MACRONUTRIENT DYNAMICS AND USE EFFICIENCY IN THREE SPECIES OF SHORT ROTATION FORESTRY DEVELOPED ON SODIC SOILS IN NORTH INDIA

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GARG, V. K. & SINGH, B. 2003. Macronutrient dynamics and use efficiency in three species of short rotation forestry developed on sodic soils in north India. Macronutrient dynamics and nutrient-use efficiency were investigated in young plantations of three fuelwood species established on a degraded sodic soil in Lucknow in north India (26° 45' N, 80° 51' E). The purpose was to generate fuelwood in short rotations on community wastelands of this region. Of the three species studied, aboveground production of mesquite, *Prosopis juliflora* was greater than *Acacia nilotica* and *Terminalia arjuna* during the six years of their growth span. In general nutrient (N, P, K, Ca and Mg) concentrations were greater in *P. juliflora* than in *A. nilotica* and *T. arjuna,* particularly in foliage component. There were little variations in woody components between the species. *Prosopis juliflora* stand had greatest nutrient capital followed by *A. nilotica* and *T. arjuna.* Nutrient fluxes (uptake, retention, retranslocation and return) were also relatively high in the *Prosopis* stand. *Acacia nilotica* had the greatest N-, K-, Ca- and Mg-use efficiencies. P-use efficiency was lowest in *A. nilotica.* Nutrient cost of wood production and removal indicated that one tonne of wood can be produced at the cost of minimum nutrient economy by *A. nilotica.* As a result of these plantations, the net effects on soil properties showed significant reductions in soil bulk density, pH and exchangeable sodium percentage after six years. Conversely, organic C, total N, exchangeable Ca and Mg increased in the soil, whereas K status remained almost constant. *Prosopis juliflora* reclaimed the soil more efficiently in comparison with the other species.

Key words: Nutrient use efficiency - fuelwood - wasteland - nutrient cost

GARG, V. K. & SINGH, B. 2003. Kecekapan dinamik dan penggunaan makronutrien dalam tiga spesies perhutanan kitaran pendek yang dibangunkan di tanah sodik di utara India. Dinamik makronutrien dan kecekapan penggunaan nutrien dikaji di ladang baru bagi tiga spesies kayu api yang dibangunkan di tanah sodik ternyahgred di Lucknow, utara India (26° 45' N, 80° 51' E). Tujuannya adalah untuk menjana kayu api dalam kitaran pendek di tanah gersang milik penduduk di kawasan ini. Daripada tiga spesies yang dikaji, mesquite, *Prosopis juliflora,* menunjukkan pengeluaran atas tanah yang lebih baik daripada *Acacia nilotica* dan *Terminalia arjuna* dalam tempoh enam tahun pembesarannya. Pada amnya, kepekatan nutrien (N, P, K, Ca dan Mg) adalah lebih tinggi dalam *P. juliflora* berbanding *A. nilotica* dan *T. arjuna,* terutamanya dalam komponen daun. Terdapat sedikit perubahan dalam komponen berkayu antara spesies tersebut. Dirian *P. juliflora* mempunyai jumlah nutrien tertinggi diikuti dengan *A. nilotica* dan *T. arjuna.* Perubahan nutrien (pengambilan, penahanan, translokasi semula dan pengembalian) juga tinggi secara relatif dalam dirian *Prosopis. Acacia nilotica* mempunyai kecekapan penggunaan N, K, dan Mg yang tertinggi. Kecekapan

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penggunaan P adalah terendah dalam *A. nilotica.* Kos nutrien bagi pengeluaran dan pemindahan kayu menunjukkan bahawa *A. nilotica* dapat menghasilkan satu tonne kayu pada kos ekonomi nutrien yang minimum. Hasil daripada perladangan ini, kesan terhadap ciri-ciri tanih menunjukkan pengurangan bererti selepas enam tahun dalam ketumpatan pukal tanih, pH dan peratusan natrium boleh tukar. Sebaliknya, C organik, jumlah N, Ca boleh tukar dan Mg meningkat di dalam tanih, manakala status K hampir malar. *Prosopis juliflora* menebus guna tanih lebih cekap berbanding dengan spesies lain.

Introduction

With the scarcity of fuelwood in many developing countries, various programmes of short rotation forestry were launched in the past two decades to fulfill this basic need of the rural communities (Hansen & Baker 1979, Toth 1981, Barrett-Lennard *et al.* 1986, Lugo *et al.* 1990, Singh & Toky 1995). In India, degraded lands of low fertility were generally allocated for this purpose and also for rehabilitation and simultaneous improvement of the area (Singh 1989, Chaturvedi & Behl 1996). Despite their slow growth and low productivity, energy plantations established on barren sodic soils reclaimed the soils significantly (Garg & Jain 1992). It is not ascertained whether nutrient removed from the site during fuelwood extraction would be replenished naturally or require fertilisation to sustain the subsequent rotation. Since forest fertilisation is not practised in many developing countries including India, it is important to know the nutrient cost of wood production and nutrient loss in the removal of wood to maintain a sustainable production system.

Species differ in their nutrient-use efficiency (NUE) for biomass production. Therefore, if poor in NUE, even a fast-growing species may deplete the soil nutrients rapidly and threaten soil sustainability (Sanchez *et al.* 1985). The removal of nutrient can be altered dramatically by varying plantation and harvest designs (Wang *et al.* 1991). A better understanding is required for the plasticity of nutrient uses under different site conditions even for the same species. Under stress conditions the quantity of nutrient uptake may not be used efficiently for optimum biomass production and, therefore, NUE cannot be adequately examined on the basis of nutrient return flux (Vitousek 1982, Gray 1983, Binkley *et al.* 1992). Instead an index of NUE, i.e. the ratio between aboveground production and uptake, is a better indicator. Hence, there is a need for more comprehensive inventory of nutrient retention in woody biomass and dynamic fluxes (uptake/return) for the many tree species used in short rotation forestry.

Very little is known about nutrient-use and recycling efficiencies by trees growing in sodic soil (Singh 1998). The objectives of the present study were to evaluate the effects of three tree species on aboveground productions, nutrient accumulation as well as uptake and return processes under the stress of soil sodicity in order to determine their NUE in a degraded system. The implication of these fluxes on soil reclamation was also observed to adopt a sustainable (nutrient efficient) land use system for such hostile soil sites. The results from Chaturvedi and Behl (1996) were also included for comparative evaluation.

Materials and methods

Site description

The study was carried out at Banthra, Lucknow in north India (26° 45' N, 80° 51' 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 soil of the site is characterised as Aquic Natrustalfs, having silt loam to silty clay loam surface texture. These soils exhibit physical and nutritional problems due to poor soil-water and soil-air relations caused by high compactness (bulk density > 1.5 g cm^{-3}), high pH (8.5 to 9.0) and high exchangeable sodium per cent (> 0.30). The soils also have very low water permeability and electrical conductivity (< 1.0 dSm^{-1}). The calcic horizon starts from 60 cm deep with thickness varying from 30 to 45 cm. Below the calcic horizon the soils are coarser in texture and remain generally moist and free from calcareous salts. The soils develop cracks during the dry hot summer but are sticky in the rainy season.

Monoculture tree plantations of *Acacia nilotica*, mesquite (*Prosopis juliflora*) and *Terminalia arjuna* were established at the Biomass Research Centre, Banthra. Planting stock was procured from old plantations of these species located at Kukrail (Lucknow) and Allen Forest (Kanpur) raised by the State Government Forest Department. These tree species were planted in a pit of 1 m^3 at a spacing of 1.5 × 1.5 m apart in a randomised block design in three replications. Experimental plot measuring 40 × 40 m contained 625 trees per plot.

Nutrient

Random samples of stem, branch and leaf were collected from six-year-old plantations after the rainy season in October. Three composite samples were taken for each of the plant component from five marked trees of different sizes and dried at 65 °C to constant weight. Samples were ground in a Wiley mill passing through 0.1-mm mesh. Nitrogen content in the plant component was estimated by macro-Kjeldahl method using a Tecator Kjeltec Auto 1030 Analyser. Following wet digestion method in perchloric acid and nitric acid (Richards 1954), P was determined by spectrophotometer using vanadomolybdo phosphoric yellow colour method. Other aliquots of wet digestion were used for K and Ca estimations by flame photometer. Magnesium was determined by titration using versenate method (Jackson 1967).

Nutrient storage in stands was obtained through mass concentration ratio of different components. Nutrient uptake was calculated by multiplying the value of different components of aerial biomass by their respective nutrient concentration. Nutrient retention was derived from the difference of nutrient storage in aboveground plant components during two consecutive years.

Retranslocation of nutrients from senescing leaves to the perennial tissue was calculated following the method outlined by Rawat and Singh (1988).

$$\text{Retranslocation} = \frac{A - B}{A} \times 100$$

where

A = Concentration of nutrient in green foliage × mass of litter fall
B = Concentration of nutrient in litter fall × mass of litter fall

Annual litter fall and forest floor litter

A total of 36 porous litter traps each of 0.25 m^2 was placed under the three species. There were four traps in each plot of a species. Litter fall was collected every month for a period of two years. The collected litter was oven dried at 65 °C and analysed for different nutrients as for plant materials. The nutrient concentration was multiplied by annual litter fall to obtain the amount of nutrients transferred to the forest floor (nutrient return flux).

Litter of forest floor was sampled during rainy, winter and summer seasons through five quadrats of 1 m^2 laid out randomly in each plot. These samples were processed and analysed for different macronutrients, as for the plant samples.

Nutrient flux and nutrient-use efficiency

Four nutrient fluxes were investigated, namely, uptake, retention, retranslocation and return. Uptake was further refined as gross and net uptake on the basis of the amount associated with aboveground production including or excluding retranslocation respectively (Singh & Singh 1991). Retention values were estimated from the annual storage of nutrients in perennial plant components whereas nutrient return through annual litter fall was estimated as return flux. NUE was calculated using the return flux (Vitousek 1982, Gray 1983, Binkley *et al.* 1992). Therefore, in the present study, NUE was examined as net production per unit of nutrient uptake.

Soil sampling and analysis

Three composite soil samples from each plot were collected in summer (May to June) from 0 to 15 cm depth before planting commenced and again when the stands were six years old to ascertain the nutrient depletion/addition in sodic soil as a result of plantation. Soil samples were homogenised, passed through a 2-mm sieve and analysed for soil characteristics. Soil pH was determined in 1:2 soil: water ratio. Organic C was determined according to the modified method of Walkley and Black (1934). Total N was determined as done for plant samples. Available P in soil was extracted in 0.5 M $NaHCO_3$ adjusted to pH 8.5 following Olsen's method described by Kalra and Maynard (1991). Exchangeable cations (Na^+, K^+, Ca^{2+} and

Mg^{2+}) were extracted from the soil with neutral normal ammonium acetate solution and their concentrations were determined by flame photometer except for Mg, which was determined following the method described for plant analysis (Jackson 1967). Exchangeable sodium percentage was calculated from the formula described by Richards (1954). Soil bulk density (stone free) was determined by weighing a known volume (100 cm^3) of undisturbed soil sample and drying it at 105 °C to constant weight.

Results and discussion

Biomass production

Aboveground production was greatest in *P. juliflora* corresponding to their fast growth and high yield in sodic soil sites (Figure 1). Maximum production was observed between stand age of four and five years in *P. juliflora* and *A. nilotica*, whereas it increased linearly in *T. arjuna* up to the age of six years . The values of aboveground production for *P. juliflora* and *A. nilotica* compare fairly well with the figures reported for five tropical tree plantations established overseas for biomass production in short rotations (Lugo *et al.* 1990). Aboveground production in short rotation harvestings varied generally from 6 to 15 t ha^{-1} $year^{-1}$ for most of the tropical tree species studied by Lugo *et al.* (1988). Therefore, growth of *P. juliflora* and *A. nilotica* in this study appeared quite encouraging. However, *T. arjuna* suffered from the adverse conditions of soil degradation and low fertility which in general led to stressed growth. Nevertheless, our study showed that local native species performed far better than fast growing exotic like *Populus deltoides* on similar site in this region (Singh 1998).

Stem and branches contributed 82 to 96% of aboveground production (Table 1). The foliage constituted 4 to 17% with the greatest value in *T. arjuna* on account of a broad laminar morphology. *Acacia nilotica* attained greater diameter growth than *P. juliflora*. However, the former was inferior to the latter in terms of height, basal area and population density. Nevertheless, population density alone did not contribute much in biomass production when dimensional growth of the individuals was highly suppressed as in the case of *T. arjuna*. The better productivity of *P. juliflora* and *A. nilotica* can be attributed to their greater tolerance to soil sodicity (Singh *et al.* 1992, Jain 1995). Therefore, these two species are commonly afforested on barren sodic soils of Gangetic alluvial plains in north India for fuelwood production and soil reclamation.

Nutrient concentration

Concentration of macronutrients in different components of the trees showed highest values in leaves because of their more active role in metabolic activities followed by branch and stem (Table 2). In general, *P. juliflora* had greater concentration of nutrients compared with *A. nilotica* and *T. arjuna*. The nutrient concentrations, particularly in foliage, differ from species to species, site to site

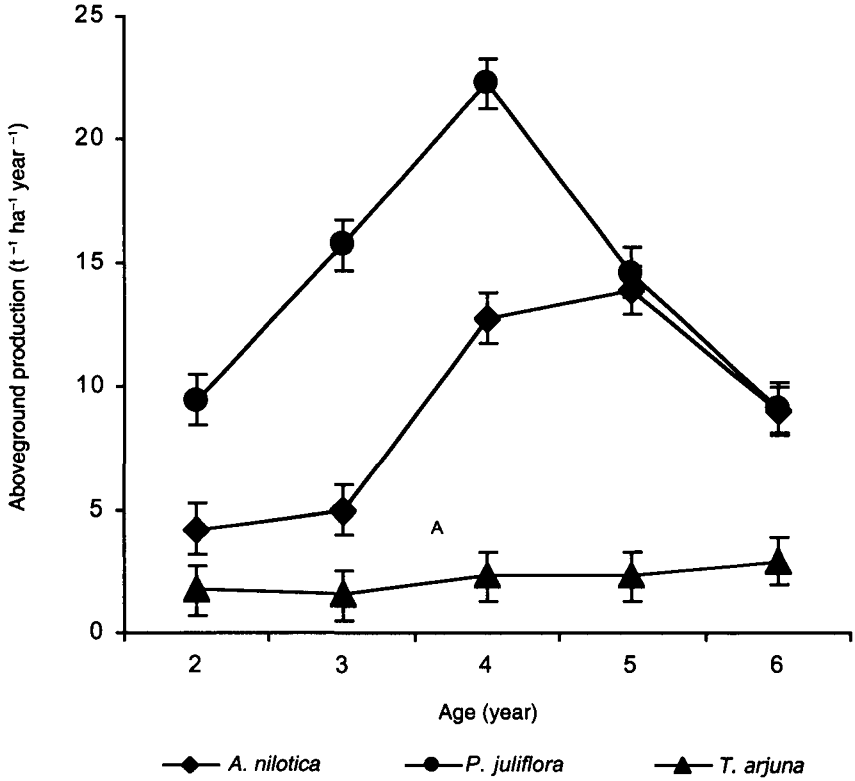

Figure 1 Aboveground production of three tree species aged six years planted on sodic soil in Lucknow, India

Table 1 Mean growth and aboveground biomass production of three fuelwood tree species aged six years (after Chaturvedi and Behl 1996 except for litter) in Lucknow, India

	Species*		
	Acacia nilotica	*Prosopis juliflora*	*Terminalia arjuna*
Growth			
Height (m)	6.9 ± 0.31	8.5 ± 0.18	4.0 ± 0.34
Diameter (cm)	8.0 ± 0.34	6.9 ± 0.38	4.0 ± 0.35
Basal area ($m^2 ha^{-1}$)	8.8 ± 1.6	10.2 ± 1.7	6.6 ± 1.6
Population density (No. ha^{-1})	1842 ± 500	2625 ± 228	5617 ± 7
Biomass (t ha^{-1})			
Stem	14.0 ± 3.6	28.0 ± 7.2	4.0 ± 1.2
Branch	17.0 ± 4.3	27.0 ± 7.1	1.7 ± 0.6
Leaf	1.6 ± 0.4	2.2 ± 0.6	1.2 ± 0.4
Total	32.6	57.2	6.9
Floor litter mass (ha^{-1})	22.5 ± 0.3	21.9 ± 0.6	7.8 ± 0.6

*± SE

and among individuals of different ages even in the same species on the same site (Singh 1982, 1998). However, when nutrient concentrations of the species under the present investigation were compared with the study by Singh (1998), we conclude that at one site different species may not respond differently when availability of nutrients in the soil is limited. Other studies have shown that ionic equilibrium of soil solution at our study site is disturbed which causes abnormal nutrient uptake (Naidu & Rangasamy 1993). Therefore, variations in nutrient concentration cannot be critically distinguished between N fixers and non N fixer species. Even *P. deltoides*, being a non-N fixer and grown on such site showed almost compatible nutrient concentrations (Singh 1998) with the species of our study. However, N concentration in the foliage of the trees in our study is slightly lower than those reported for natural forests of this region (Singh & Misra 1978). Probably N deficiency in the soil of our study site could not sustain adequately the growth and productivity of the three species. Nutrient concentrations in the foliage were in the order: N > K > Ca > Mg > P. This order is slightly different from the values reported for young plantations of other tropical trees, where Ca was greater than K (Toky & Singh 1995). In general, nutrient concentrations in litter decreased in the same order as the foliage.

Standing state of nutrients

Nutrient accumulation was much less in *T. arjuna* than in the other two species (Table 3). *Acacia nilotica* and *P. juliflora* had greater accumulation in branches because of their high branch biomass. Most tropical species exhibit vigorous branching in which nutrients are allocated in the order branches > stem > leaves > root, whereas in many other fast growing species like *Populus* and *Eucalyptus*, foliage may accumulate the largest proportion of total nutrient storage in the standing trees (Bargali *et al.* 1992b, Singh 1998). The present study showed about 47% of the tree nutrients in branches, 41% in stem and 12% in leaves of *A. nilotica* and *P. juliflora*. On the other hand, in *T. arjuna*, contribution of leaf was relatively higher (33%). Such distribution pattern affects nutrient recycling and soil sustainability in different ways. If greater amounts of nutrients are allocated to woody components, nutrient depletion may occur with frequent harvesting and removal of woody biomass.

Nitrogen storage was greater than other elements during the six-year growth of *A. nilotica* and *P. juliflora*, but in the case of *T. arjuna*, Ca storage was greater than N due to slow growth (Table 3). In other species, namely, *Eucalyptus* and *Dalbergia sissoo* grown on normal soils, Ca contributed the largest proportion of nutrient storage followed by N, K, Mg, P (George 1984, Sharma *et al.* 1988). Our results also show that forest floor accumulated considerable amounts of nutrients in the litter mass, particularly under *A. nilotica* and *P. juliflora* species. Soil was found to be the largest reservoir for most of the nutrients under these stands.

Table 2 Chemical composition in different component of three tree species afforested on sodic soil in Lucknow, India

Species	Component	Nutrient (%)*				
		N	P	K	Ca	Mg
Acacia nilotica	Stem	0.40 ± 0.02	0.10 ± 0.01	0.35 ± 0.07	0.73 ± 0.13	0.05 ± 0.01
	Branch	0.56 ± 0.06	0.13 ± 0.01	0.45 ± 0.03	0.38 ± 0.11	0.06 ± 0.02
	Leaf	2.47 ± 0.08	0.18 ± 0.01	1.01 ± 0.04	0.56 ± 0.02	0.29 ± 0.02
	Litter	1.72 ± 0.08	0.10 ± 0.02	0.25 ± 0.07	0.41 ± 0.04	0.25 ± 0.02
Prosopis juliflora	Stem	0.48 ± 0.02	0.11 ± 0.04	0.46 ± 0.02	0.55 ± 0.08	0.07 ± 0.03
	Branch	0.53 ± 0.03	0.12 ± 0.01	0.61 ± 0.03	0.36 ± 0.07	0.03 ± 0.001
	Leaf	3.14 ± 0.07	0.17 ± 0.02	1.81 ± 0.22	0.88 ± 0.03	0.56 ± 0.05
	Litter	1.55 ± 0.20	0.11 ± 0.02	0.84 ± 0.32	0.60 ± 0.02	0.35 ± 0.04
Terminalia arjuna	Stem	0.34 ± 0.03	0.04 ± 0.01	0.40 ± 0.03	0.58 ± 0.04	0.07 ± 0.01
	Branch	0.49 ± 0.05	0.04 ± 0.01	0.54 ± 0.04	1.21 ± 0.12	0.15 ± 0.05
	Leaf	1.57 ± 0.20	0.15 ± 0.02	0.91 ± 0.13	0.81 ± 0.02	0.59 ± 0.04
	Litter	0.82 ± 0.05	0.11 ± 0.01	0.17 ± 0.08	0.65 ± 0.07	0.50 ± 0.02

* ± SE

Table 3 Nutrient accumulation in stands of three species aged six years planted on sodic soil in Lucknow, India

Species	Component	Nutrient (kg ha^{-1})				
		N	P	K	Ca	Mg
Acacia nilotica	Stem	57.5 ± 0.07	14.8 ± 0.3	49.5 ± 2.5	103.7 ± 4.7	7.40 ± 0.4
	Branch	96.2 ± 2.8	21.7 ± 0.6	76.5 ± 1.4	65.0 ± 4.9	9.9 ± 0.9
	Leaf	40.0 ± 0.3	3.0 ± 0.04	16.4 ± 0.15	9.1 ± 0.08	4.7 ± 0.06
	Total	193.7	39.5	142.4	177.8	22.0
	Litter	387.3 ± 5.6	22.5 ± 0.3	56.3 ± 0.8	92.3 ± 1.33	56.3 ± 0.81
	Soil	1350	17	413	4.52	2.43
Prosopis juliflora	Stem	133.8 ± 1.3	33.3 ± 0.3	130.5 ± 1.5	153 ± 5.8	18.7 ± 2.2
	Branch	142.5 ± 2.5	31.6 ± 0.7	165.9 ± 2.2	97.7 ± 0.5	86.3 ± 0.1
	Leaf	69.8 ± 10.5	3.8 ± 2.8	40.2 ± 12.9	19.7 ± 4.5	12.4 ± 7.8
	Total	346.1	68.7	336.6	270.4	117.4
	Litter	339.8 ± 8.7	24.0 ± 0.6	184.0 ± 4.7	131.5 ± 3.4	76.73 ± 1.95
	Soil	1370	20	457	3.9	2.6
Terminalia arjuna	Stem	12.3 ± 0.4	1.4 ± 0.02	14.2 ± 0.4	20.7 ± 0.5	2.5 ± 0.07
	Branch	8.3 ± 0.6	0.7 ± 0.01	9.2 ± 0.6	20.6 ± 1.5	2.6 ± 0.6
	Leaf	18.1 ± 0.8	1.7 ± 0.08	10.5 ± 0.5	9.4 ± 0.1	6.8 ± 0.2
	Total	38.7	3.8	33.9	50.7	11.9
	Litter	64.0 ± 5.3	8.6 ± 0.7	13.3 ± 1.1	50.8 ± 4.2	39.1 ± 3.2
	Soil	1460	16	397	3.6	3.0

* ± SE

Nutrients dynamics

The gross annual uptake of nutrients was greatest in *P. juliflora* and least in *T. arjuna* (Table 4). These figures compare fairly well with *Eucalyptus* hybrid and *Dalbergia sissoo* (Sharma *et al.* 1988). In our study, retranslocation of 17% N from senescing leaves of *A. nilotica* was relatively low compared with *P. juliflora* and *T. arjuna* with 34 and 37% respectively. Retranslocation values for other nutrients were 9, 10 and 13% for P, 32, 26 and 39% for K, 7, 15 and 10% for Ca,

Table 4 Nutrient fluxes during six year in three fuelwood tree plantations on sodic soils at Lucknow, India

Species	Nutrient fluxes	Nutrient ($kg\ ha^{-1}$)*				
		N	P	K	Ca	Mg
Acacia nilotica	Gross annual uptake	78 ± 13	11 ± 2	38 ± 3	43 ± 7	9 ± 1
	Net uptake	65 ± 11	10 ± 2	26 ± 7	40 ± 7	8 ± 1
	Retention	30 ± 7	7 ± 0.8	18 ± 4	32 ± 7	3 ± 0.8
	Retranslocation	13 ± 2	1 ± 0.2	12 ± 2	3 ± 0.6	1 ± 0.2
	Return	35 ± 7	3 ± 0.5	8 ± 2	8 ± 2	5 ± 0.9
Prosopis juliflora	Gross annual uptake	100 ± 11	10 ± 2	68 ± 10	46 ± 7	16 ± 3
	Net uptake	67 ± 8	9 ± 2	51 ± 8	39 ± 7	11 ± 1
	Retention	27 ± 8	6 ± 2	29 ± 9	25 ± 8	3 ± 0.9
	Retranslocation	34 ± 6	1 ± 0.1	18 ± 5	7 ± 1	5 ± 1
	Return	39 ± 7	3 ± 0.6	21 ± 4	14 ± 3	8 ± 2
Terminalia arjuna	Gross annual uptake	27 ± 10	3 ± 0.9	18 ± 7	21 ± 8	9 ± 3
	Net uptake	17 ± 8	2 ± 0.9	11 ± 4	19 ± 8	8 ± 3
	Retention	5 ± 2	0.5 ± 0.2	6 ± 2	10 ± 4	1 ± 0.3
	Retranslocation	10 ± 4	0.4 ± 0.1	7 ± 3	2 ± 0.1	1 ± 0.2
	Return	12 ± 4	2 ± 0.3	6 ± 2	9 ± 3	7 ± 2

* ± SE

and 11, 31 and 11% for Mg in *A. nilotica, P. juliflora* and *T. arjuna* respectively. Our results show that *T. arjuna* retranslocated highest percentages of N, P and K with less aboveground production and storage of nutrients in which internal nutrient cycle was dominant.

Under stress conditions, species returning greater quantity of nutrients to the soil through litter fall may be considered more efficient for maintaining soil sustainability. However, it was observed that only 37 to 43% of the uptake of nitrogen was returned to the soil by these species (from Table 4); the rest remained accumulated in the perennial plant component of the trees. A fraction of that, i.e. the amount which is retranslocated at the time of senescence in the present year, will be remobilised in the formation of new tissues of leaf and twigs in the following year.

Nutrient-use efficiency

NUE has been measured in different ways by several workers depending upon the nutrient flux considered, namely, acquisition, transfer, use or return (Vitousek 1982, Gray 1983, Aerts 1990, Binkley *et al.* 1992). Our calculation for this index was based on aboveground production per unit gross annual uptake of different nutrients. Large differences were found in aboveground production per unit gross uptake among the species studied (Figure 2). NUE, on the basis of per unit gross N uptake, appears to be a useful index because the retranslocated amount of nutrient will be used for growth in the following years. With the exception of P, *A. nilotica* had the greatest NUE followed by *P. juliflora* for a few elements (Ca, Mg) and *T. arjuna* for others (N, K). Phosphorus-use efficiency was highest in *T. arjuna. Prosopis juliflora,* although superior in aerial production (Figure 1), was not as good in NUE, indicating that production consumed large amounts of nutrients.

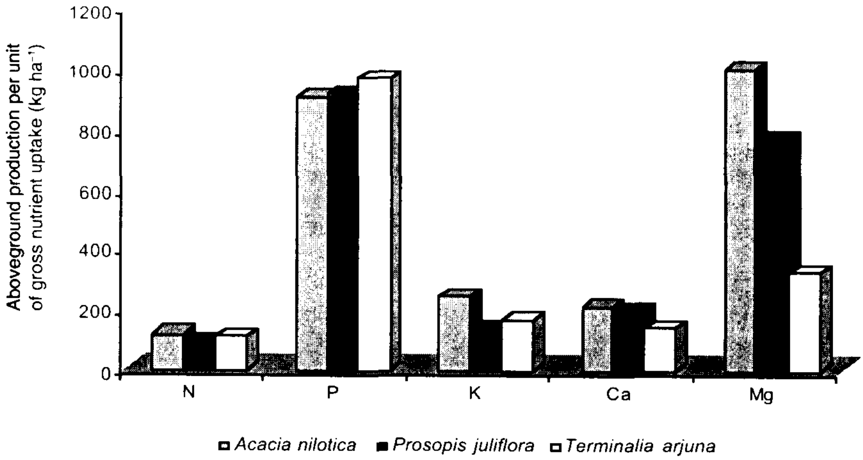

Figure 2 Nutrient-use efficiency of three tree species at the age of six years based on aboveground production per unit of gross nutrient uptake in Lucknow, India

On average, our study showed that these short rotation plantations yielded only 100 kg of net production from 1 kg of gross N uptake, compared with 200 to 280 kg for the other fast growing trees like *Eucalyptus*, pine and poplar raised on better sites (Singh 1982, Baker & Attiwill 1985, Tandon *et al.* 1991, Bargali *et al.* 1992a, b). Thus, the quantity of nutrient return through litter fall assumes considerable importance in maintaining soil sustainability if frequent harvesting and removal takes place in short rotation fuelwood forestry programmes. However, substrate quality, microclimate and biological conditions between the stands may vary to some extent on which mineralisation depends to a greater extent. Microbial population in these stands has been found to be variable (Garg 1998) and decomposition and nutrient mineralisation studies should be further investigated.

Nutrient cost

Nutrient cost of wood production and removal was determined on the basis of amount of nutrient consumed or lost for the production or removal of one tonne of aboveground woody biomass (stem and branch) respectively. The production cost for one tonne of wood measured for three nutrients, namely, N, P and Mg was almost similar in *A. nilotica* and *P. juliflora* whereas K uptake was relatively high in *P. juliflora* (Figure 3). Calcium need was very high for *T. arjuna* species in comparison with the other two species. Most of the nutrients are recycled between plant and soil through death and decay of delicate plant parts (leaf, twigs, fine roots). Some nutrients are lost from the system due to harvesting and removal of wood from the site. Thus, if one tonne of wood is harvested and removed from the site, different quantities of nutrients will be lost from the system by different species (Figure 3).

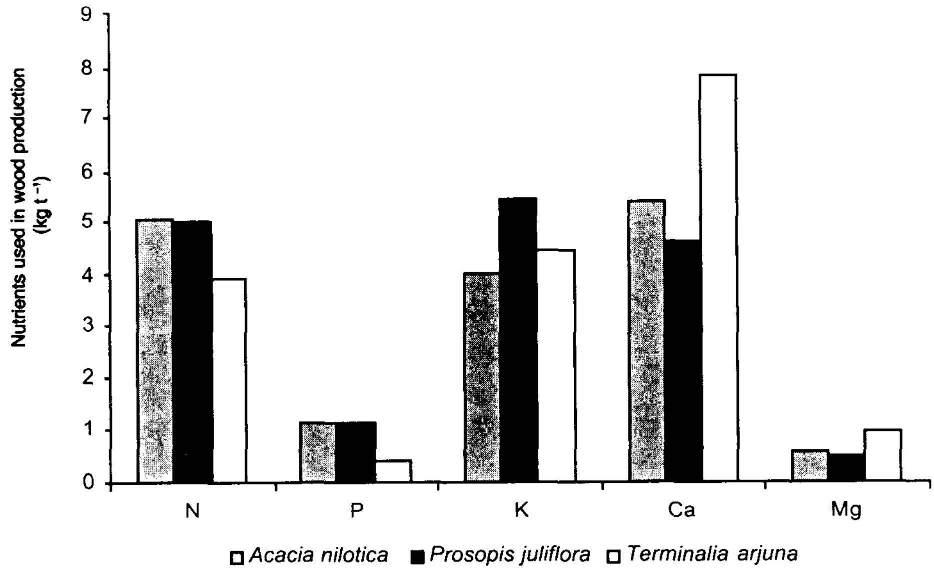

Figure 3 Nutrient cost of wood production by three tree species in Lucknow, India

Soil amelioration

The effects of these plantations on soil properties are positively related to soil amelioration. A marked reduction in soil pH and bulk density was noticed after six years (Table 5). There was an increase in soil organic C to almost three to four times during this period. The status of exchangeable cations (Ca^{2+}, Mg^{2+}, Na^{+}) changed significantly. We observed more than 50% reduction of sodium in the soil and as much enhancement of Ca^{2+} and Mg^{2+} from the initial levels. However, K and P did not vary significantly. The maximum reduction (75%) of exchangeable sodium in the soil was noted under *Prosopis* stand. As a consequence, pH value was lowest in this stand. Singh *et al.* (1989) also noticed significant reductions in pH and exchangeable cations and improvements in organic carbon C and available P contents in sodic soil planted with mesquite after two to three years. *Prosopis* is quite tolerant to sodicity on account of its wide occurrence in semi-arid and arid regions of southern USA (Felker *et al.* 1981). The main reason for better amelioration by *P. juliflora* was also reported to be due to its relatively high litter production and nutrient cycling (Garg 1998, 1999).

In conclusion, *P. juliflora* reclaimed the soil more efficiently than *A. nilotica* and *T. arjuna*. Nevertheless, suitability of *A. nilotica* cannot be ruled out in view of its relatively better NUE in sodic soils of low fertility.

Table 5 Soil characteristics under three tree species aged six years as well as at the time of initial planting (in parentheses) in Lucknow, India.

Soil characteristic	Species		
	Acacia nilotica	*Prosopis juliflora*	*Terminalia arjuna*
Bulk density (g cm^{-3})**	1.61 ± 0.015 (1.80 ± 0.025)	1.43 ± 0.035 (1.80 ± 0.025)	1.55 ± 0.015 (1.80 ± 0.025)
pH**	8.8 ± 0.02 (9.4 ± 0.15)	8.6 ± 0.10 (9.5 ± 0.10)	8.8 ± 0.20 (9.4 ± 0.10)
Organic C (%)*	0.564 ± 0.003 (0.178 ± 0.002)	0.646 ± 0.002 (0.156 ± 0.002)	0.649 ± 0.002 (0.160 ± 0.003)
Total N (%)*	0.056 ± 0.002 (0.017 ± 0.001)	0.064 ± 0.003 (0.023 ± 0.001)	0.063 ± 0.002 (0.025 ± 0.002)
Available P (μg g^{-1})^{ns}	8.00 ± 0.20 (6.00 ± 0.15)	9.00 ± 0.25 (6.00 ± 0.15)	7.00 ± 0.20 (6.00 ± 0.15)
Exchangeable K^+ (c mol kg^{-1})^{ns}	0.47 ± 0.03 (0.41 ± 0.04)	0.52 ± 0.02 (0.41 ± 0.04)	0.52 ± 0.02 (0.41 ± 0.04)
Exchangeable Ca^{2+} (c mol kg^{-1})^{ns}	9.4 ± 0.15 (4.5 ± 0.10)	9.0 ± 0.23 (5.8 ± 0.10)	7.7 ± 0.15 (5.9 ± 0.15)
Exchangeable Mg^{2+} (c mol kg^{-1})*	8.3 ± 0.20 (4.6 ± 0.15)	9.8 ± 0.10 (4.5 ± 0.15)	10.7 ± 0.15 (4.90 ± 0.10)
Exchangeable Na (%)*	16.6 ± 0.20 (30 ± 2.00)	10.8 ± 0.15 (31 ± 2.00)	25.0 ± 0.35 (28 ± 3.00)

* = Significant at $p < 0.01$ between zero and six years
** = Significant at $p < 0.05$ between zero and six years
ns = Not significant

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