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Differential response to tree fallows in rotational woodlot systems in semi-arid Tanzania: Post-fallow maize yield, nutrient uptake, and soil nutrients

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Abstract

Agroforestry tree species producing high quality litter may enhance post-fallow soil nutrient availability and crop yields through mineralization of soil organic matter and green manure. A split-plot field experiment was used to evaluate maize yield and soil N and P status after fallowing indigenous and exotic tree species of contrasting litter quality. Responses were compared with recommended inorganic fertilizer use. The objective was to assess efficacy of 5-year tree fallows in improving soil productivity to screen species for increased crop yield under rotational woodlot culture, an agroforestry system mainly used for on-farm fuelwood production in semi-arid Tanzania. Post-fallow maize yield and soil nutrients differed significantly among tree fallows. Low C:N and L:N ratios enhanced nutrient release from slash. *Acacia polyacantha* (indigenous) and *Gliricidia sepium* fallows doubled maize yield compared to the natural fallow probably due to high soil N and P levels resulting from net release by high quality foliage. First season maize yield was similar to that from combined N and P fertilizers indicating high capacity of the fallows to improve crop yields and reduce fertilizer inputs usually unaffordable to small-scale farmers. Comparatively low maize yield and soil N and P levels after exotic *Acacia crassicarpa* and *Acacia mangium* fallows were attributed to net N immobilization by poor quality litter during growing seasons. This study suggests that rotational woodlot systems utilizing tree species with high litter quality can improve both post-fallow maize yield and soil fertility as well as produce sufficient fuelwood. In this aspect, *A. polyacantha* would be the most appropriate species.

Keywords: *Acacia*; Litter quality; Maize yield; Semi-arid; Soil fertility; Woodlot

1. Introduction

Soil nutrient depletion, through repeated crop harvest and soil erosion, is among the major constraints for sustainable food production in sub-Saharan Africa (Mafongoya et al., 2006). This problem is aggravated by the wide spread practice of continuous cropping that use little if any fertilizer and manure because of high farm acquisition costs (Kwesiga et al., 2003). The adoption of agroforestry practices has been advocated as an alternative to continuous cropping because of high capacity to replenish soil fertility, improve crop production, and enhance food security and household income in regions where commercial fertilizers are unaffordable to most smallholder farmers (Kwesiga et al., 2003; Mafongoya et al., 2006).

The rotational woodlot system is an agroforestry system that has been introduced in semi-arid Tanzania to increase on-farm fuelwood production as well as improving soil fertility and crop yield (Nyadzi et al., 2003a,b; Kimaro et al., 2007). This system consists of three interrelated phases of

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trees and crops grown sequentially in rotations of 4–5 years on the same land. The first phase involves inter-planting fast growing trees with crops until tree canopy closure. This is followed by a tree-fallow phase in which cropping is discontinued and trees are left to grow to desirable size for fuelwood supply. During this phase soil fertility restoration through nutrient cycling is enhanced, and the site can be managed for dry-season fodder production or apiary culture. 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 in the case of non-sprouting species. A fresh cycle starts after 2–3 years of sequential cropping when crop yields decline to unacceptable levels (Nyadzi et al., 2003a).

Earlier studies of rotational woodlot systems noted that indigenous tree species such as *Acacia polyacantha* Willd., produced less fuelwood (7–13 Mg ha^{-1} year^{-1}) compared to exotics such as *Acacia crassicarpa* A. Cunn. ex Benth. (10–19 Mg ha^{-1} year^{-1}), the most productive Australian species tested under this system (Nyadzi et al., 2003a; Kimaro et al., 2007). However, Australian acacia species may have a drawback of poor nutrient recycling capacity due to slow litter decomposition and potential nutrient immobilization (Jamaludheen and Kumar, 1999) that limit soil fertility improvement and post-fallow maize yield (Nyadzi et al., 2003b). The species also may have adverse effects on soil moisture due to high transpiration rates (Nyadzi et al., 2003b). Thus, farmers may well benefit more by utilizing fast growing indigenous trees that are better adapted to local environments, and may have greater capacity to produce fuelwood and improve soil fertility (Kimaro et al., 2007). The present study examines these issues by assessing effects of tree species of contrasting litter quality on post-fallow soil nutrient availability and maize yields.

The tree component in rotational woodlot systems can improve soil fertility through inputs by biological nitrogen (N) fixation, recycling of nutrient from deep soil horizons, and by reducing nutrient loss from leaching and soil erosion (Buresh and Tian, 1998; Nyadzi et al., 2003b). Trees also can increase post-fallow soil fertility through nutrient release from soil organic matter, litter, and green manure (Barrios et al., 1997; Chikowo et al., 2006). These replenishment processes are influenced by many factors that include species used, fallow length, soil type, and climatic conditions (Buresh and Tian, 1998). For instance, mineralization of organic resources from trees is known to be inversely related to ratios of carbon (C), lignin (L), and polyphenol contents, which are indices of organic resource quality (Baggie et al., 2004; Zingore et al., 2003). Barrios et al. (1997) have demonstrated that tree fallows with the lowest (lignin + polyphenol):N ratios in litter significantly improved N availability to crops after tree fallowing. Hence, leaf quality can be a critical factor influencing tree fallow effects on soil nutrient availability and crop yields, and may serve as a useful criterion for selecting tree species that improve both fuelwood and crop production in rotational woodlot systems.

Intensive repeated nutrient exports through wood and crop harvests may adversely affect long-term site productivity under rotational woodlot systems (Nyadzi et al., 2003a; Kimaro et al., 2007). However, as mentioned earlier, tree species with high quality litter may be appropriate for sustaining crop production because of high nutrient recycling capacities. Hence this paper evaluates post-fallow soil nutrient status and maize yields under this system using indigenous and exotic N-fixing tree species of different leaf quality. As a reference, crop responses were compared to monoculture maize culture with recommended fertilizer prescriptions to assess efficacy of low cost agroforestry system as an alternative to continuous cropping practices needing commercial fertilizers. The experiment was conducted for three consecutive seasons after a 5-year fallow period in order to evaluate crop response persistence. We hypothesized that post-fallow maize yield and soil N and phosphorus (P) status differ among tree species, and that C:N and L:N ratios controlled decomposition and nutrient release patterns of leafy biomass applied as green manure after fuelwood harvest. Specific objectives were to assess effects of tree species and fertilization on maize yield and nutrient uptake, soil inorganic N and extractable P, and *in situ* leaf decomposition and nutrient release patterns of leaves. Findings will contribute to improve management of rotational woodlot systems for sustaining soil fertility and crop yield, besides fuelwood production.

2. Materials and methods

2.1. 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 to December) from the long rains (March to 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) or Regosol (FAO–UNESCO classification system) with ochric epipedon horizon and predominantly kaolinitic clay mineralogy (Msanya et al., 2003). Physio-chemical characteristics of the top 0–15 cm soil have been described by Kimaro et al. (2007). The 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).

2.2. Maize yield trials

The rotational woodlot experiment was established in 1999 to assess tree fallows effects on soil fertility, nutrient use efficiency, fuelwood and maize yield. Details of the experimental establishment and management as well as assessment of soil fertility and fuelwood production after a 5-year fallow period can be found in Kimaro et al. (2007). This paper focuses on post-fallow effects of tree fallows on soil nutrient availability and maize yield and nutrient uptake in relation to conventional fertilizer regimes to evaluate the efficacy of fallow species to improve farm productivity. *In situ* leaf decomposition and nutrient release were also assessed to evaluate the impact of litter quality on post-fallow nutrient availability to crops. Trees remaining after fuelwood assessment were felled and stems and branches were harvested while foliage was incorporated into the soil as green manure using hand hoes during site preparation. Then maize (*Zea mays* L. var. Kito) was sown between trees stumps at a spacing of 90 cm between rows and 45 cm within rows for three consecutive seasons, starting from 2004. This short-duration maize variety was preferred due to inherently short rainfall seasons in semi-arid areas. Stumps of *Gliricidia sepium* (Jaqua) sprouted, but these were severed and mulched at 2-week intervals to reduce possible competition for moisture and light as well as recycling nutrients.

A split-plot experiment with three replications was laid out in a randomized complete block design (RCBD). The whole plot factor was tree species: *A. crassicarpa*, *Acacia mangium* Willd., *A. polyacantha*, *G. sepium* and the natural fallow. Rationale for species selection for this experiment has been described by Kimaro et al. (2007). *A. polyacantha* and *G. sepium* leaves have higher nutrient concentrations and low C:N and L:N ratios reflecting higher leaf quality compared to those of *A. crassicarpa* and *A. mangium* (Table 1). Except for *A. polyacantha*, other species were exotic but their seeds were collected locally. The natural fallow treatment represented traditional shifting cultivation in which degraded farmland was abandoned to allow regeneration of native vegetation to replenish soil fertility. The sub-plot factor was inorganic N and P fertilizer additions at four levels: Control (no fertilizer), 80 kg N ha^{-1}, 40 kg P ha^{-1}, and a combination of N and P fertilizer rates. The rates used are the recommended fertilizer rates for Morogoro area (Ussiri et al., 1998). Each whole plot was split into four sub-plots of 6 m × 6 m, and then fertilizer treatments were randomly allocated to each sub-plot at the onset of each cropping season. Sources of N and P were urea and triple super phosphate (TSP), respectively. Urea was split-applied on the 3rd and 5th week after maize planting, while TSP was applied before maize sowing. The experiment was repeated for three consecutive post-fallow seasons in order to evaluate persistence of maize responses to fallow treatments.

Soil samples were collected at 0–15 cm soil depth from 5 randomly selected points within the 4 m × 4 m inner sub-plot area during each cropping season at 0, 4, 6, and 8 weeks after maize sowing. The samples were then transported in a cooler, and frozen in a deep freezer prior to analysis of N and P within 1 week. At the end of each cropping season, maize was harvested from the 4 m × 4 m inner sub-plot area, and partitioned into grain, stover, and cobs; weighed, and sub-sampled for moisture content determinations at 70 °C in the oven. The moisture content was used to estimate dry weight of each biomass component and the values were extrapolated to 1 ha based on yield per area.

2.3. Leaf decomposition trials

A litterbag technique (Guo and Sims, 1999) was adopted to evaluate the effects of leaf quality on *in situ* decomposition and nutrient release of *A. crassicarpa*, *A. mangium*, *A. polyacantha*, *G. sepium* leaves. The experiment was laid out in a RCBD, adjacent to maize trials so as to reduce site-to-site variations. Seventy-two litterbags of 20 cm × 20 cm were constructed from nylon materials with 1 mm mesh size and filled with 10 g of air-dried leaves to obtain 18 bags per species. This mesh size was preferred because it both

Table 1
Decay constant (k, $week^{-1}$), and initial chemical and biochemical characteristics ($g\ kg^{-1}$) and their ratios in tree leaves used for decomposition experiment at Mkundi, Morongo, Tanzania

Parameter	*Acacia crassicarpa*	*Acacia mangium*	*Acacia polyacantha*	*Gliricidia sepium*	MSD[a]
k	−0.0305 a[b]	−0.0452 a	−0.1527 b	−0.3040 c	0.02
N	12.80 b	16.37 b	31.40 a	30.53 a	2.75
P	0.50 d	0.70 c	1.37 b	1.47 a	0.09
K	7.90 c	12.73 b	14.70 b	23.17 a	4.32
C	578.1 a	566.3 a	538.6 b	514.9 b	26.5
L[c]	137 a	142 a	86 b	110 ba	50
C:N	45.2 a	34.6 b	17.2 c	16.9 c	6.0
L:N	10.7 a	8.8 a	2.7 b	3.6 b	2.3
N:P	25.6 a	23.3 ba	22.9 bc	20.8 c	1.90

[a] MSD = minimum significant difference.
[b] Means with the same letter in a given row are not significantly different at $\alpha = 5\%$ according to Tukey's studentized range test.
[c] L = lignin.

prevents major losses of small leaves and permits aerobic microbial activities (Guo and Sims, 1999).

Three bags per species were oven-dried to constant weight at 70 °C to determine initial moisture content, ground, and analyzed for N, P, and K. The remaining bags were sealed with plastic bindings, kept in the plastic bags to minimize losses while being transported to the field. The litterbags were randomly buried to 15 cm soil depth in 1 m × 1 m plots located adjacent to each block of maize trials, and retrieved after 2, 4, 6, 8, and 12 weeks. Soil particles and extraneous plant materials in the retrieved leaf samples were removed manually followed by washing the leaves with distilled water and decanting through a 0.2 mm sieve. Apparently, such brief washing may cause nutrient leaching (Anderson and Ingram, 1993), but it will not affect relative comparisons of treatments, because of systematic application to all samples. The samples were then placed in envelopes and oven dried to constant weight at 70 °C to determine dry weight and for nutrient analysis. Due to fast decomposition rates, *G. sepium* samples retrieved after 6 weeks were not sufficient for nutrient analysis. Therefore, only the dry weight of these samples was recorded.

The decay constant was calculated from data on the dry weight of residual materials remaining using a single negative exponential decay model: $M_t = M_0\,e^{-tk}$, where, M_0 and M_t are leaves mass (g) initially and at time t (week), respectively, and k is the decay constant (week^{-1}). This constant was estimated from a slope of the line of the regression between natural logarithms of the remaining leaf dry mass ($\mathrm{Ln}\,M_t$) against time. Nutrient content of the retrieved leaf samples was calculated as described by Guo and Sims (1999) and expressed as a percent of the initial amount.

2.4. Chemical analysis of plant and soil samples

The oven-dried samples of maize and litterbags were finely ground and wet-digested using hydrogen peroxide and sulphuric acid solution. Total N in the digests was determined using a Technicon II analyzer System (Schulman et al., 1973), total P by stannous chloride method, and total K by atomic absorption. Soil inorganic N was extracted using 2 M KCl solution, and the extracts analyzed for ammonium-N and nitrate-N and summed to obtain total inorganic N. Soil P was extracted using Bray-1 method and measured calometrically using the molybdate-blue method. Except for total N, chemical analysis of samples was carried according to procedures described by Anderson and Ingram (1993). Nutrient contents in maize and litterbag samples were calculated as a product of its biomass and the corresponding concentration of each element. Organic carbon in litterbag samples was determined by Walkley and Black method and lignin by digesting leaf samples in a boiling detergent solution followed by hydrolysis with sulphuric acid (Anderson and Ingram, 1993).

2.5. Vector analysis

Graphical vector diagnosis has been used to examine plant nutritional response to nutrient supply in both forestry and agroforestry systems (Imo and Timmer, 2000; Salifu and Timmer, 2001). Compared to other diagnostic techniques such as critical nutrient concentrations and nutrient optimum ratios, vector diagnosis simultaneously evaluates both growth and nutrient responses to treatments. Vector nomograms (diagrams) simplify ranking relative importance of nutrients in stimulating plant growth, discriminating single and multiple nutrient deficiencies, identify possible sufficiency or toxicities, synergism and antagonisms, luxury consumptions and dilution effects. Vector analysis plots nutrient concentration (vertical axis), nutrient content (bottom horizontal axis), and biomass (upper horizontal axis) in a vector nomogram. The vector diagram reflects the function that nutrient content (or amount) in a plant (in this case maize) is the product of its nutrient concentration multiplied by its biomass. Hence, diagonals are isopleths representing changes of maize nutrient concentrations and contents at constant biomass. Changes in these parameters relate to maize responses to nutrient supply associated with treatments, i.e., tree species or inorganic fertilizers. These responses are expressed relative to the controls (natural fallow or unfertilized treatments) set as a reference that is normalized to 100 to facilitate comparisons between treatments. The relative responses are depicted by vectors (arrows) that may differ in length and direction. Vector length represents response magnitude, and vector direction identifies specific nutritional responses (Imo and Timmer, 2000; Salifu and Timmer, 2001). Thus, a shift in which both nutrient uptake and dry mass increased with decreased nutrient concentration (Shift A) would reflect a growth dilution of nutrients due to accelerated growth. A similar response without change in concentration (Shift B) is associated with sufficiency since both growth and nutrient uptake increased without changes in concentration. Shift C in which biomass, nutrient concentration, and nutrient content increase; depicts a deficiency response of plants because both growth and nutrient uptake are improved (Salifu and Timmer, 2001). Vector analysis was based on the above ground maize yield data of the first cropping season at which tree fallows exhibited the highest growth responses.

2.6. Statistical analysis

Prior to analysis of variance (ANOVA), decomposition data and soil mineral N and P were log-transformed to correct for normality and homoscedasticity (i.e. constant variance) of residuals. Thereafter, mixed models of split-plot and RCBD designs were used to carryout ANOVA for assessing the effects of tree species and fertilizer on: maize yield, maize N, P, and K content; soil inorganic N and extractable P; and dry mass, decay constant, and N, P, and K nutrient contents of the litterbag samples, using procedure mix in SAS version 8 (SAS, 2000). Following ANOVA, significant means were separated using Tukey's studentized range test. All analyses were conducted at 5% level of significance.

3. Results and discussions

3.1. Post-fallow maize yield

After a 5-year tree occupancy, tree fallowing resulted in higher maize yield than that from the natural fallow (Fig. 1) presumably because of soil nutrient replenishments by various tree-associated processes (Buresh and Tian, 1998; Kimaro et al., 2007). Maize grain yield after *A. polyacantha* and *G. sepium* fallows ranged from 1.7 to 3.4 Mg ha^{-1} and averaged 100% more than the mean yield obtained under the natural fallow over the three seasons (1.3 Mg ha^{-1}). Corresponding grain yield after *A. mangium* and *A. crassicarpa* fallows ranged from 1.2 to 2.6 Mg ha^{-1}, and averaged 50% higher compared to yield after the natural fallow (Fig. 1). The higher maize yield associated with *A. polyacantha* and *G. sepium* fallows probably reflect high soil fertility improvement during the fallow period. After fallowing these species, respectively, accumulated more soil inorganic N (50 and 53 mg N kg^{-1}), and extractable soil P (13 and 22 mg P kg^{-1}) than the natural fallow (29 mg N kg^{-1} and 12 mg P kg^{-1}), and recycled the most nutrients through slash (Kimaro et al., 2007).

Annual inorganic N and P fertilizer additions significantly increased maize grain yield over the control in all growing seasons indicating that these elements limited maize growth (Fig. 1). Average maize yields from N (2.35 Mg ha^{-1}) and P (1.87 Mg ha^{-1}) fertilization alone for the three seasons were, respectively, 70% and 30% higher than the control (1.41 Mg ha^{-1}). Combined applications of these fertilizers doubled maize yield relative to the control probably reflecting additive effects of mixed N and P fertilizers. These results suggest that initial soil N and P levels were deficient for maize culture as previously reported by Msanya et al. (2003). Since maize yield was more responsive to N than P, the former was considered more limiting.

In the first season, maize yield after both *A. polyacantha* and *G. sepium* fallowing (3.4 Mg ha^{-1}) were the highest ($p < 0.0001$), and matched yields (3.6 Mg ha^{-1}) obtained by combined application of N and P fertilizers (Fig. 1). Similar results have been reported by Nyadzi et al. (2003a) for *A. polyacantha*, and by Makumba et al. (2006) for *G. sepium*. The relatively high grain yields also reflect the potential of these fallows to increase maize yield without the need of high fertilizer inputs usually unaffordable to most smallholder farmers in the tropics (Kwesiga et al., 2003; Mafongoya et al., 2006). Fertilized maize yield was comparatively higher than under tree fallows in the second and third season, but it must be kept in mind that the higher response was associated with annual reapplication of N fertilizers (Fig. 1). Enhanced soil nutrient availability and maize yield after tree species persisted to the third season ($p = 0.0042$), except after *A. crassicarpa* where yield declined to levels of the natural fallow (Fig. 1). The longer response persistence observed demonstrates the extended benefit of tree fallow system over natural fallow practices. The seasonal yield drop off was mainly attributed to soil nutrient depletion through harvests (Fig. 2), and other processes such as leaching and surface runoff with time (Zingore et al., 2003; Chikowo et al., 2006). Annual rainfall patterns probably had little influence on seasonal variations of maize yield because the yield trend did not match with that of rainfall (Fig. 1). This limited impact may be due to narrow seasonal variations in rainfall during the maize growing period (February to May) amounting to 318, 274,

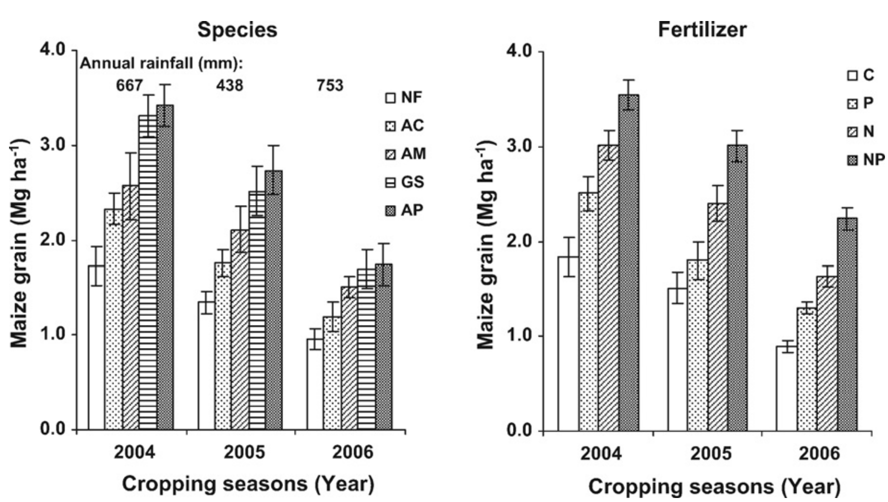

Fig. 1. Effects of tree species and fertilizer treatments on maize grain yield after a 5-year fallow period of rotational woodlot culture at Mkundi, Morogoro, Tanzania. Treatments consisted of fallow types: AP = *Acacia polyacantha*, GS = *Gliricidia sepium*, AM = *Acacia mangium*, AC = *Acacia crassicarpa*, and NF = natural fallow; and fertilizer additions: C = control (no fertilizer), P = 40 kg P ha^{-1}, N = 80 kg N ha^{-1} and combined N and P application. Vertical bars indicate standard error of means ($n = 3$).

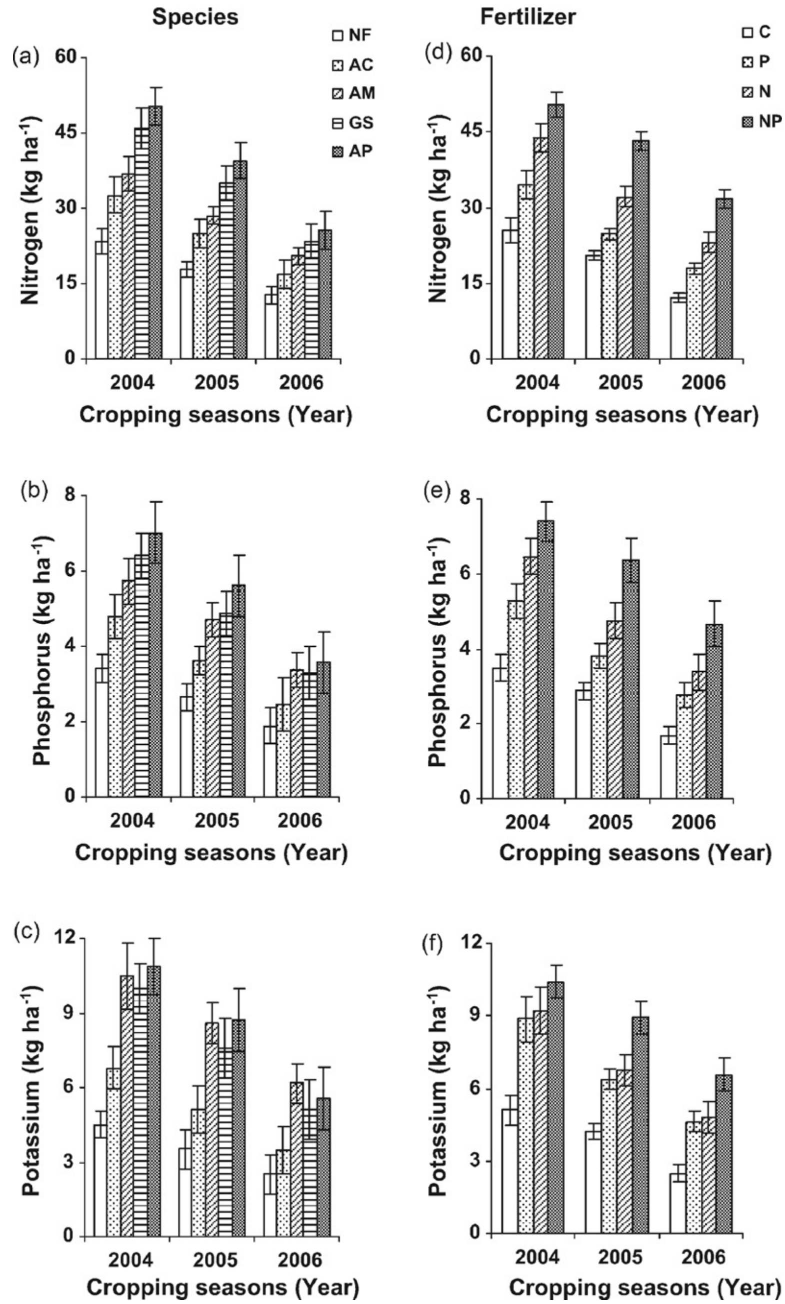

Fig. 2. Maize grain nutrient contents as influenced by tree species (a–c) and fertilizer (d–f) treatments after a 5-year fallow period of rotational woodlot culture at Mkundi, Morogoro, Tanzania. Treatments consisted of fallow types: AP = *A. polyacantha*, GS = *G. sepium*, AM = *A. mangium*, AC = *A. crassicarpa*, and NF = natural fallow; and fertilizer additions: C = control (no fertilizer), P = 40 kg P ha^{-1}, N = 80 kg N ha^{-1} and combined N and P application. Vertical bars indicate standard error of means ($n = 3$).

and 365 mm for the 2004, 2005, and 2006 cropping seasons, respectively.

3.2. Seasonal nutrient uptake by maize

Nutrient uptake of maize after tree fallows was higher than that in natural fallows, which affirmed the nutrient replenishment capacity of the planted trees (Fig. 2a–c). In the first post-fallow season, maize N uptake was the highest ($p < 0.0001$) in fallows of *A. polyacantha* and *G. sepium*, followed by *A. mangium* and *A. crassicarpa*. The lowest uptake was found in the natural fallow (Fig. 2a). A similar pattern was also observed with crop P uptake in the first season (Fig. 2b, $p = 0.0005$). However, species differences in N and P uptake became less apparent in the subsequent cropping seasons probably reflecting diminishing nutrient supply due to exports by harvest as well as leaching and surface runoff as mentioned before (Zingore et al., 2003). The highest uptake of N and P by maize was associated with *A. polyacantha* and *G. sepium* fallows suggesting that these

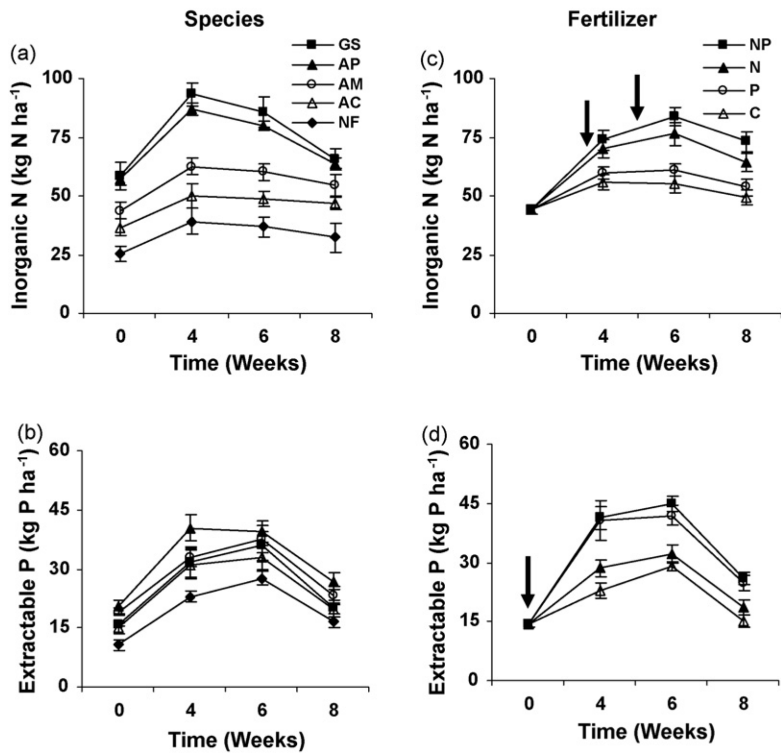

Fig. 3. Tree species (a and b) and fertilizer (c and d) effects on soil total inorganic N (i.e. NO_3^--N + NH_4^+-N) and extractable P during the first cropping season after 5-year fallow period of rotational woodlot culture at Mkundi, Morogoro, Tanzania. Treatments consisted of fallow types: AP = *A. polyacantha*, GS = *G. sepium*, AM = *A. mangium*, AC = *A. crassicarpa*, and NF = natural fallow; and fertilizer additions: C = control (no fertilizer), P = 40 kg P ha^{-1}, N = 80 kg N ha^{-1} and combined N and P application. Vertical bars indicate standard error of means ($n = 3$). Arrows indicate time of fertilizer applications. Statistical analysis was performed on log-transformed data, but points represent untransformed means.

species were the most effective in enhancing soil N and P supply. Tree fallowing improved maize K uptake relative to the control with highest values obtained by maize after *A. polyacantha*, *G. sepium* and *A. mangium* in the first ($p = 0.0179$) and second ($p < 0.0001$) season. The enhanced K uptake (Fig. 2c) was probably associated with increased soil K status after fallowing as noted by Kimaro et al. (2007) due to rapid K mineralization after green manuring (Zaharah and Bah, 1999).

Both N and P fertilizers, either singly or combined, significantly improved N and P uptake relative to control (Fig. 2d), which exemplify likely occurrence of soil N and P deficiency in this site. Uptake was the highest with combined N and P fertilization also reflecting an additive response. Sole addition of N fertilizer increased both N and P uptake, but sole P fertilizer increased only P uptake (Fig. 2d and e), suggesting that N was the major driver of the yield response. Potassium fertilizer was not applied, due to reported sufficiency in the soil (Msanya et al., 2003). However, sole or mixed application of N and P fertilizers improved maize K uptake (Fig. 2f) presumably because of enhanced nutrient uptake associated with greater biomass response (Marschner, 1995).

3.3. Soil nutrient supply

During the first cropping season, soil inorganic N in both tree fallows and fertilizer treatments increased significantly compared to the controls (Fig. 3a and c). Levels of total inorganic N rose consistently, culminating in the 4th ($p = 0.0002$) and 6th ($p = 0.0117$) week after maize planting that corresponded with the active growth period of maize (4–8 weeks after sowing) and peak plant nutrient demand in the tropics (Lehman et al., 1995). With fertilizers, this curvilinear trend probably reflected the split dressing schedule of N that was designed to match annual nutrient demand (Fig. 3c). Rapid N increase from early to mid-season after tree fallows may be associated with high release from green manure mineralization (Imo and Timmer, 2000) and other *in situ* sources of N such as turnover of labile organic matter (Chikowo et al., 2006). Soil inorganic N status in both *G. sepium* and *A. polyacantha* fallows during the 4th and 6th week after maize planting averaged 86.5 kg N ha^{-1}; this level was similar to those obtained with N based-fertilizer treatments (Fig. 3a and c). The high soil N levels were attributed to input from green manure after fuelwood harvests and improved soil N during the fallow period (Kimaro et al., 2007).

Apparently, green manure from the *G. sepium* and *A. polyacantha* stands decomposed and mineralized most rapidly (Fig. 4a), releasing more N when compared to other species. This pattern was attributed to low C:N and L:N ratios in leaves of the former species (Table 1), because such ratios are inversely related to decomposition and mineralization rates of organic materials (Zingore et al.,

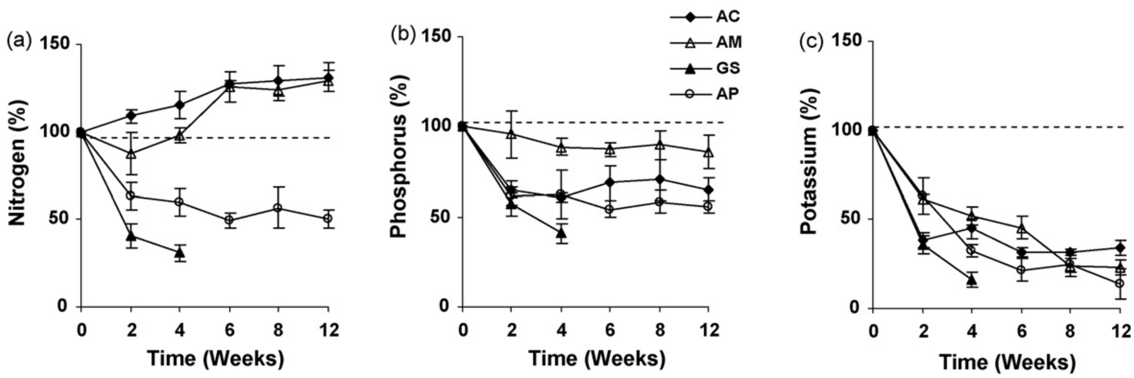

Fig. 4. Concentrations of foliar N (a), P (b) and K (c), (expressed as a percent of initial values) of tree species of a 5-year-old rotational woodlot experiment during a 12-week litter bag study at Mkundi, Morogoro, Tanzania. Values below and above 100% indicate mineralization and immobilization of nutrient, respectively. Treatments consisted of fallow types: AP = *A. polyacantha*, GS = *G. sepium*, AM = *A. mangium*, and AC = *A. crassicarpa*. Vertical bars indicate standard error of means ($n = 3$). Statistical analysis was performed on log-transformed data, but points represent untransformed means.

2003; Baggie et al., 2004). Lower soil inorganic N status in *A. crassicarpa* and *A. mangium* fallows (15–63 kg N ha^{-1}) when compared to other tree fallows was probably associated with high N immobilization (Fig. 4a) because of comparatively higher concentrations of foliar C and lignin and lower foliar N concentrations as green manure (Table 1).

Extractable soil P under tree fallows was higher than that under the natural fallow, peaking (33–40 kg P ha^{-1}) between 4 ($p = 0.0003$) and 6 weeks after maize sowing. These levels were similar to those obtained under P fertilization (Fig. 3b and d). After 5-year tree occupancy, soil P status was raised close to 40 kg ha^{-1}, the level recommended for maize culture in Morogoro (Ussiri et al., 1998). The enrichment was attributed to increased P mineralization of leafy biomass applied as green manure after wood harvest (Fig. 4b). Also P recycling through nutrient pumping during the fallow period (Buresh and Tian, 1998) may have partly contributed to the high post-fallow soil P levels. Unlike N, mineralization of P (Fig. 4b) occurred in leaves of all species, probably accounting for little variation in soil extractable P levels among tree fallows during the cropping season (Fig. 3b). Seasonal variation in soil P levels was attributed to rapid release from decomposing green manure accompanied by low uptake by maize during the early season, followed by a high uptake at the active growth period reducing P availability (Imo and Timmer, 2000).

Overall, lower litter C:N and L:N inputs from *G. sepium* and *A. polyacantha* resulted in higher soil mineral N and P status (Fig. 3a and b) and greater maize grain yield than high C:N and L:N litter from *A. crassicarpa* and *A. mangium* (Fig. 5). The results demonstrate the potential of tree fallows selected for high litter quality to enhance post-fallow soil N and P availability as well as improving crop yield and wood supply as was also noted by Barrios et al. (1997). In this respect, *A. polyacantha*, an indigenous species with high capacity to produce fuelwood (Nyadzi et al., 2003a; Kimaro et al., 2007), would be a desirable species for incorporation in rotational woodlot systems.

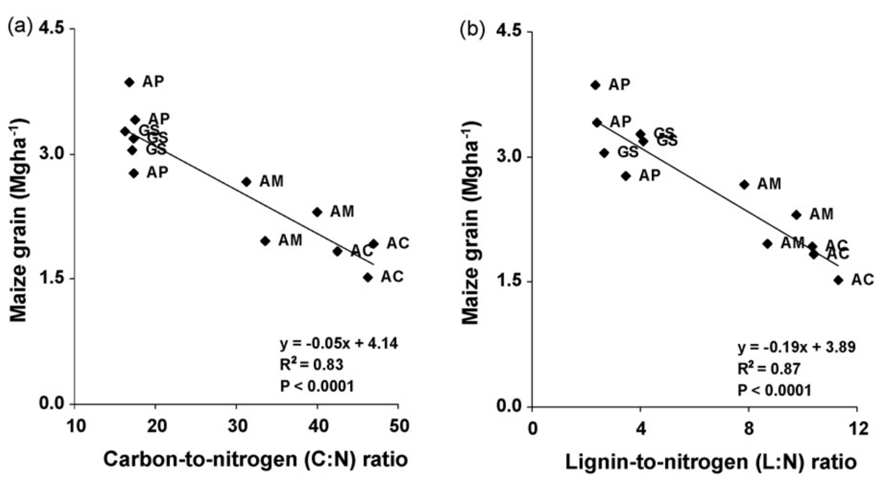

Fig. 5. Correlation between foliar carbon-to-nitrogen (C:N) and lignin-to-nitrogen (L:N) ratios of tree species and maize grain yield during the first cropping season after 5-year fallow period of rotational woodlot culture at Mkundi, Morogoro, Tanzania. Treatments consisted of fallow types: AP = *A. polyacantha*, GS = *G. sepium*, AM = *A. mangium*, AC = *A. crassicarpa*.

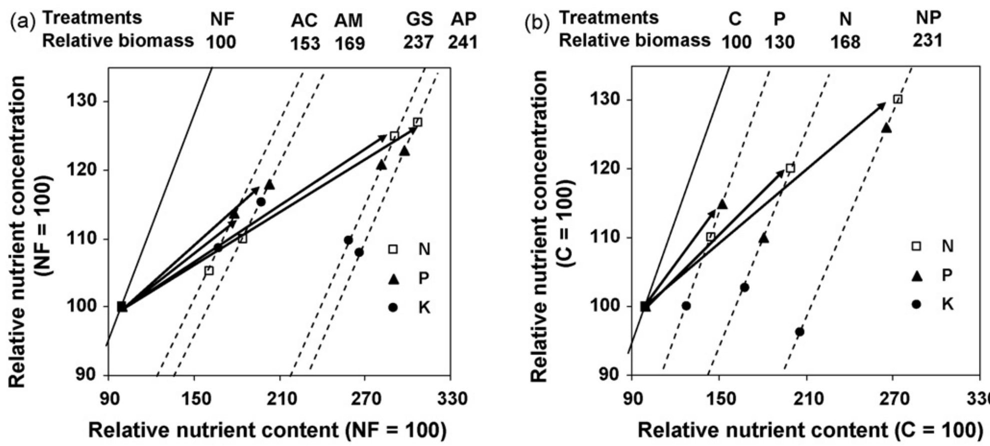

Fig. 6. Vector nomogram of the relative change in maize grain biomass, nutrient concentration and nutrient content testing tree species (a) and fertilizer treatments (b) in a 5-year fallow period of rotational woodlot culture at Mkundi, Morogoro, Tanzania. Treatments consisted of fallow types: AP = *A. polyacantha*, GS = *G. sepium*, AM = *A. mangium*, AC = *A. crassicarpa*, and NF = natural fallow; and fertilizer additions: C = control (no fertilizer), P = 40 kg P ha^{-1}, N = 80 kg N ha^{-1}, and combined N and P application. See Figs. 1 and 2 for statistical differences between treatments. To minimize clutter only the largest vector for each treatment is drawn.

3.4. Nutrient diagnosis of maize

Crop response to nutrient supply is usually reflected in changes in plant nutrient concentration, nutrient content, and biomass yield (Marschner, 1995). These changes were simultaneously plotted in a vector nomogram to simplify comparison of key nutrients stimulating plant growth (Salifu and Timmer, 2001). Relative to the natural fallow, maize yield was increased after *G. sepium* fallows by 137% (237 − 100) and by 141% (241 − 100) after *A. polyacantha* fallowing (Fig. 6a). The increase was respectively accompanied by stimulated N concentration (25% and 27%) and N content (190% and 205%). The longest right-pointing vector in *A. polyacantha* and *G. sepium* fallows was associated with N, indicating that N was probably the most limiting nutrient (Shift C, Salifu and Timmer, 2001). This response was similar to that of combined N and P fertilizer where both elements were added (Fig. 6b), and suggests that high quality litter species can similarly improve post-fallow soil N supply and crop yield. Relatively lower biomass yields after *A. mangium* (69%) and *A. crassicarpa* (53%) fallows (Fig. 6a) were associated with higher P content (103% and 79%) compared to N content (85% and 61%), probably reflecting limited N availability during the growing seasons (Fig. 3a) due to net N immobilization by poor quality green manure (Fig. 4a).

Vector analysis of fertilizer treatments revealed deficiency responses to N and P application (Shift C, Salifu and Timmer, 2001) since increase in maize grain yield relative to the control (131% for combined N and P treatment) was accompanied with improved N content (175%) and P content (166%), as well as raised N and P concentrations (Fig. 6b). Apparently N was more limiting than P as it was associated with the highest yield and nutritional responses (Fig. 6b). As noted earlier (Figs. 1 and 2d, e), this pattern suggests N as most limiting. The lowest yield was noted after P-only treatments that showed accumulation of more P than N in the crop exemplifying low soil N availability without any N supplementation (Fig. 6b).

Vector analysis also depicted a synergistic N and P interaction on maize yield (Fig. 6b) since relative N and P content after combined additions (N = 175%, P = 166%) was higher than corresponding content from either N-alone (N = 100%, P = 80%) or P-alone (N = 50%, P = 46%). This synergism was attributed to improved P assimilation following enhanced growth by N, since P is an important element in energy production required for metabolic reactions (Marschner, 1995). Positive correlations found between maize yield and soil mineral N and P under either tree fallows or fertilization (Fig. 7) also support vector interpretations of these deficiency responses. The stronger correlation with N (0.78 and 0.83) than with P (0.42 and 0.24) would further affirm that N was more limiting than P for maize growth.

Tree fallowing improved content and concentration of K (Fig. 6a), likely reflecting high recycling through litter fall during the fallow period (Kimaro et al., 2007), and increased K mineralization of green manure applied after fuelwood harvest (Fig. 4c). However, higher soil K supply probably had little impact on post-fallow maize yield because the largest responses were associated with either N for *A. polyacantha* and *G. sepium*, or P for *A. mangium* and *A. crassicarpa* (Fig. 6a). There was no significance response in K concentration after fertilization since K was not applied. Hence, despite increased maize biomass and K content after fertilization, tissue K concentration remained unchanged (Fig. 6b) exemplifying probable sufficiency of this element since K concentration was undiluted and content kept pace with growth (Shift B, Salifu and Timmer, 2001). These results corroborate an earlier study that noted adequate soil K supply for crop production (Msanya et al., 2003).

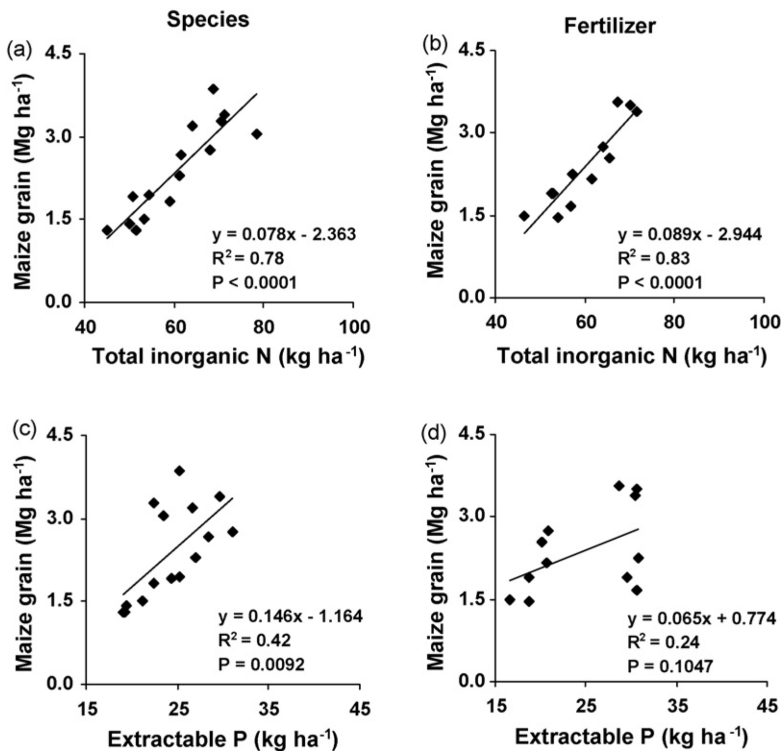

Fig. 7. Correlation between soil total inorganic N or soil extractable P and maize yield under tree fallows (a and c) and fertilizer (b and d) during the first cropping season after 5-year fallow period of rotational woodlot culture at Mkundi, Morogoro, Tanzania.

4. Conclusions

Rotational woodlot systems utilizing tree fallows with high leaf quality (*G. sepium* and *A. polyacantha*) can improve post-fallow maize yield and soil nutrients to levels similar to those of inorganic fertilizers. The improvements reflected the high capacity of these species to enhance nutrient availability to post-fallow crops as well as to reduce the need for supplementary fertilizer inputs, usually too costly for small-scale farmers in the tropics. Apparently, *A. polyacantha*, a fast growing indigenous tree species with high leaf quality, exhibited the most promise to enhance post-fallow soil nutrient availability and maize yields under rotational woodlot systems.

Post-fallow maize response to tree species mainly depended on nutrient release (especially N) from slash applied as green manure after wood harvest. Significant positive correlations between maize yield and soil N and P under either tree fallows or fertilizer treatments inferred that enhanced soil N and P availability during the cropping season was the main driver for the increased crop yield. Vector analysis confirmed these responses, and further revealed that N was more limiting than P. Consequently, *A. polyacantha* and *G. sepium* fallows, which produced leafy biomass with low C:N and L:N ratios, exhibited the highest soil N supply and doubled maize yields relative to the natural fallow. However, green manure of *A. crassicarpa* and *A. mangium* fallows likely stimulated N immobilization during the growing season due to high foliar C:N and L:N ratios, resulting in lower maize yields compared to other fallow species. This study suggests that these ratios may be useful indicators for selecting tree species for rotational woodlot culture.

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