

Nitrogen dynamics in maize-based agroforestry systems as affected by landscape position in southern Malawi

Rebbie Harawa · Johannes Lehmann ·
Festus Akinnifesi · Erick Fernandes ·
George Kanyama-Phiri

Received: 22 September 2005 / Accepted: 31 May 2006 / Published online: 1 August 2006
© Springer Science+Business Media B.V. 2006

Abstract In Malawi, agroforestry is very promising for N replenishment; however, there are still large variations in the performance of these agroforestry technologies on farmers' fields. A study was conducted on-farm to determine the influence of three landscape positions on N dynamics in maize (*Zea mays* L.)-based agroforestry systems. The agroforestry systems were relay fallow using *Sesbania sesban* (L.) Merr or *Tephrosia vogelii* (Hook F.), simultaneous fallow using *Gliricidia sepium* (Jacq.) Walp., and maize without trees as a control. *Sesbania* was superior to other systems in the bottom slope, producing the highest tree

biomass (1,861 kg ha⁻¹), whereas, *gliricidia* gave the highest tree biomass production in the mid-slope (2,147 kg ha⁻¹) and upper slope (1,690 kg ha⁻¹). Preseason inorganic N, maize flag leaf N concentration, maize total N uptake and maize yields followed a similar trend to tree biomass production with tree-based cropping systems exhibiting higher productivity ($P < 0.05$) than the cropping systems without trees. Nitrogen leaching from *gliricidia* agroforestry systems was lower than in the other agroforestry systems across all landscape positions as evidenced by 17% lower amounts ($P < 0.05$) of inorganic N adsorbed to ionic exchange resin membranes at 60 cm soil depth most likely due to the permanent root system of *gliricidia*. The difference between $\delta^{15}\text{N}$ values of the trees and the soil did not change between landscape positions suggesting that if the leguminous trees fixed atmospheric N₂, the proportion of total N uptake was identical at all locations. We concluded that landscape positions have a significant effect on tree performance with *sesbania* remarkably adapted to the bottom slope, *gliricidia* to the mid-slopes and *tephrosia* fairing similar in both the bottom slope and mid-slopes.

R. Harawa (✉) · J. Lehmann
Department of Crop and Soil Sciences, Cornell
University, Ithaca, NY 14850, USA
e-mail: rh87@cornell.edu

F. Akinnifesi
SADC-ICRAF Agroforestry Programme, Chitedze
Agricultural Research Station, P.O. Box 30798,
Lilongwe 3, Malawi

E. Fernandes
The World Bank, 1818 H Street, Washington, DC
20433, USA

G. Kanyama-Phiri
Bunda College of Agriculture, University of Malawi,
P.O. Box 219, Lilongwe, Malawi

Keywords Tree biomass · N uptake ·
N₂ fixation · Leaching · Fallow

Introduction

Nitrogen is the most limiting nutrient to production of maize (*Zea mays* L.)—the main staple food crop in southern Africa. In Malawi the use of inorganic fertilizers to replenish nutrient losses has declined by more than 50% because of removal of subsidy on fertilizers between 1988 and 1997 (Carr 1997). Consequently low external input practices such as crop rotation with legumes, use of organic manures, such as composting (Kumwenda et al. 1995; Jones et al. 1996), and intercropping with N-fixing agroforestry tree species are now being promoted (Akinnifesi and Kwesiga 2002; Akinnifesi et al. 2002; 2005a, b).

Tree legume fallows of one to 3 year durations have shown to increase N availability to subsequent crops on N deficient soils. Barrios et al. (1997) reported increases in soil inorganic N, and N mineralization in *Sesbania sesban* (L.) Merr fallows in Eastern Zambia. This was also in agreement with the findings of Maroko et al. (1998) in Western Kenya who reported that application of sesbania foliage biomass had resulted in increases in subsequent maize yields, which were strongly correlated to N release. The effect of the fallows on soil fertility depends on the fallow length (Tiessen et al. 1992), soil type, climatic conditions and the amount of biomass applied (Barrios et al. 1997; Maroko et al. 1998). Since the benefits of fallows depend upon biomass accumulation, longer fallow periods generally result in greater increases in crop yield and residual effect (Kwesiga et al. 1999; Szott et al. 1999). However, high population density in Malawi makes extended fallow periods impractical to smallholder farmers. Therefore, the relay fallow cropping with sesbania or *Tephrosia vogelii* (Hook F.) and simultaneous fallow intercropping with *Gliricidia sepium* (Jacq.) Walp fit well to the farming systems in southern Malawi where the landholdings per farm family range from 0.2 ha to 0.5 ha.

In both relay and simultaneous cropping systems the crops and trees co-exist at the same time on the same piece of land and do not decrease planting density of maize. The maize is planted on ridges, whereas, the trees are planted in every other furrow (space between ridges which is often

left bare). In relay fallow cropping systems, however, the trees are harvested at 10 months old, whereas in simultaneous fallow intercropping, trees can be left in the field for over 10 years because of their ability to continuously re-sprout when pruned (Akinnifesi et al. 2002).

Results from 6 years of experimentation at Makoka in Malawi have shown that sesbania and tephrosia relay fallow and gliricidia simultaneous fallow systems positively improve maize yields (ICRAF 2000). In a watershed in southern Malawi, sesbania accumulated 30–60 kg N ha⁻¹ in its above-ground biomass during 10 months of growth, tephrosia was highly variable, often having only 10% of the biomass of sesbania (Kanyama-Phiri and Snapp 1997). Success stories of sesbania relay cropping on farmers field have also been reported by Phiri et al. (1999), where maize yields increased about twofold.

However, there are still large variations in the performance of these agroforestry technologies on farmers' fields. The amount of N input by biological N fixation and improved N cycling efficiency achieved by the tree legumes may vary across landscape positions due to tree adaptations to different soil physical properties such as soil depth, temporal water accumulation and physical position in the catena (Pan and Hopkins 1991). In a study conducted in the Palouse region of eastern Washington in USA which evaluated the effect of slope positions on N fixation by peas, greater BNF was observed at the bottom than the upper slopes (Mahler et al. 1979). At Farmington in the USA, differences in residual soil N levels among landscape positions were between 49 kg ha⁻¹ and 149 kg ha⁻¹ and average values for N mineralization were as high as 110 kg ha⁻¹ on bottom slopes and as low as 5 kg ha⁻¹ on upper slopes (Elliot and de Jong 1992). Although the influence of landscape position is well known in temperate regions of the world, there is little if any, quantitative data to objectively confirm these observations for sub humid tropical regions such as Malawi where agroforestry is very promising for N replenishment. We expect similarly important effects of landscape position on N dynamics in cultivated watersheds of Southern Malawi. The objectives of this study therefore were to determine the effect of landscape positions on N dynamics in

maize-based agroforestry cropping systems and the performance of different agroforestry cropping systems as reflected by maize productivity.

Materials and methods

Study area

The study was conducted on farmers' fields for two cropping seasons in Domasi valley (15°18.5' S, 35°23.5' E) Malosa Extension Planning Area (EPA). Malosa EPA is part of the Zomba Rural Development Project (RDP) of the Machinga Agriculture Development Division (ADD), Southern Malawi. The area has a population density of approximately 400 persons per square kilometer and the average land holding size is 0.4 ha, which is typical for southern Malawi. The average elevation is 853 m above sea level and receives an average annual rainfall of 1139 mm. The rainfall pattern is unimodal and the rains are between November and April followed by a dry season from May to October. The soils are described as Alfisols and Ultisols (Kanyama-Phiri et al. 1994) with sandy loam textures. The topsoil (0–20 cm) has a pH (1:2.5 soil/water) of 5.6, organic C content of 9.5 g kg⁻¹, inorganic N content of 2.7 mg kg⁻¹ and Olsen-P concentration of 17.5 mg kg⁻¹ (ICRAF 2000). The vegetation is semi-deciduous woodland called miombo dominated by *Brachystegia* spp.

Descriptions of the cropping systems

The cropping systems are dominated by maize; the main staple food crop and major intercrops include pigeon peas [*Cajanus cajan* (L.) Millsp.] and cassava (*Manihot esculenta* Crantz). All crops are planted on ridges, which are prepared by tilling the soils every year using tradition hoes. Additionally, leguminous service trees (relay fallow cropping systems with sesbania and tephrosia and simultaneous fallow intercropping with gliricidia) were recently introduced into the traditional farming system.

Sesbania plants are established by seedling prepared from nurseries and transplanted when they are about 8 weeks old. The planting

coincides with the beginning of the rainy season, which is mostly around the month of January. However, with tephrosia, seeds are directly sown in the field. After maize harvest in April, the trees are left to grow in the field during the dry season and in October, they are clear felled at the ground level and leaves and twigs are separated from wood and incorporated in the maize ridges. The relay fallow therefore requires trees to be established every year for the subsequent maize crop.

The establishment of gliricidia trees is similar to that of sesbania. However, gliricidia trees are pruned to a height of 30 cm three times during the maize cropping season. The first pruning is done in August, which is during the first land preparation. The second pruning takes place in November during the first weeding of maize. The third pruning takes place in December/January during the second weeding of maize. During pruning fresh leaves and twigs are incorporated as in the relay fallow cropping.

Farmer selection, treatment design and management

Farmers were selected among those who have been participating in an on-farm agroforestry trial under the International Centre for Research in Agroforestry (ICRAF). The trial is a Type II experiment, where farmers provide management and researchers give information and provide small inputs of seeds and sometimes labor (Franzel and Nduka 1994). The experiment was established in October 1998 in 60 farmers's fields at three landscape positions, such as bottom slope, mid-slope and upper slopes (Table 1). The farmers had planted trees in their maize fields either as a relay fallow cropping with sesbania or tephrosia and/or simultaneous fallow intercropping with gliricidia.

The treatments included a factorial combination of three landscape positions: 1. bottom slope 2. mid-slope and 3. upper slope, and 4 types of cropping systems: 1. relay fallow cropping with sesbania; 2. relay fallow cropping with tephrosia; 3. simultaneous fallow intercropping with gliricidia; and 4. maize without tree as a control. Farmers' fields were used as replicates. In total, 28 farmers were selected for the study: 8 farmers

Table 1 Description of the landscape positions in Domasi valley site, southern Malawi

	Bottom slope	Mid-slope	Upper slope
Average elevation (m)	714	753	850
Slope (%)	0–2	2–12	>12
Soil	Vertisols (Usterts) with dark, clay loams	Alfisol (Ustalfs) and Ultisol (Ustults) with red, sandy loams	Alfisol (Ustalfs) and Ultisol (Ustults) with red, sandy loams

in the bottom slope, 11 farmers on the mid-slope and 9 farmers in the upper slope. All agroforestry systems and the control were managed for maize production intercropped with pigeon pea. Individual plots had a size of 10 m × 10 m with trees planted in furrows at 0.9 m within and 1.5 m between rows giving a density of 7,400 trees per hectare. Maize hybrid, NSCM 41 was planted on ridges in all plots, at 0.90 m within and 0.75 m between rows, three maize plants per station. Two pigeon pea seeds were sown in the spaces between adjacent maize planting stations at 0.90 m within and 0.75 m between rows in all systems.

Maize was first planted in November of 2002/03 cropping season and sesbania and tephrosia trees were planted in January 2003 and cut in October 2003. Gliricidia tree pruning was done in the three times as follows: September 2003, November 2003 and January 2004. The second maize crop was planted in November of 2003/04 cropping season. In both seasons pigeon pea was sown approximately 4 weeks after maize planting and was harvested in late September. Pigeon pea yields were not assessed because farmers began to harvest the green pods before they dried for immediate consumption.

Soil sampling and analyses

In August 2002, 4 years after tree establishment, soil samples were collected from 0 cm to 20 cm soil depth in all plots using an Edelman auger (7-cm diameter). In each plot, soil was collected and bulked from 10 locations. Subsamples were subdivided into two parts: one part of the sub-sample for inorganic N analysis and these soils were immediately stored at 4°C prior to extraction within 2 days of collection. The other part of the

sub-sample was air-dried and sieved through a 2-mm mesh and analyzed for pH, total N and organic C, available P, K, Ca and Mg. The soils in this site do not contain inorganic C and therefore measurements of total C reflected organic C.

To extract inorganic N, 30 g of field-moist soils from each treatment was weighed into 200-ml plastic bottles into which 100 ml of 2 M KCl were added. The soil was shaken for 1 h horizontally on a rotary shaker and the samples were allowed to settle for 5 min after which they were filtered through 2-µm filters using plastic syringes into vials. The extracts were frozen for analyses of NO₃⁻ and NH₄⁺ on a Technicon Auto Analyzer (Chauncey, CT, USA).

The pH-H₂O and pH-KCl were determined in 1:2.5 soil/water and soil/KCl suspension, respectively, using a glass electrode. Available P, K, Ca and Mg were determined using Mehlich 3 extraction (Anderson and Ingram 1993). To 3 g of the air-dried soil, 30 ml of Mehlich 3 solution was added and shaken for 5 min horizontally on a rotary shaker and then filtered through a Whatman No. 42 filter paper. The solution was analyzed using inductively coupled plasma (ICP) mass spectroscopy (Spectro CIROS, CCD, Germany) (Soltanpour 1991).

Total N and organic C were analyzed by dry combustion. During the analyses, 0.5 g of each sample was weighed and then ground for 10 min using a ball mill, until a very fine material was obtained. From the fine material, 15 mg sample was weighed into Sn capsules and analyzed in an Automatic Elemental Analyzer (NC 2100 Soil, Thermo Quest Italia S.P.A, Milan, Italy).

Soil bulk density was assessed by randomly taking 10 undisturbed soil samples with a volume of 385 cm³ from each plot and weighing them. A

sub-sample was oven dried at 105°C for 48 h and reweighed. Bulk density was determined by dividing the oven-dry mass of the sample by the sample volume (Blake and Hartge 1986). The bulk density was used to convert nutrient concentrations to soil stocks.

Leaching assessment using ionic exchange resin membrane

Ionic exchange resin membranes were used to quantify inorganic N (NH_4^+ and NO_3^-) over time, below 60 cm soil depth, as an indicator of nutrients leached. Two types of resin membranes: cationic-resin and anionic-resin were prepared for NH_4^+ and NO_3^- , respectively. Methods for membrane preparation were similar to those described by Cooperband and Logan (1994). Twelve and a half square centimeters (2.5×5 cm) strips were cut from each type of resin membrane sheet (type 204-U-435, Ionics, Water Town, MA) and rinsed with deionized water to remove propylene glycol from its storage containers, which prevents desiccation. Sodium chloride of 0.5 M was used for sorbing the nutrients (Cooperband et al. 1999). When ready to take to the field, the strips were transported in water-containing wide mouth bottles (Ionics recommends storage and transport in aqueous medium to prevent cracking and disfiguration upon drying). Setting up was done by removing several soil columns using a soil corer up to a depth of 60 cm and then excavating on the sides of the wall until we created room under undisturbed soil for placing the membrane. A thin thread was attached to each membrane for easy recovery. We then vertically inserted the ionic exchange resin membrane near the bottom of a PVC pipe, which was used for channeling and the top of the pipe was covered to prevent debris from falling inside. Two membranes (cationic and anionic) were placed under each PVC pipe and four of these pipes were randomly placed per plot for a period of about one month for the first four consecutive periods (October 28–November 28, November 28–December 28, December 28–January 28, January 28–February 28) and for 4 months for the last period (February 28–June 28). At the end of each period the resin

membranes were exchanged with new ones and upon removing the resin membranes from the soil, they were cleaned using distilled water removing debris and excess soil. To extract NH_4^+ and NO_3^- , resin membrane strips were each placed separately in centrifuge tubes with 30 ml of 1 M NaCl and shaken horizontally on a rotary shaker for 1 h. The extracts were analyzed for NH_4^+ and NO_3^- on a Technicon Auto Analyzer (Chauncey, CT, USA).

Plant sampling and analyses

Tree biomass, N uptake and $\delta^{15}\text{N}$ determinations

During the cutting of sesbania and tephrosia, and gliricidia pruning the total fresh weight of each of the tree components (leaves, twigs and wood) was determined from a net plot of 8×8 m. Representative samples of material of each of the components were taken to the laboratory where they were dried in an oven at 75°C for 48 h and their dry matter contents were determined. All dried plant materials were finely ground in a Wiley mill to pass a 0.4-mm sieve. The total N and $\delta^{15}\text{N}$ of the dried ground samples were determined by dry combustion using an automatic N and C analyzer interfaced with a stable isotope mass spectrometer (Isotope Mass Spectrometer 20–20, PDZEuropa, Crewe, England).

Maize N nutrition, yields and N uptake determinations

Maize N nutrition, yields and N uptake were determined from a net plot of 8×8 m. For maize N nutrition, samples of maize flag leaves were randomly sampled from four planting stations in each of the four plots in January 2004. We took one leaf from each of the maize plants on the stations and leaves were cleaned with distilled water before drying. To determine maize yield, we randomly selected 30 cobs and recorded the weight before and after shelling to calculate the grain-to-cob ratio. All maize stover harvested in the net plot was also weighed. Samples of grain, rachis and stover were collected. All plant materials were dried in an oven at 75°C for 48 h

for determination of dry matter contents. The dried plant materials were then finely ground in a Wiley mill to pass a 0.4-mm sieve. Samples of grain, rachis and stover were analyzed for total N and $\delta^{15}\text{N}$, and maize flag leaf samples were analyzed for N concentrations in an automatic N and C analyzer coupled to an isotope mass spectrometer. Foliar N concentration was expressed as the proportion of N in the flag leaf. Nitrogen uptake was calculated as the product of the yields (stover, rachis and grain) and the proportion of N.

Estimating biological N fixation

The occurrence of biological N fixation and differences in the proportion of biological N fixation between landscape positions was estimated using the ^{15}N natural abundance. The difference between measured $\delta^{15}\text{N}$ of the plant material sampled from the N_2 -fixing legume (leaves, twigs and stems) with that of maize plant, a non-fixing (reference) plant was the evidence of biological N fixation. With the determination of relative dilution of ^{15}N by biological N fixation, only comparisons between landscape positions were intended in our study, but absolute values of biological N fixation were not measured. A reliable determination of biological N fixation by trees is difficult to achieve especially in intercropping systems, since suitable reference trees are usually not available and soil sources of ^{15}N can only be estimated (Giller 2001; Lehmann et al. 2002).

Statistical analyses

A two-way analysis of variance (ANOVA) with agroforestry systems and landscape positions as the main factors was performed using the general linear mixed model procedure of the SAS 8.2 Release program (SAS Institute Inc. Cary, NC, USA). In case of significant effects and interactions between the agroforestry systems and landscape positions, Tukey's test was used to separate the means. Simple correlation coefficients were determined for the linear relationships between variables.

Results

Soil chemical characteristics

Mean values of organic C and total N were generally higher in the bottom slope, intermediate in the upper slope and lowest in the mid-slope (Table 2). Available P contents were highest in the mid-slope and lowest in the upper slope. Contents of Ca and Mg decreased from bottom slope to the upper slope. Only K contents were highest in the upper slope. There were no significant differences in soil pH across all landscape positions.

Tree biomass production

Tree biomass production significantly varied ($P < 0.001$) across different landscape positions

Table 2 Soil chemical characteristics (0–20 cm) for the three landscape positions in 2002/03 season in Domasi valley site, southern Malawi

	Bottom slope ($n = 8$)	Mid-slope ($n = 11$)	Upper slope ($n = 9$)	<i>P</i> value
Organic C (g kg^{-1})	9.02 (2.21)*	5.85 (0.94)	6.94 (0.93)	< 0.01
Total N (g kg^{-1})	0.82 (0.20)	0.59 (0.09)	0.73 (0.07)	< 0.05
P (mg kg^{-1})	49.4 (12.1)	76.8 (5.4)	33.7 (6.5)	< 0.05
K (mg kg^{-1})	117 (7)	129 (12)	185 (9)	< 0.05
Mg (mg kg^{-1})	144 (13)	116 (3)	75 (3)	< 0.01
Ca (mg kg^{-1})	735 (54)	599 (60)	407 (27)	< 0.01
pH in water (1:2.5)	5.94 (0.08)	6.04 (0.07)	6.15 (0.13)	ns

*Numbers in parentheses are standard errors of the means

Means followed by the same letters in a row are not significantly different according to Tukey's test; ns = not significant at $P < 0.05$

and there was a significant interaction between biomass and landscape position in 2003/04 (Table 3, Fig. 1), which was 4 years after tree establishment. In the bottom slope, sesbania biomass was significantly higher than gliricidia and tephrosia biomass. In the mid-slope and upper slope, however, gliricidia biomass was significantly higher than sesbania and tephrosia biomass. Tephrosia performed similar in both the mid-slope and bottom slope but showed significantly lower growth in the upper slope. Sesbania also had the lowest tree biomass production in the upper slope. During the study we observed that the establishment of gliricidia was always a problem in waterlogged conditions of the bottom slope. This performance was reversed, however, with sesbania that grew faster and yielded more biomass in such conditions.

Maize yield

Maize yield significantly varied ($P < 0.05$) for the different cropping systems at different landscape positions. In the 2002/03 season, maize intercropped with gliricidia resulted in the highest yield in the mid-slope position (Fig. 2). In the bottom slope, the highest yield was observed with sesbania relay cropping and there were no significant differences in maize yields between fields with

Table 3 Analysis of variance for the effect of landscape position on tree biomass production in Domasi valley site, southern Malawi

Factors and levels	Biomass (kg ha ⁻¹)
Trees	
Gliricidi	1,572 (114)*
Sesbania	1,057 (111)
Tephrosia	908 (113)
Landscape position	
Bottom slope	1,271 (115)
Mid-slope	1,398 (102)
Upper slope	868 (122)
<i>F</i> -value for trees	9.4
<i>P</i> -value for trees	0.002
<i>F</i> -value for landscape position	6.3
<i>P</i> -value for landscape position	0.003
<i>F</i> -value for tree × landscape position	9.0
<i>P</i> -value for tree × landscape position	<0.001

*Numbers in parentheses are standard errors

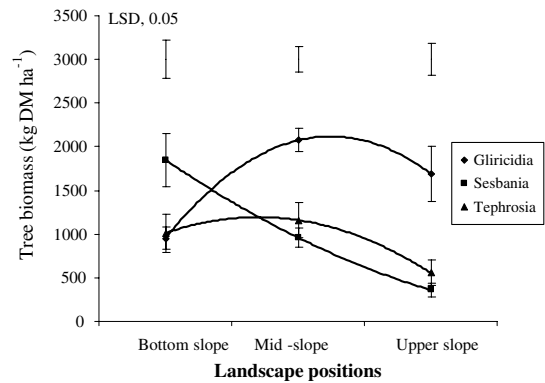


Fig. 1 Tree biomass production at different landscape positions in the 2003/2004 season in Domasi valley site, southern Malawi. The bars are the standard errors. $n = 8, 11, 9$ in the bottom slope, mid-slope and upper slope respectively

sesbania and tephrosia in the mid-slope and also between tephrosia and gliricidia in the upper slopes. Maize yields in the 2003/04 season followed a similar pattern as the previous year's yields (Fig. 2). However, the yields were generally

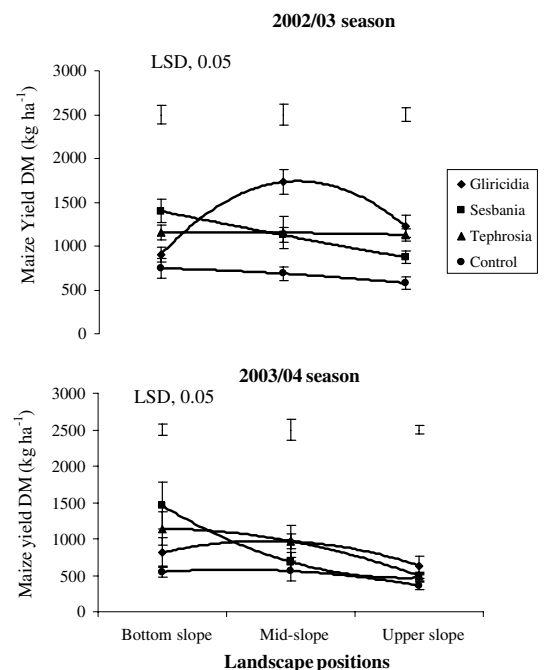


Fig. 2 Maize grain yield for the cropping systems at different landscape positions in seasons of 2002/03 and 2003/04 in Domasi valley site, southern Malawi. The bars are the standard errors. $n = 8, 11, 9$ in the bottom slope, mid-slope and upper slope respectively

lower in this season compared to the previous season and there were no significant differences among the agroforestry cropping systems at each landscape position despite substantial quantities of biomass applied (1,861 kg ha⁻¹ for sesbania in the bottom slope and about 2,147 kg ha⁻¹ for gliricidia in the mid-slope). In general, the yields in all agroforestry system were constantly above the monocropped maize across all three landscape positions in both seasons ($P < 0.05$).

Preseason inorganic soil N

Preseason inorganic N in the 2002/03 cropping season varied among the cropping systems in each of the landscape positions (Fig. 3). Inorganic N was significantly higher ($P < 0.05$) in the agroforestry systems compared to the traditional system (control) in the mid-slope and upper slope positions. This was expected because the incorporation of legume tree biomass would lead to an accumulation of N in the soil. However, presea-

son inorganic N only weakly correlated ($r^2 = 0.3$, $P < 0.05$) with tree biomass (data not shown).

Maize N concentration

In the bottom slope, maize grown in relay cropping systems with sesbania had significantly higher foliar N concentrations ($P < 0.05$) than maize grown in gliricidia and tephrosia agroforestry cropping systems (Table 4). In the mid and upper slopes, maize intercropped with gliricidia had significantly higher N concentrations than in the rest of the agroforestry systems. In the upper slope, maize grown with sesbania had significantly higher N concentrations than in the other agroforestry systems.

Total N uptake in maize

As expected, maize intercropped with tree legumes had significantly greater N uptake ($P < 0.05$), while the maize without trees had the lowest N uptake across all landscape positions (Fig. 3). The N uptake in maize intercropped with trees ranged from 11 kg ha⁻¹ to 38 kg ha⁻¹. In the bottom slope, maize intercropped with sesbania had the highest N uptake compared to maize intercropped with gliricidia but there was no significant difference between maize intercropped with sesbania and tephrosia. In the mid-slope, N uptake was highest in maize intercropped with gliricidia compared to maize under tephrosia but did not significantly differ between maize intercropped with gliricidia and sesbania. There were no significant differences in N uptake among maize intercropped with tree legumes in the upper slope. This could be a result of poor maize growth in the upper slopes, which was also reflected in low yields (Fig. 2).

Evidence of inorganic N leaching

There were significant differences in total ionic exchange resin membrane-inorganic N for the entire cropping season between the different agroforestry systems (Fig. 4). In the bottom slope, soil under gliricidia had the lowest ($P < 0.05$) ionic exchange resin membrane-inorganic N compared to soil in the other cropping systems. In

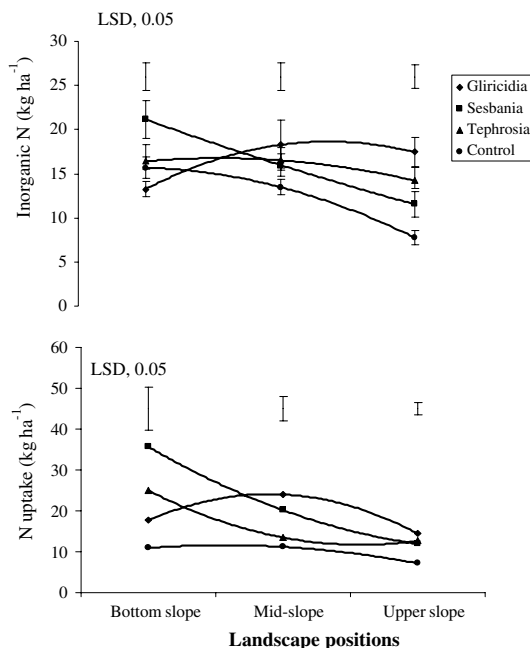


Fig. 3 Preseason inorganic N and maize N uptake for the cropping systems at different landscape positions in the 2002/03 season in Domasi valley site, southern Malawi. The bars are the standard errors. $n = 8, 11, 9$ in the bottom slope, mid-slope and upper slope respectively

Table 4 Nitrogen concentration (mg g^{-1}) in flag leaves of maize in 2003/04 cropping season in Domasi valley site, southern Malawi

	Bottom slope ($n = 8$)	Mid-slope ($n = 11$)	Upper slope ($n = 9$)
Gliricidia	19.7b	27.2a	19.9b
Sesbania	36.4a	18.4b	25.2a
Tephrosia	25.2b	13.2b	17.1b
Control	12.1c	13.9b	16.2b

Means in a column followed by different letters are significantly different at $P < 0.05$

the mid-slope, also soil under gliricidia had significantly lower ionic exchange resin membrane-inorganic N compared to tephrosia. The ionic exchange resin membrane-inorganic N for soil under sesbania and tephrosia cropping systems was not significantly different from the control-maize treatment in the bottom slope and mid slopes. However, there were no significant differences in ionic exchange resin membrane-inorganic N at 60 cm soil depth among the three landscape positions over time. As expected strongest evidence for N leaching was observed when the highest rainfall was received.

Biological N fixation

There were no significant differences in $\delta^{15}\text{N}$ values among the tree species in all landscape positions and therefore $\delta^{15}\text{N}$ values of all the trees

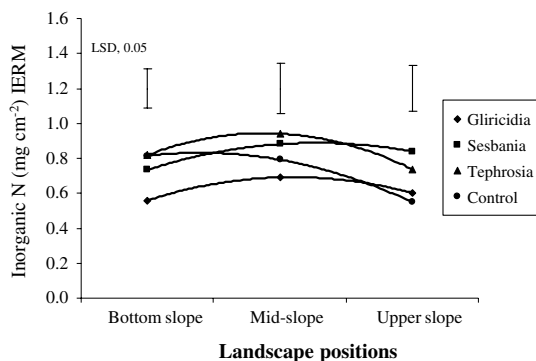


Fig. 4 Total ionic exchange resin membrane-inorganic N at 60 cm soil depth for the cropping systems at different landscape positions in the 2003/04 cropping season in Domasi valley, southern Malawi. $n = 8, 11, 9$ in the bottom slope, mid-slope and upper slope respectively. IERM = (ionic exchange resin membrane)

were averaged (Fig. 5). In general, $\delta^{15}\text{N}$ values of soil were significantly higher than those of the trees as well as the maize growing in association with trees in all landscape positions. Surprisingly, there were no significant differences in $\delta^{15}\text{N}$ values between tree species and the maize in all landscape positions. The $\delta^{15}\text{N}$ values were relatively uniform across all landscape positions and soil and plant $\delta^{15}\text{N}$ only slightly decreased from bottom slope to upper slope to the same extent.

Discussion

Agroforestry cropping systems effect

Maize yield differed under different agroforestry systems. In sesbania relay fallow, maize yield was highest in the bottom slope and lowest in the upper slope, but intermediate in the mid-slope. For gliricidia, the highest yield was obtained in mid-slope positions, intermediate yields at the upper slope and lowest yields in the bottom slope. Maize yields under tephrosia were nearly the same in all the landscape positions ($P > 0.05$). This yield trend was largely attributed to substantial amounts of tree biomass that was incorporated in the bottom slope and mid-slope positions for sesbania and gliricidia, respectively, which led to a subsequent release of large amounts of N. Substantial amounts of N-rich

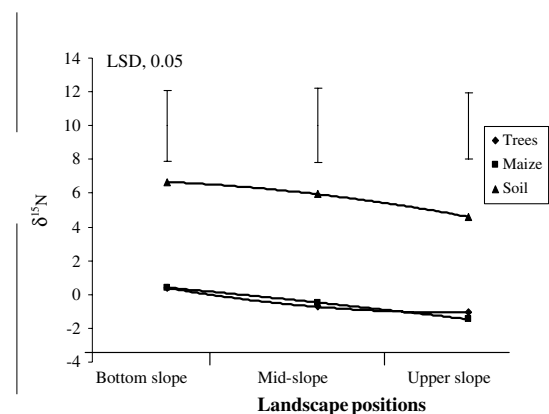


Fig. 5 Delta ^{15}N for the cropping systems and soil at different landscape positions in the 2003/04 cropping season in Domasi valley site, southern Malawi. $n = 8, 11, 9$ in the bottom slope, mid-slope and upper slope respectively

organic materials are needed to make a significant impact on crop yields (Giller et al. 1997).

The low maize yields observed in 2003/04 season were generally attributed to the low rainfall that was received during that particular season. In the 2002/03 season, the mean rainfall was 958 mm whereas in 2003/04 it was as low as 672 mm and there was little or no rain for a period of 3–4 weeks close to maize tasseling. However, in both seasons, the maize yields under agroforestry cropping systems were higher ($P < 0.05$) than the maize yields without trees. This was also attributed to the additions of N-rich organic materials and their residual effects compared to the continuous cropping without organic amendments. Significant increases in maize yields following addition of legume tree prunings have also been observed in previous studies in Malawi (Maghembe et al. 1997; Ikerra et al. 1999; Phiri et al. 1999; Akinnifesi et al. 2005b). In on-farm studies in the same area, Phiri et al. (1999) found a threefold increase in maize yield receiving sesbania pruning compared to the unfertilized maize.

The agroforestry cropping systems also affected both foliar N and total N uptake of the maize crop. The higher foliar N levels in the tree-based systems were probably a direct result of the application of tree prunings with a high N content. The high quality green manure provided a significant source of N to satisfy the immediate nutrient requirements of maize during its vegetative and reproductive growth phases. Thus improved soil N availability was reflected by increased foliar N contents. Chirwa et al. (2003) found significantly higher N concentrations in maize flag leaf with application of tree prunings than the unfertilized maize. Also Makumba (2003) reported that application of gliricidia prunings significantly increased N uptake in maize.

The weak correlations between tree biomass and maize grain yield ($r^2 = 0.2$, $P < 0.05$) and also maize grain yields with pre-season inorganic N ($r^2 = 0.3$, $P < 0.05$) in this study presumably resulted from a combination of factors such as highly variable tree growth due to different farmer management and varying rainfall between 2002/03 and 2003/04 seasons. In contrast, Ikerra et al. (1999) found a strong correlation ($r^2 = 0.92$) between pre-season topsoil inorganic N and maize

yields in gliricidia intercropping in one season, however, in the subsequent season there was a weak correlation ($r^2 = 0.34$) and the differences were attributed to varying rainfall regimes between the two seasons.

The pigeon pea that was intercropped in all the cropping systems did not appear to affect the maize yields in both seasons. In the 2002/03 and 2003/04 seasons pigeon pea yields were below 200 kg ha^{-1} in all cropping systems suggesting a minimal effect on maize. Chirwa et al. (2003) reported no beneficial influence of pigeon pea on maize performance in either tree/maize/pigeon pea or maize/pigeon intercropping.

Landscape effects

Trees

The significant effect of landscape positions on tree performances was an indication of differences in adaptation. Sesbania was suitable for use in the bottom slope, while gliricidia was better adapted to well-drained soils in the mid-slope and upper slope. Tephrosia was intermediary. The high biomass production by sesbania in the bottom slope is in line with the general pattern of ecological distribution of the plant. It nearly always naturally occurs in sites, which are wet for at least part of the year (Odee 1990). The bottom slope has heavy textures with high clay contents ($>47\%$) (Phiri 1998) which usually holds more water well into the dry season. The occurrence of nodulation of sesbania was higher in soils with higher clay content (Bala et al. 2002) which may improve biomass production. In a multilocational trial of sesbania fallows in the same region, performance was poorest on shallow or very coarse-textured soils, which was related in part to insufficient water during the dry season (ICRAF 1996). Researchers elsewhere (Brewbaker et al. 1990) have demonstrated, however, that sesbania can establish successfully on varied soil environments. This generalization did not hold true under the conditions of our study as poor establishment was observed on upper slopes. Our work suggests that sesbania growth can be limited by a biophysical gradient, such as soil moisture.

Gliricidia biomass production was generally high in mid-slope and lowest in the bottom slope. This suggests that this tree is adapted to well-drained soil conditions. In this study, the mid-slopes had high levels of P (Table 2) compared to the other landscape positions and this could probably explain why gliricidia performed better here than in the upper soils with similar drainage. The mean gliricidia biomass of 2000 kg ha⁻¹ in the mid-slope reported in this study was lower than those found by other researchers in similar landscape positions in the same agroecological zone. Chirwa et al. (2003) reported gliricidia tree biomass production of between 4,000 and 5,000 kg ha⁻¹ during the third year of tree establishment on farm. However, their trial was researcher managed compared to the present farmer-managed trial. Under full farmer management, biomass production will most likely be less due to improper management. For example, at the beginning of our study it was noted that some plots were not pruned during the previous season. Pruning of gliricidia coincides with a labor-intensive period during the rainy season especially during the second and third pruning cycles, when labor requirements are greatest (Nair 1989; Mugendi et al. 1999). In Malawi, this is the time when tobacco (*Nicotiana tabacum* L.), a major cash crop, is grown and farmers naturally give greater priority to the allocation of labor to the financially more profitable tobacco than to maize, which is primarily required for subsistence purposes. However, the sesbania tree biomass production is in line with another on-farm study in Malawi, where sesbania biomass production ranged from 500 kg ha⁻¹ to 3,000 kg ha⁻¹ with high biomass in the bottom slope (Phiri et al. 1999).

Higher tree biomass applications resulted in more inorganic N in soils under sesbania in the bottom slope and for soils under gliricidia in the mid-slope and upper slope than under other trees and locations. Makumba (2003) and Ikerra et al. (1999) also found that the application of gliricidia prunings increased inorganic N in an experiment on similar soil. The N-richness of the biomass is expected because these trees derive part of their N requirement from biological N₂-fixation. The similarly lower $\delta^{15}\text{N}$ contents in the trees and crop does not allow a conclusion whether or not the

trees were fixing atmospheric N in our study. Using the ¹⁵N dilution method, Akinnifesi et al. (1997) showed that leucaena derived only 2% of its N from the applied ¹⁵N-isotope. The absence of significant differences in $\delta^{15}\text{N}$ values among trees indicated that if biological N fixation occurred it was at a similar proportion between the tree species. The relatively uniform $\delta^{15}\text{N}$ values in trees across the landscape positions also suggested that there were no significant differences in the proportion of N derived from fixation between landscape positions. Therefore, quantification of total N uptake by trees appears to be sufficient for optimization of N input by biological N fixation into the studied agroecosystem.

The trees also varied in their ability to capture subsoil inorganic N. Leaching and denitrification are thought to be responsible for substantial N losses in agricultural systems in Malawi (MacColl 1989; Thornton et al. 1995). The higher inorganic N observed in soils under sesbania is contrary to other findings. For instance, Hartemink et al. (1996) found lower subsoil inorganic N in sesbania fallow than in unfertilized maize monocultures and suggested that fast growing trees such as sesbania, grown in rotation with cultivated annual crops can capture and recycle subsoil inorganic N otherwise unavailable to shallow rooted crops. Mekonnen et al. (1997) also found significantly higher inorganic N in maize monoculture compared to sesbania fallow. However, in these studies the sesbania fallows were more than 1 year old and the trees already had well-established roots and are actively growing. In the present study the sesbania was only less than 3 months old during the time when highest leaching was observed. This was also true for tephrosia, which had just been established from seeds. On the other hand, gliricidia trees had been established 4 years earlier and despite its shallow rooting characteristics, their roots appeared to be sufficiently established to reduce leaching at 60 cm. Gliricidia is known to have their roots actively growing in the upper 45 cm. Rowe et al. (2001) suggested that the more even horizontal distribution of gliricidia roots may imply greater below-ground competition and, such a distribution is likely to result in more efficient interception of leaching N i.e. forming a safety net. On the

other hand studies at Makoka in Malawi observed that gliricidia has very deep rooting systems (>3 m), with <15% at the top 0–20 cm soil and 79% to 63% of the roots below the effective rooting zone of maize (0–30 cm depth), indicating a differential rooting pattern between trees and crops and low potential for competition. A similar study in Côte d'Ivoire had also suggested that gliricidia have few surficial roots and minimally compete with associated crops (Schroth and Zech 1995). These studies confirmed that gliricidia rooting patterns are different from those of maize. Therefore gliricidia has low capacity to compete with crops, and is capable of retrieving nutrients and water from sub-soil beyond the rooting depth of annual crops.

Crop performance

The performance of maize without trees was nearly identical in all landscape positions. This was surprising because we expected high yields in the relatively fertile soils of the bottom slope. Total and available nutrient contents were high in the bottom slope (Table 2). In addition, pre-season inorganic N (Fig. 3) was also higher in the bottom slope than in the other landscape positions. One likely explanation could be that the levels of N in the bottom slope are not high enough to result in significant increases in maize yields. During the first month of maize growth there are usually no differences in appearance of maize with and without nutrient inputs. However, by the second month yellowing of maize starts to show in the maize without inputs.

The large amounts of intercepted mineral N found at 60 cm depth in the maize monoculture (especially in the bottom slope and mid-slope) in this study suggest that maize took up significantly less N from the subsoil than the agroforestry trees. The lower N depletion in the subsoil by maize is also evidenced by the low total N uptake in aboveground maize biomass (Fig. 3). Maize root systems do not reach 45–65 cm depth until later in the growing season, when much of the N taken up is used in filling grain (Rowe et al. 2001). However, most of the inorganic N intercepted by the exchange resins was retrieved before maize tasseling.

Conclusions

The extent to which agroforestry cropping systems influenced maize yields and N dynamics varied significantly according to landscape positions. *Sesbania* was remarkably adapted to the waterlogged bottom slope positions and accumulated more biomass, while gliricidia was well established in the mid-slopes and tephrosia performed fairly similar in both the bottom slope and mid slopes. *Sesbania* and tephrosia agroforestry systems performed poorly in the upper slopes. This suggests that these agroforestry systems are not a viable option in this landscape position. In upper slopes most of the nutrients were limiting including P, which is very critical for tree establishment. Gliricidia trees appeared to be more effective in reducing N leaching into the sub-soil than *sesbania* and tephrosia in all landscape positions. The observed differences in performance among the tree cropping systems across landscape positions have practical implications. The farmer recommendations of these cropping systems need to be fine-tuned to landscape positions. Landscape criteria should be developed that allow easy identification of the slope positions adapted to certain agroforestry systems.

Acknowledgements The authors are greatly indebted to the Rockefeller Foundation for providing the fellowship for Rebbie Harawa through the African Food Security and Natural Resources Management (AFSNRM) Program at Cornell International Institute for Food and Agriculture Development (CIIFAD). The authors are grateful to the International Center for Research in Agroforestry (ICRAF) in Malawi for hosting the field research and allowing us to use their laboratory and office facilities.

References

- Akinnifesi FK, Makumba WI, Kwesiga FR (2005a) "Fertilizer trees" and Malawi's new food security initiative. A policy briefing on the potential of fertilizer trees. World Agroforestry Centre (ICRAF), Lilongwe Malawi, 8 pp
- Akinnifesi FK, Makumba WI, Kwesiga FR, Maghembe JA (2005b) Sustainable maize production using gliricidia/maize intercropping in Southern Malawi. *Exp Agric* (in press)
- Akinnifesi FK, Kwesiga FR (2002). Can agroforestry make a difference as exit strategy for the starter pack scheme in Malawi? *Malawi J Agric Sci* 1:53–65

- Akinnifesi FK, Zuze P, Phiri R, Kwesiga FR, Ajayi O, Mhango J, Franzel S, Makumba W, Boehringer A, Aggumya A (2002) On-farm assessment of agroforestry technology performance and spontaneous modification of field management by farmers in southern Malawi. In: Southern Africa agroforestry conference, 20–24 May. Aventura Warmbaths, South Africa
- Akinnifesi FK, Kang BT, Sanginga N, Tijani-Eniola H (1997) Nitrogen use efficiency and N-competition between *Leucaena* hedgerows and maize in an alley cropping system. *Nutr Cycl Agroecosyst* 47:71–80
- Anderson JM, Ingram JSI (1993) Tropical soil biology and fertility: a handbook of methods. CAB International, Wallingford, UK
- Bala A, Murphy P, Giller KE (2002) Occurrence and genetic diversity of rhizobia nodulating *Sesbania sesban* in African soils. *Soil Biol Biochem* 34:1759–1768
- Barrios E, Kwesiga F, Buresh RJ, Sprent JI (1997) Light fraction soil organic matter and available nitrogen following trees and maize. *Soil Sci Soc Am J* 61:826–831
- Blake GR, Hartge KH (1986) Bulk density. Klute A (ed) *Methods of soil analysis. Part 1. Agronomy 9*. American Society of Agronomy Inc, Madison, Wisconsin
- Brewbaker JL, Macklin B, Evans DO (1990) The perennial sesbania. In: Evans DO, Macklin B (eds) *Perennial sesbania, its production and use*. Nitrogen Tree Fixing Association, pp 7–12
- Carr SJ (1997). A green revolution frustrated lessons from Malawi experience. A paper presented at the First All Africa Crop Science Congress, 13–17 January 1997. Pretoria, South Africa
- Chirwa PW, Black CR, Ong CK, Maghembe JA (2003) Tree and crop productivity in gliricidia/maize/pigeonpea cropping systems in southern Malawi. *Agrofor Syst* 59:265–277
- Cooperband LR, Gale PM, Comerford NB (1999) Refinements of anion exchange membrane method for soluble phosphorus measurement. *Soil Sci Soc Am J* 63:58–64
- Cooperband R, Logan TG (1994) Measuring in situ labile soil phosphorus with anion exchange membrane. *Soil Sci Soc Am J* 58:105–114
- Elliot JA, de Jong E (1992) Quantifying denitrification on a field scale hummocky terrain. *Can J Soil Sci* 72:21–29
- Franzel S, Nduka JK (1994) Guidelines for conducting farmer-designed multipurpose tree trials. ICRAF, p. 9
- Giller KE (2001) Nitrogen fixation in tropical cropping systems. CABI, London UK
- Giller KE, Cadisch G, Ehalotis C, Adams E, Sakala WD, Mafongoya PL (1997) Building soil nitrogen capital in Africa. In: Buresh RJ, Sanchez PA, Calhoun F (eds) *Replenishing soil fertility in Africa*. Soil Science Society of America, Madison, Wisconsin, USA, Special Publication Number 51, pp 150–192
- Hartemink AE, Buresh RJ, Bashir J, Janssen BH (1996) Soil nitrate and water dynamics in sesbania fallow, weed fallows and maize. *Soil Sci Soc Am J* 60:568–574
- ICRAF (2000) Makoka annual report. International Centre for Research in Agroforestry, Zomba, Malawi
- ICRAF (1996) Makoka annual report. International Centre for Research in Agroforestry, Zomba, Malawi
- Ikerra ST, Maghembe JA, Smithson PC, Buresh RJ (1999) Soil nitrogen dynamics and relationships with maize yields in gliricidia-maize intercrop in Malawi. *Plant Soil* 211:155–164
- Jones RB, Snapp SS, Phombeya SK (1996) Management of leguminous leaf residues to improve nutrient use efficiency in the sub humid tropics. In: Cadisch G, Giller KE (eds) *Driven by nature. Plant litter quality and decomposition*. CAB International, Wallingford, UK, pp 239–250
- Kanyama-Phiri GY, Snapp SS (1997) Developing improved organic matter technologies in partnership with smallholder farmers in southern Malawi. A paper presented at the First All Africa Crop Science Congress Africa Crop Science, 13–17 January 1997. Pretoria, South Africa
- Kanyama-Phiri GY, Wellard K, Kamangira JB (1994) Preliminary findings on adoption of agroforestry technologies by smallholder farmers in Zomba RDP. In: *Agroforestry symposium, 24–28 October*. Bvumbwe Agricultural Research Station, Limbe, Malawi
- Kumwenda JDT, Waddington SR, Snapp SS, Jones RB, Blackie MJ (1995) Soil fertility management in smallholder maize based cropping systems of Africa. In: *The emerging maize revolution in Africa: the role of technology, institutions and policy*, 9–12 July. Michigan State University, USA
- Kwesiga F, Franzel S, Place F, Phiri D, Simwanza CP (1999) *Sesbania sesban* improved fallows in eastern Zambia: their inception, development and farmer enthusiasm. *Agrofor Syst* 47:49–66
- Lehmann J, Gebauer G, Zech W (2002) Nitrogen cycling assessment in a hedgerow intercropping system using N-15 enrichment. *Nutr Cycl Agroecosyst* 62:1–9
- MacColl D (1989) Studies on maize (*Zea mays* L.) at Bunda, Malawi: II yield in short rotations with legume. *Exp Agric* 25:367–374
- Maghembe JA, Chirwa PW, Kooi G, Ikerra S (1997) SADC-ICRAF annual report for 1997. Makoka Agricultural Research Station, Malawi
- Mahler RL, Bezdeck DF, Witters RE (1979) Influence of slope position on nitrogen fixation and yield of dry peas. *Agron J* 71:348–351
- Makumba W (2003) Nitrogen use efficiency and carbon sequestration in legume tree-based agroforestry systems. PhD Thesis, Wageningen University and Research Center, Wageningen, The Netherlands
- Maroko JB, Buresh RJ, Smithson PC (1998) Soil nitrogen availability as affected by fallow-maize systems on two soils in Kenya. *Biol Fert Soils* 26:229–234
- Mekonnen K, Buresh RJ, Jama B (1997) Root and inorganic nitrogen distributions in sesbania fallow, natural fallow and maize fields. *Plant Soil* 188:319–327
- Mugendi DN, Nair PKR, Mugwe JN, O'Neill MK, Woormer PL (1999) Alley cropping of maize with calliandra and leucaena in the sub humid highlands of Kenya. Part 1: soil fertility changes and maize yield. *Agrofor Syst* 46:39–50

- Nair PKR (1989) Agroforestry systems, practices and technologies. In: Nair PKR (ed) Agroforestry systems in the tropics. Kluwer Academic Publishers, Dordrecht, The Netherlands, pp 67–73
- Odee DW (1990) Some characteristics of *Rhizobium* symbiosis of *Sesbania sesban* and its potential for biological nitrogen fixation in Kenya. In: Macklin B, Evans DO (eds) Perennial *Sesbania* species in agroforestry systems. ICRAF and Nitrogen fixation Tree Association, Wimanalo, Hawaii, pp 201–209
- Pan WL, Hopkins AG (1991) Plant development, and N and P use in winter barley: evidence of water stress-induced P deficiency in eroded toposequence. *Plant Soil* 135:9–19
- Phiri RH (1998) Nitrate budgeting and dynamics in a maize cropping system involving a multipurpose tree species. MSc Thesis, Bunda College of Agriculture, University of Malawi, Lilongwe, Malawi
- Phiri RH, Snapp SS, Kanyama-Phiri GY (1999) Soil nitrate dynamics in relation to nitrogen source and landscape position in Malawi. *Agrofor Syst* 47:253–262
- Rowe EC, van Noordwijk M, Suprayogo D, Hairiah K, Giller KE, Cadisch G (2001) Root distributions partially explain ^{15}N uptake patterns in *Gliricidia* and *Peltophorum* hedgerow intercropping systems. *Plant Soil* 235:176–179
- Schroth G, Zech W (1995) Root length dynamics in agroforestry with *Gliricidia sepium* as compared to sole cropping in the semi-deciduous rainforest zone of West Africa. *Plant Soil* 170:297–306
- Soltanpour PN (1991) Determination of nutrient availability and elemental toxicity by AB-DTPA soil test and ICPS. *Adv Soil Sci* 16:165–190
- Szott LT, Palm CA, Buresh RJ (1999) Ecosystem fertility and fallow function in the humid and subhumid tropics. *Agrofor Syst* 47:163–196
- Thornton PK, Saka AR, Singh U, Kumwenda JDT, Brink JE, Dent JB (1995) Application of a maize crop simulation model in the central region of Malawi. *Exp Agric* 31:213–226
- Tiessen H, Salcedo IH, Sampaio EVSB (1992) Nutrient and soil organic matter dynamics under shifting cultivation in semi-arid northern Brazil. *Agric Ecosyst Environ* 38:139–151