decreased in the surface layers and accumulated in the lower layers due to leaching of salts and the soil containing plant roots in the presence of CO_2 enhanced $CaCO_3$ dissolution, resulting in replacement of adsorbed Na^+. Cumulative infiltration rate was higher under *P. juliflora* plantation followed by *C. equisetifolia* and *P. pinnata* due to reduced sodicity, higher leaf litter, and growth of understory vegetation. G. Singh et al. 1989 showed the large improvement in infiltration rate and enhanced soil biological activities under *P. juliflora*. Similar observations were also recorded in this study.

Conclusion

Based upon the results of this investigation, species such as *P. juliflora*, and *A. nilotica* were identified as highly promising for growth on degraded sodic soils and to alleviate sodicity by leaching salts and improvement in the soil fertility. It was concluded that the establishment and performance of these tree species in terms of their survival, growth, and biomass production was also better than the other species evaluated under study. *P. juliflora* was found to be the most salt tolerant species as evident from the improvement in soil fertility in terms of organic carbon, available N, P, K, and reduction in soil pH and exchangeable Na^+. Soil physical properties such as soil bulk density, soil porosity, soil moisture, and infiltration rate were improved significantly due to plantation of *P. juliflora, A. nilotica, C. equisetifolia, T. arjuna, P. pinnata, E. tereticornis,* and *P. dulce*. The study indicated that sodic lands ameliorated by growing of these tree species for ten years can be put under crop production. The results of this investigation will be widely used under public private partnership (PPP) mode for planning energy plantation and amelioration of sodic soils.

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