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Nutrient use efficiency and biomass production of tree species for rotational woodlot systems in semi-arid Morogoro, Tanzania

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Abstract Frequent nutrient removals accompanying wood and crop harvests from rotational woodlot systems may contribute to declining site productivity and sustainability because of soil nutrient depletion. However, selecting for nutrient-efficient tree species may well sustain productivity under this system. To test this hypothesis, a randomized complete block experiment was adopted to assess effects of five tree species on soil nutrients status, nutrient use efficiency and wood yield in semi-arid Tanzania. After 5 years rotation, top soils under *Gliricidia sepium* (Jaqua), *Acacia polyacantha* Willd. and *Acacia mangium* Willd. were the most fertile with soil organic carbon and exchangeable cation status raised close to those in natural Miombo systems. Soil inorganic N and extractable P levels reached sufficiency levels for subsequent maize culture. Wood productivity in tree fallows averaged three times higher than that of Miombo woodlands indicating the high potential of the woodlot system to supply fuelwood, and consequently relieve harvesting pressures on the natural forests. *Acacia crassicarpa* A. Cunn. ex Benth. produced the most wood (51 Mg ha^{-1}) at low nutrient ''costs'' presumably due to high nutrient use efficiency. Wood yield of this species was 42 and 120% greater than that of *A. polyacantha* and A. *nilotica*, respectively, but contained comparatively less nutrients (42–60% less for P, K, and Ca). *Gliricidia sepium* and *A. polyacantha* returned the largest amount of nutrients through slash at harvests. Of all test species, *A. crassicarpa* exhibited the most promise to sustain wood production under rotational woodlot systems due to relatively high productivity and low nutrient export at harvest.

Keywords Acacia · Fuelwood · Nutrient use efficiency · Soil fertility · Sustainability

Introduction

Plantations and woodlots of fast growing tree species play a significant role in meeting the rapidly increasing demands for timber, fuelwood and other wood products in the tropics. On suitable soils, fast-growing tree species such as *Pinus patula* Schldl. Cham and *Cupressus lusitanica* Mill. produce as much as 25–35 m^3 ha^{-1} year^{-1} of wood compared to 4.35 m^3 ha^{-1} year^{-1} produced from the natural

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Miombo woodlands of Tanzania (Ek 1994). Such fast growth requires ample supplies of soil nutrients and other growth resources that can be rapidly depleted without effective nutrient recycling or fertilizer supplementation. Large amounts of nutrients are exported in tree harvests; with wood accounting as much as 50% of nutrients exports (Kumar et al. 1998). Intensive repeated harvesting may result in site degradation due to soil fertility decline in subsequent rotations (Nykvist 2000). The deterioration may be critical on inherently infertile soils because of frequent nutrient loss accompanying repeated biomass harvests (Fölster and Khanna 1997; Nykvist 2000). This may also apply to agroforestry practices, such as rotational woodlot systems, because of nutrient loss through continual firewood collections as well as crop harvests.

The rotational woodlot system is an agroforestry technology developed recently to curb fuelwood deficit in semi-arid areas of Western Tanzania where intensive tobacco curing and livestock grazing have accelerated deforestation through forest clearing, continuous farm cropping, and high grazing pressure (Ramadhani et al. 2002; Nyadzi et al. 2003a). The woodlot system consists of three interrelated phases of trees and crops grown sequentially in rotations on the same land. The first phase is an establishment phase in which fast growing multipurpose trees are intercropped with crops for the first 2–3 years until canopy closure. This is followed by a tree-fallow phase in which trees are allowed to fallow for another 2–4 years to produce wood and replenish soil fertility. The final phase is a post-fallow period in which trees are harvested and crops are either intercropped with coppicing tree stumps that later produce wood or grown with stumps uprooted. A fresh cycle starts after 2–3 years of sequential cropping when crop yields decline to unacceptable levels (Nyadzi et al. 2003a). Compared to simultaneous agroforestry systems such as hedgerow intercropping, the rotational woodlot system is more suitable for semi-arid conditions because sequential cropping arrangements minimize competition for growth resources, especially soil moisture (Rao et al. 1998) and produce higher wood yields due to longer tree fallows (Nyadzi et al. 2003a). Maize production from this system is usually higher than natural fallow and continuous cropping due to improved soil nutrient build up during the tree fallow phase (Nyadzi et al. 2003a).

One way to sustain soil fertility and crop production in rotational woodlot systems is to reduce the amount of nutrients exported in harvested wood by preferentially planting low nutrient demanding tree species. Nutrient use efficiency, defined as the ratio of biomass production to nutrient uptake, has been proposed as a criterion for selecting tree species for this purpose (Wang et al. 1991; Kumar et al. 1998). This ratio describes differential abilities of tree species to use soil nutrients for growth (Marschner 1995; Schroth et al. 2003). It also provides a basis for comparing nutrient ''costs'' of biomass production (Kumar et al., 1998), and the potential of plant species to grow well under conditions of limited soil nutrient supply (Marschner, 1995; Safou-Matondo et al. 2005). The role of nutrient use efficiency in sustaining productivity of short-rotation tropical plantations by minimizing nutrient loss from harvesting has been studied before (Wang et al. 1991; Kumar et al. 1998; Safou-Matondo et al. 2005). The general consensus is that nutrient-efficient tree species reduce nutrient export at harvests because of low nutrient content per unit biomass.

Previous approaches for selecting tree species for woodlots in Tanzania considered rate of biomass yields and climatic adaptation alone as suitable criteria (Karachi et al. 1997; Nyadzi et al. 2003a). However, to ensure sustained productivity of the rotational woodlot system, it may be more appropriate to consider nutrient use efficiency as additional selection criteria. Ideally, trees should grow rapidly to produce high wood biomass and export few nutrients at each harvest (Wang et al. 1991). The approach in this study was to assess these factors in a 5-year-old rotational woodlot experiment. Specific objectives were to examine effects of tree species on soil nutrients status, wood yield, nutrient use efficiency, and exports in order to evaluate species suitability for rotational woodlot culture. The results would contribute to the refinement of criteria for screening tree species for such agroforestry practices.

Methods

Study site

The study was carried out at Mkundi village located at 6°40′ S, 37°39′ E, about 20 km west of Morogoro, Tanzania, at an altitude of about 475 m. The area experiences a bimodal rainfall distribution characterized by two rainfall peaks per year with a dry spelt separating the short rains (October–December) from the long rains (March–May). The mean annual rainfall and air temperatures are 800 mm and 24°C, respectively. The soils are fairly young, classified as Entisols (USDA soil taxonomy) with predominantly kaolinitic clay mineralogy (Msanya et al. 2003). Average soil physio-chemical characteristics of the top 0–15 cm soil depth were: pH = 6.7, organic carbon = 0.61%, total nitrogen (N) = 0.083%, extractable Bray-1 phosphorus (P) = 8.5 mg kg^{-1}, exchangeable potassium (K) = 0.44 cmol kg^{-1}, exchangeable calcium (Ca) = 4.30 cmol kg^{-1}, exchangeable magnesium (Mg) = 2.10 cmol kg^{-1}, effective cation exchange capacity = 7.26 cmol kg^{-1}, bulk density = 1.35 g cm^{-3}, and sandy loamy texture. For agricultural production, total N and extractable P levels in the soil were considered deficient while exchangeable K status was marginal (Msanya et al. 2003). Natural vegetation at the study site is degraded Miombo woodland dominated by scattered tree species of *Sclerocarya birrea* (A. Rich.) Hochst., *Dalbergia melanoxylon* (Guill. and Perr.), *Balanites aegyaptica* (L.) Del., *Dichrostachys cinerea* (L.) Wight and Arn., *Acacia* species, and *Albizia* species (Mugasha et al. 2005). The rotational woodlot experiment was carried out on-farm using continuously cropped farmland hired from local farmers.

Experimental design and management

A rotational woodlot experiment was established in March 1999 in a randomized complete block design with three replications. The trial comprised seven treatments evaluating soils under *Acacia crassicarpa* A. Cunn. ex Benth., *Acacia mangium* Willd., *Acacia nilotica* (L.) (Del), *Acacia polyacantha* Willd., *Gliricidia sepium* (Jaqua), a natural fallow and a continuous cropping system. The natural fallow treatment represented typical Miombo soils recovering from degradation due to continuous crop production. The continuous cropping treatment was on land adjacent to the experiment. The planted tree species represented a wide array of nitrogen fixing trees and shrubs species that have potential to produce wood and fodder in Tanzania (Karachi et al. 1997; Nyadzi et al. 2003a). *Acacia crassicarpa*, *A. mangium*, and *G. sepium* are exotic species, but their seeds were collected locally from Tabora, Kibaha, and Morogoro regions, respectively. *Acacia nilotica* and *A. polyacantha* are indigenous species. Seeds of these species were purchased from the National Tree Seed Agency in Morogoro. The tree seedlings were raised in pots for 5 months in a nursery at the Sokoine University of Agriculture. The seedlings were then planted at a 3 by 3 m spacing, giving 36 trees per plot. The size of each plot was 16 by 16 m separated by a 4 m-wide unplanted buffer strip. The distance between blocks was 5 m. Two years after establishment, a 0.5 m wide and 1.5 m deep trench was dug around each plot yearly during long-rain seasons to minimize below-ground inter-plot interactions.

Soil sampling and analysis

At the onset of the 2004 long-rain season prior to wood yield assessment, soil samples were collected at 0–15 cm depth from five randomly selected points within a 10 by 10 m inner plot area using a hand hoe. The soil samples were bulked by plot, mixed thoroughly, and sub-sampled to get a composite sample for nutrient analysis. Prior to laboratory analysis, the composite samples were air-dried, ground, and sieved through a 2 mm sieve. Soil texture was determined by the hydrometer method, soil pH in 1:2.5 soil–water aqueous suspensions by pH meter, organic carbon by Walkley and Black method, extractable P by Bray-1 method, exchangeable K, Ca, and Mg by atomic absorption spectrophotometer; exchangeable acidity by titration, and effective cation exchange capacity by summation of exchangeable cations and exchangeable acidity (Anderson and Ingram 1993). Similarly, soil samples for inorganic N determination were collected at the onset of the 2004 long rain season immediately after clear felling and before site preparation for maize planting. This sampling took place 10 weeks after the first rain. The soil samples were kept in a cooler, transported to laboratory, and frozen in a deep freezer prior to analysis of inorganic N within 1 week after collection. Soil inorganic N was extracted using 2 M KCl solutions and extracts analyzed for ammonium and nitrate N as described by Okalebo et al. (1993). Soil samples for bulk density determination were collected from five random points in each plot at a depth of 0–15 cm using 5 by 5 cm core cylinders. The samples were oven-dried at 105°C to constant weight and the bulk density calculated as described by Anderson and Ingram (1993).

Biomass yields and nutrient use efficiency determinations

Prior to the onset of the 2004 long-rain season, all surviving trees species (maximum 16 per plot) in the 10 by 10 m inner plot area were sampled to assess height, biomass yield, nutrient contents, and nutrient use efficiency. Each sampled tree was measured for diameter at breast height (DBH). The DBH of multi-stemmed trees was estimated from the arithmetic mean of diameters of individual stems measured at 1.3 m above the ground (Nyadzi et al. 2003a). The trees were then felled by a power saw at 10 cm from the ground, measured for height, and partitioned into stems, branches, and foliage (including twigs and leaves). Each tree biomass component was tied into bundles and weighed in the field to the nearest 0.1 kg using spring balance (Philips) to determine green weight. Discs of about 2 cm thick (Kumar et al. 1998) were sampled at base, middle and tip of stems and big branches, weighed immediately to determine green weight to the nearest 0.1 g using a portable balance (Philips). Similarly, branches and foliage components were sampled and weighed in the field. Thereafter, samples of each biomass component were oven dried at 70°C to constant weight and moisture content calculated. The moisture content was used to estimate biomass yield of each component, and the values were extrapolated to a hectare based on biomass yield per tree. The biomass yield per hectare was then divided by rotation length (i.e. 5 years) to determine mean annual increment (MAI) of each species.

The oven-dried samples of each biomass component were pooled by plot, sub-sampled and finely ground for N, P, K, Ca, and Mg analysis. Total N was determined by the Kjeldahl method following digestion of tree samples with hydrogen peroxide and sulphuric acid. Total P, Ca, K, and Mg were determined by dry ashing as described by Okalebo et al. (1993). Nutrient content of each biomass was the product of its biomass and corresponding concentration of each nutrient. Finally, nutrient use efficiency was expressed as a ratio of biomass to nutrient content (Marschner 1995; Safao-Matondo et al. 2005).

Data analysis

Prior to the analysis of variance (ANOVA), data were tested for normality and homoscedasticity (i.e., constant variance) of residuals using a statistical analysis system (SAS 1988). Thereafter, tree species effects on soil nutrients, DBH, height, MAI, wood yields, nutrient content and nutrient use efficiency were tested using the generalized linear model procedure in SAS. Following ANOVA, significant means were separated using Fishers protected least significant difference (PLSD).

Results and discussion

Changes in soil nutrients

After a 5-year fallow period, soil organic carbon in tree fallows (0.8–1.3%) were significantly higher (P = 0.0078) than in the continuous-cropping treatment (0.6%) (Fig. 1a). This improvement is usually associated with litter accumulation and fine root turn over during the fallow period as reported in other studies (Rao et al. 1998; Tian et al. 2001). Soil organic carbon under *A. mangium* (1.3%) and under *A. nilotica* (1.1%) was higher than in soils under the natural fallow (0.9%), but similar to those found in the natural Miombo soils of semi-arid areas of Tanzania (Msanya et al. 2003; Dondeyne et al. 2004). This would indicate that carbon pools in our tree fallows were replenished close to natural status (Fig. 1a).

Tree fallows significantly improved (P = 0.0056) soil inorganic N compared to the natural-fallow and continuous-cropping treatments (Fig. 1b), probably reflecting N fixation and retrieval from deep soil layers by trees during the fallow period. Comparatively, soil inorganic N among tree fallows was the highest in *G. sepium* and *A. polyacantha*, intermediate in *A. nilotica* and *A. mangium*, and the lowest in *A. crassicarpa*. Soils under tree fallows also contained more extractable P (13–23 mg P kg^{-1}) than the soils under continuous cropping (Fig. 1c, $P = 0.0074$). These levels were even higher compared to

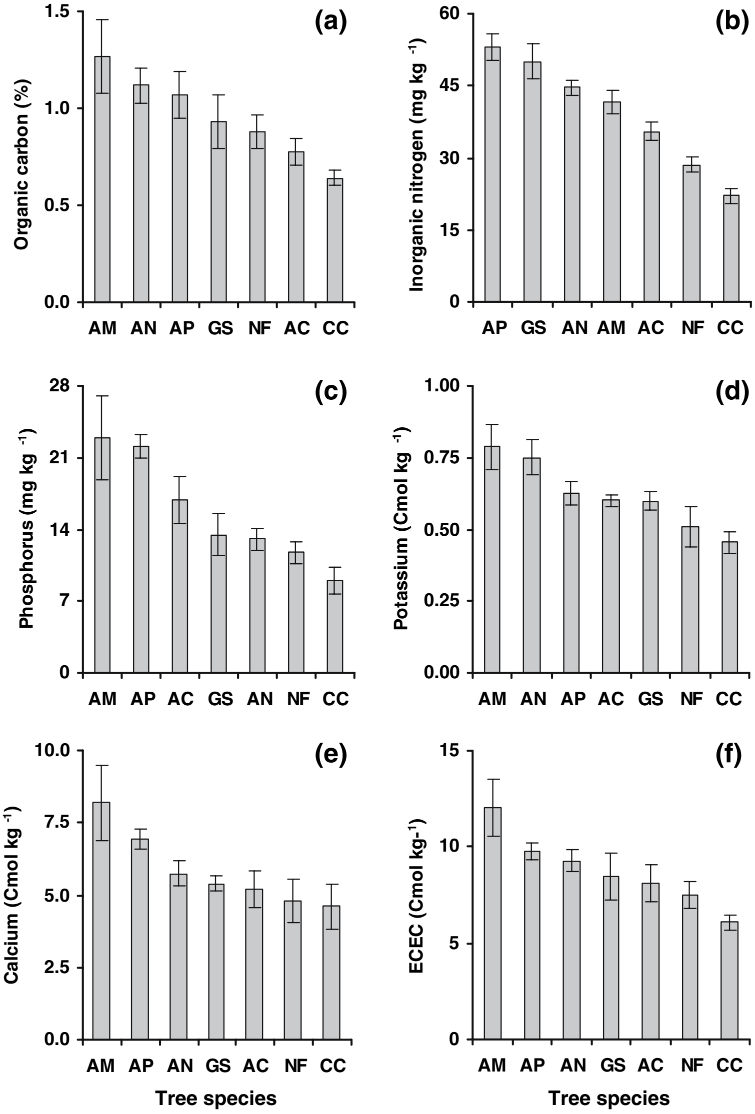

Fig. 1 Effects of tree species on soil organic carbon (**a**), Inorganic nitrogen (**b**), extractable phosphorus (**c**), exchangeable potassium (**d**), calcium (**e**) and effective exchange capacity (**f**) at Mkundi, Morogoro, Tanzania. AC = *Acacia crassicarpa*, AM = *Acacia mangium*, AN = *Acacia nilotica*, AP = *Acacia polyacantha*, GS = *Gliricidia sepium*, NF = Natural fallow, CC = Continuous cropping and ECEC = Effective cation exchange capacity. Vertical bars indicate standard errors of means of three replicates

9.8 mg P kg^{-1} found in the natural fallowed Miombo soils in Morogoro (Msanya et al. 2003), demonstrating the capacity of tree fallows to recycle P effectively. Relative to the natural fallow, the improvement of soil extractable P was significant for *A. mangium*, *A. polyacantha*, and *A. crassicarpa*.

Maximum soil inorganic N and extractable P levels were 53 mg N kg^{-1} soil and 23 mg P kg^{-1} soil, respectively, which corresponds to about 100 kg N ha^{-1}and 40 kg P ha^{-1} based on a top soil bulk density of 1.35 g cm^{-3}. Initially deficient in these nutrients (Msanya et al. 2003), post-fallow soil levels were sufficient to support one cropping season of maize production (Ussiri et al. 1998), illustrating that tree fallowing can benefit subsequent maize culture. In this respect, *A. mangium*, *A. polyacantha*, and *G. sepium* were the most effective species in building up soil organic carbon, and N and P supplies (Fig. 1a–c).

The fallow of *A. mangium* significantly improved soil exchangeable K ($P = 0.0052$), Ca ($P = 0.0125$), and effective cation exchange capacity ($P = 0.0146$) (Fig. 1d–f) compared to the natural fallow and continuous cropping systems. Similarly, *A. nilotica* and *A. polyacantha*, respectively, increased exchangeable K and Ca (Fig. 1d, e) over the natural fallow. The increase in cation exchange capacity matched those of the natural Miombo fallow dominated by *Acacia* and *Heyperhenia* grass species and also a 7-year *Eucalyptus* planted fallow in Morogoro (Msanya et al. 2003). Soil fertility replenishment under tree fallows is usually associated with a number of enrichment and conservation mechanisms that include biological N fixation, pumping up or retrieval of nutrients from lower soil horizons, interception of nutrients that would otherwise be lost through leaching and surface runoff, and release of nutrients during litter and root decomposition (Rao et al. 1998). Presumably these mechanisms contributed to the marked improvement in soil nutrients observed in our study (Fig. 1).

Nutrient use efficiency

The above ground use efficiency for N ($P = 0.0035$), P ($P < 0.0001$), K ($P < 0.0001$), Ca ($P = 0.001$), and Mg ($P = 0.0081$) varied significantly among the tree species (Fig. 2). In general, *A. crassicarpa* was the

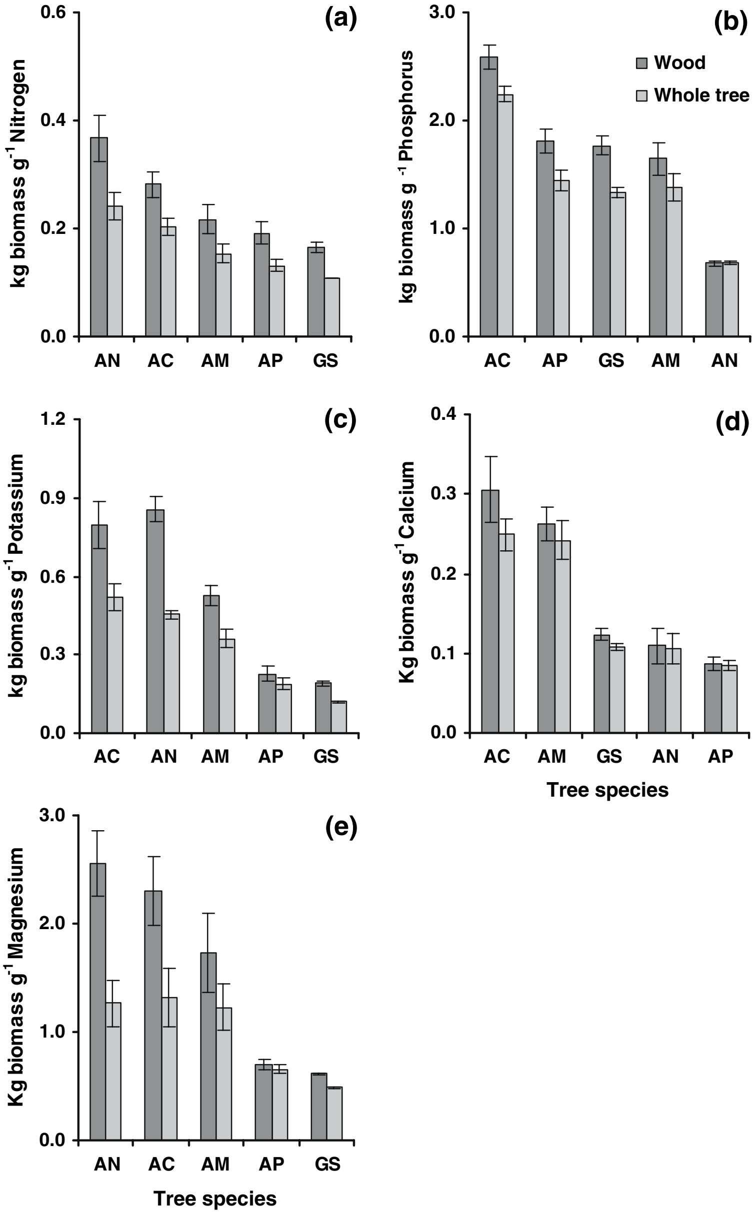

Fig. 2 Use efficiencies of nitrogen (**a**), phosphorus (**b**), potassium (**c**) calcium (**d**) and magnesium (**e**) in wood and aerial tree biomass of tree species in a 5-year-old rotational woodlot at Mkundi, Morogoro, Tanzania. AC = *Acacia crassicarpa*, AM = *Acacia mangium*, AN = *Acacia nilotica*, AP = *Acacia polyacantha*, GS = *Gliricidia sepium*. Vertical bars indicate standard errors of means of three replicates

most efficient for all nutrients except for N and Mg (Fig. 2); exemplifying that this species produced the highest above ground biomass at lowest nutrient ''costs''. Its K-use efficiency was four times higher than that of *G. sepium* while P-use efficiency was three times as high as that of *A. nilotica*. Similar results were also observed for nutrient use efficiency based on wood production (Fig. 2). Overall, nutrient use efficiency of wood was consistently higher than that of whole-tree biomass except for K, Ca, and Mg in *A. polyacantha* (Fig. 2c–e), and for P and Ca in *A. nilotica* (Fig. 2b, d). These results reveal the importance of harvesting wood only from the site to leave the slash as green manure because of higher nutrient concentrations of the latter (Fig. 2)

The variation in nutrient use efficiency among species may be attributed to several reasons related to uptake, transport, and utilization within plants (Marschner 1995; Schroth et al. 2003). For example, extensive root systems and abundant mycorrhizal associations are characteristics that increase P-use efficiency of plants (Schroth et al. 2003). Higher rates of nutrient retranslocation during either vegetative or reproductive growth also increase nutrient use efficiency due to better utilization of organically bound nutrients for growth (Marschner 1995). These mechanisms probably accounted for the observed species variability in nutrient use efficiency (Fig. 2), since Australian *Acacia* species usually form mycorrhizal associations and have low litter nutrient concentrations (Doran et al. 1997; Jamaludheen and Kumar 1999) that may reflect high nutrient retranslocation rates.

Wood production

Wood yield was highest ($P = 0.0007$) in the *A. crassicarpa* (51 Mg ha^{-1}) fallow, moderate in the *A. mangium* and *A. polyacantha* fallows, and lowest in the *A. nilotica* fallow (Fig. 3). Wood biomass produced by *A. crassicarpa* was comparable to yields reported in other drier parts of Tanzania (Nyadzi et al. 2003a) and Thailand (Doran et al. 1997).

Generally, tree species with wide canopies as well as extensive and deep root systems would be expected to produce high biomass under limited supply of growth resources due to superior acquisition capacities. However, these parameters may have limited effects on the yield differences among tested species at this early stage of woodlot development because canopy closure and resource competition in fast growing tropical plantations usually commence 4–6 years after planting (Evans and Turnbull 2004). Apparently, inherent nutrient use efficiency is a major factor driving wood production because the most efficient tree species yielded the most wood (Fig. 3). Improved productivity of Australian *Acacia* species has also been attributed to lower transpirational loss of water and wider adaptability (Kumar et al. 1998).

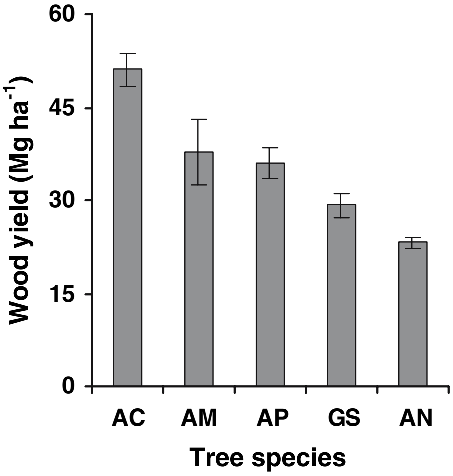

Fig. 3 Wood biomass yields of tree species in a 5-year-old rotational woodlot at Mkundi, Morogoro, Tanzania. AC = *Acacia crassicarpa*, AM = *Acacia mangium*, AN = *Acacia nilotica*, AP = *Acacia polyacantha*, GS = *Gliricidia sepium*. Vertical bars indicate standard errors of means of three replicates

Height, DBH, and mean annual increment of tree species were also significantly greater in *A. crassicarpa, A. mangium*, and *A. polyacantha* (Table 1). The mean annual wood increment ranged from 4.6 Mg ha^{-1} year^{-1} to 10.2 Mg ha^{-1} year^{-1}, which is at least three times higher compared to 0.04–2.91 Mg ha^{-1} year^{-1} of typical Miombo woodland vegetation (Kityo 2004). Such high wood yields exemplify the significance and potential of rotational woodlot systems in meeting local firewood demands, as well as conserving natural forests that currently serve as the main local source of fuelwood in the region. Per capita firewood consumption for an average family of six dependent on the Miombo source is 10 kg per week (Biran et al. 2004). Based on this estimate, per hectare wood yields of rotational woodlot systems utilizing our test species would be sufficient to meet the household fuelwood demands for 7–16 years.

Table 1 Diameter at breast height (DBH), total height and mean annual wood increment (MAI) of tree species in a 5-year rotational woodlot at Mkundi, Morogoro, Tanzania

Tree species	DBH (cm)	Height (m)	MAI ($Mg\ ha^{-1}\ year^{-1}$)[1]
Acacia polyacantha	10.34a[2]	9.20a	7.20b
Acacia crassicarpa	10.12ba	10.10a	10.20a
Acacia mangium	10.25a	7.77b	7.54b
Acacia nilotica	7.23ba	5.37c	4.64c
Gliricidia sepium	4.76b	6.18c	5.83cb
P[3]	0.0303	<0.0001	0.0007
LSD[4]	3.736	1.046	1.3035

[1] Mean annual increment

[2] Means in a given column followed by the same letter are not significantly different ($P < 0.05$) according to Fishers PLSD

[3] Probability for greater *F*-ratio

[4] LSD = Least significant difference

Nutrient removals

Nutrient accumulation and export from the site are crucial considerations for sustained productivity of short-rotation high yield plantation systems where nutrient removal through frequent biomass harvests may exceed replenishment rates through natural processes, such as mineral weathering, atmospheric inputs, and biological fixation (Fölster and Khanna 1997; Nykvist 2000). The amounts of nutrient removed from the site vary with both nutrient use efficiency and biomass yield of the tree (Wang et al. 1991).

On a relative basis, *A. crassicarpa* produced 42 and 120% more wood compared to *A. polyacantha* and *A. nilotica* respectively (Fig. 3), but contained considerably less nutrients (Fig. 4). For example, wood of this species contained 42% less P ($P = 0.0003$), and 60% less K ($P < 0.0001$) and Ca ($P = 0.0016$) compared to that of *A. nilotica* and *A. polyacantha*, respectively (Fig. 4b–d). Similarly, wood of *A. crassicarpa* contained less Ca and Mg ($P = 0.0014$), but similar amounts of N and P to that of other species except for *A. nilotica*. Despite the highest biomass production, *A. crassicarpa* required relatively fewer nutrients consequently exporting fewer nutrients when harvested. These results clearly demonstrate the importance of proper tree selection to reduce nutrient exports at harvest and sustain future site productivity; since heavy nutrient drains may adversely impact long term site quality and sustained woodlot production (Kumar et al. 1998; Nykvist 2000). Generally, nutrient-efficient tree species exported less nutrients in harvested wood biomass (Figs. 2 and 4), affirming that nutrient use efficiency is a sensitive and useful criterion to screen tree species for this purpose.

Nutrient restitution

Under a rotational woodlot system tree slash (leaves and twigs) remaining after wood harvest is usually applied as green manure to provide nutrients for subsequent crops upon decomposition (Nyadzi et al. 2003a). A previous study of this system reported limited ability of tree fallows to improve soil fertility due to an inherently short fallow period of 4 years (Nyadzi et al. 2003b). In contrast, our results involving 5-year fallows, revealed that inorganic N and extractable P status in soils increased after this period to achieve adequacy for one cropping season of maize (Fig. 1). Thus, given extended fallow intervals, the amounts of nutrients recycled by on-site slash retention would contribute substantially to subsequent crop responses. Slash from *A. polyacantha* and *G. sepium* restituted the most N ($P = 0.0009$), P ($P = 0.0114$) and K ($P < 0.0001$) to the soil, ranging from 110 kg ha^{-1} to 148 kg ha^{-1}, 7 kg ha^{-1} to 10 kg ha^{-1}, and 49 kg ha^{-1} to 135 kg ha^{-1}, respectively (Fig. 4a–c). When decomposed, these nutrients will potentially be available to crops grown after wood harvest. Except for Ca and Mg, the most nutrient-efficient tree species returned the lowest amounts of nutrients through slash (Figs. 2 and 4) likely because of low cellular nutrient concentrations in biomass as well as high nutrient retranslocation abilities (Schroth et al. 2003).

Conclusions

Although limited by a single rotation assessment, results from this study showed that tree species are effective in improving soil fertility, and have promise to sustain productivity of rotational woodlot systems. Based on soil tests, soils under *G. sepium,*

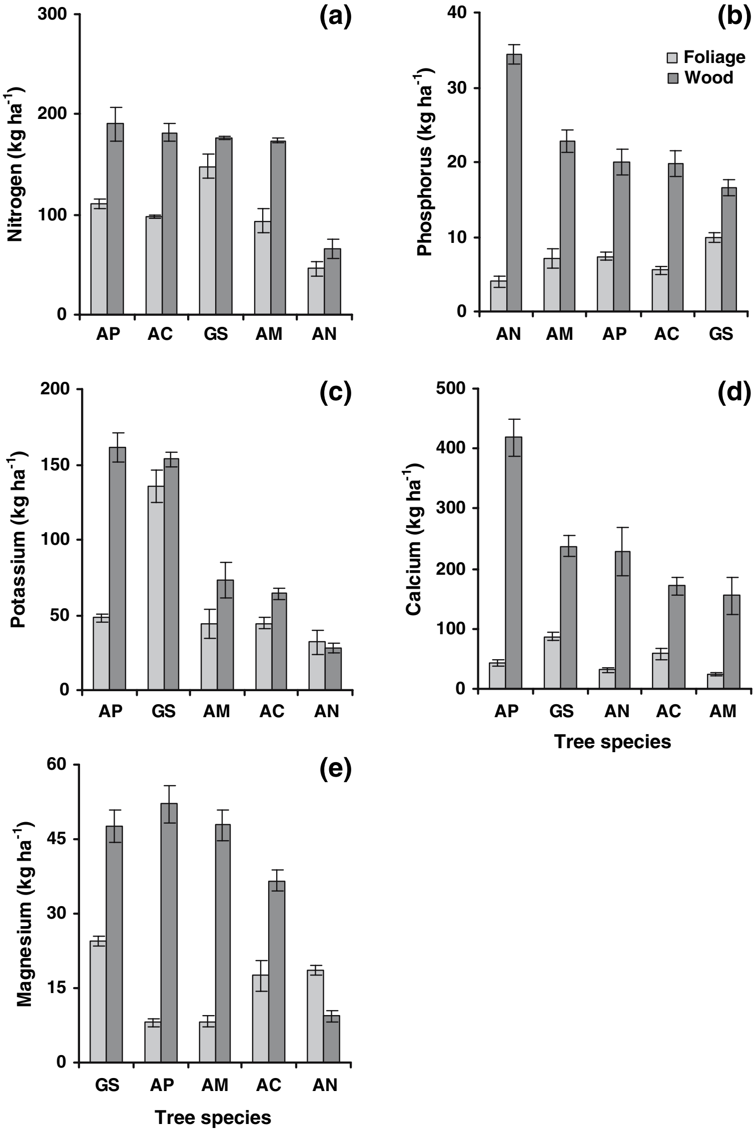

Fig. 4 Nitrogen (**a**), phosphorus (**b**), potassium (**c**) and calcium (**d**) accumulated in foliage and wood biomass of tree species in a 5-year-old rotational woodlot system at Mkundi, Morogoro, Tanzania. AC = *Acacia crassicarpa*, AM = *Acacia mangium*, AN = *Acacia nilotica*, AP = *Acacia polyacantha*, GS = *Gliricidia sepium.* Vertical bars indicate standard errors of means of three replicates

A. polyacantha, and *A. mangium* woodlots were the most fertile. Soil organic carbon and exchangeable cation levels in tree fallows reached close to natural status of Miombo woodlands. Initially deficient in soil N and P for maize culture, top soils after fallowing were replenished sufficiently in nutrients to support one cropping season of maize without fertilizer supplementation. These results reflect the high potential of tree fallows to improve maize production after wood harvest. Wood productivity in rotational woodlot systems was about three times higher than that of local Miombo woodland vegetation, and was sufficient to meet household firewood demands for 7–16 years. Operationally, this agroforestry system exhibited the capacity to contribute appreciably to firewood demand in the region, which would in turn lead to reduced harvesting pressures on the natural forests without adversely affecting maize productivity. Incorporating nutrient use efficiency criteria in tree selection for rotational woodlot system management would minimize nutrient export through wood harvests while maintaining site productivity. Based on such criteria, *A. crassicarpa* would be the preferred species for planting because of the highest wood yield produced apparently at the lowest nutrients ‘‘cost’’.

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