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SUSTAINABLE MAIZE PRODUCTION USING GLIRICIDIA/MAIZE INTERCROPPING IN SOUTHERN MALAWI

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SUMMARY

Maize production in Malawi is limited by high costs and sub-optimal use of chemical fertilizers under continuous cultivation. A long-term gliricidia/maize trial was undertaken on a Ferric Lixisol from 1991/92 to 2001/02. The purpose of the study was to assess the performance of a gliricidia/maize intercropping system as a low-input soil fertility replenishment option in southern Malawi. The experiment was a 2 × 3 × 3 factorial design with three replications. Treatments included two maize cropping systems (with and without gliricidia trees), and three rates of inorganic N fertilizer (0, 24 and 48 N kg ha^{-1} representing 0, 25 and 50% of the national recommended N rate), and three rates of P fertilizer application (0, 20 and 40 P ha^{-1} representing 0, 50 and 100% of the recommended rate). No effect of P was detected on yield early in the trial, and this treatment was discontinued. The gliricidia pruning biomass did not decline after 10 years of intensive pruning, with strong correlation between tree biomass production and years after establishment ($r = 0.91$, $p < 0.001$). Application of gliricidia prunings increased maize yields by three times compared to the yield of unfertilized sole maize. Maize yield from the unfertilized gliricidia pruning treatment was superior to the yield from sole maize supplemented with a quarter or half the recommended N rate. The study confirmed that a gliricidia/maize intercropping system is a promising soil fertility replenishment option in southern Malawi and elsewhere in southern Africa.

INTRODUCTION

The declining soil fertility resulting from shortened fallow periods and continuous cultivation, with few or no inputs, has been cited as the most important constraint threatening food production on smallholder farms in sub-Saharan Africa (Adesina *et al.*, 2000; Kwesiga *et al.*, 2003). Malawi is a maize deficit country and shortfalls are increasingly inevitable despite long-standing policy bias towards maize (Rubey, 2003). The staple food shortage in the country was estimated at 700 000 t in 2002 (www.futureharvest.org/pdf/malawi.pdf). The major causes of food shortage in Malawi include sporadic rainfall and frequent droughts, high fertilizer costs and lack of farm input loan facilities. Unless the situation is reversed, continuous cropping without inputs will continue to cause soil degradation and a food crisis every year.

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A cropping system that involves either tree-fallow sequentially followed by crops, or simultaneous tree-crop intercropping is needed to help improve yields (Kwesiga *et al.*, 2003). A leguminous tree species can improve soil fertility through enhanced nutrient availability and nitrogen supply through biological N fixation, organic matter build-up, recycling of N from depth and improved soil physical and biological conditions (Kang *et al.*, 1985; Kwesiga *et al.*, 1999). The potential constraints to the adoption of simultaneous intercropping of tree legumes and crops include some socio-economic factors such as insecure land tenure, high labour costs for tree pruning, as well as the area of land lost to trees (Adesina *et al.*, 2000). Other technical factors, include tree management, choice of species (Akyeampong *et al.*, 1995), and lack of adequate planting material (Kwesiga *et al.*, 2003), and below and above ground competition between trees and crops (Rao *et al.*, 1999; Singh *et al.*, 1989).

The socio-economic and biophysical conditions in southern Malawi seem to meet most of the broadly defined criteria for success of simultaneous intercropping of crops with trees. The scarcity of land, relatively low cost of labour and high cost of fertilizer coupled with the fact that maize, a high nitrogen-demander, is the major staple food creates the prospect for wide adoption of gliricidia/maize intercropping in southern Malawi.

Three separate but related experiments have been conducted on different fields at Makoka Agricultural Research Station in the past decade investigating different aspects of the gliricidia-based production systems. First, an in-depth study of the soil N dynamics (in space and time) undertaken over two seasons by Ikerra *et al.* (1999) showed that soil N contents remained constant during the dry season but rose rapidly in gliricidia plots after onset of the rains. The study concluded that a combination of pre-season soil inorganic N and potential N mineralization appears to provide a good estimate of N supply to maize in systems receiving both organic and inorganic sources of N.

Second, Chirwa *et al.* (2003) investigated the temporal and spatial N availability and use in a gliricidia/maize/pigeon pea system and sole crops of each species. The study concluded that tree-based production systems were more productive and exhibited greater fractional light interception than sole cropping systems.

Third, in an effort to understand the synchrony between N-released and N-applied, Makumba *et al.* (2005) investigated the effects of the time of application of prunings to maize. The study concluded that although split-applications in December and February prolonged mineral N availability in the soil, they did not increase N uptake compared to a single application in October (a month before maize planting).

In scaling up a gliricidia/maize intercropping system, the biophysical performance provides a sound foundation on which socio-economic decisions can be built (Van Noordwijk, 1999). To date, the long-term data needed for assessing the functioning of gliricidia/maize intercropping as a sustainable production system in southern Malawi, such as maize yield performance, tree biomass production and nutrient yields following intensive pruning have not been reported. This paper presents the results of a long-term gliricidia/maize intercropping trial, which evaluated intercropping as a potential soil fertility improvement option in the high population density region of southern Malawi.

The objectives of the study were to assess (i) the suitability of a gliricidia/maize intercropping system, in terms of tree biomass production response to intensive pruning management, and (ii) the effects of gliricidia prunings as a nutrient source on maize yields, with and without mineral N supplementation. The study is relevant for the Chinyanja Triangle of Southern Africa, involving southern Malawi, eastern Zambia and northern Mozambique, large part of the areas identified for the Sub-Saharan Africa Challenge programme in southern Africa. These areas exhibit geographical, climatic and cultural similarities.

MATERIALS AND METHODS

Study site description

The experiment was located at Makoka Agricultural Research Station, near Zomba, in southern Malawi (15°30′S, 35°15′E; 1030 m asl). The soil is classified as a Ferric Lixisol (FAO/UNESCO) or Oxic Hapleustalf (USDA). The soil texture is 46% sand, 46% clay and 8% silt. The surface (0–20 cm) soil chemical characteristics at the time the trial was set up (baseline) is presented under results. The clay content increases with depth, but major chemical characteristics are relatively constant to $>$ 1 m depth (Ikerra *et al.*, 1999).

The total annual rainfall ranges from 560 to 1600 mm, with a 30-year mean of 1024 mm (Makoka Research Station, unpublished data). The rainfall is unimodal, with most of the rains occurring from November to April. The annual rainfall pattern over the 10-year period of the study is shown in Figure 1.

Experimental design

The experiment was originally a randomized complete block design with $2 \times 3 \times 3$ factorial arrangement with three replications. The treatment factors were: (i) production system (sole maize with or without intercropping with *Gliricidia sepium*); (ii) three rates of N fertilizer (0, 23 and 46 kg N ha^{-1}) applied at four weeks after planting. The inorganic fertilizer rates correspond to zero (unfertilized), one-quarter (25%) and one-half (50%) of the recommended national fertilizer rate for maize. The recommended N rate for Southern Malawi is 92 kg N ha^{-1} by side dressing (MAIFS, 2004). Calcium ammonium nitrate (CAN) fertilizer was used as a source of N. Fertilizer was applied only to the maize crop. (iii) Three levels of inorganic phosphorus were applied (triple superphosphate) early in the trial (0, 20 and 40 kg P ha^{-1}) corresponding to fertilizer rates of 0, 50% and 100% of the recommended level. These treatments were discontinued in 1993/94 as P had had no significant effect on maize yields. Indeed data analysis for P showed no significant effect for the first eight years of the experiment, except for two years (1998/99 and 1999/00) when the effect of the residual P application was significant. Therefore, P results will be presented only for the 1998/99 and 1999/00 seasons. After the end of the current trial a new experiment was set up in 2002/03 season focusing on P-dynamics, and treatment with P-fertilizer

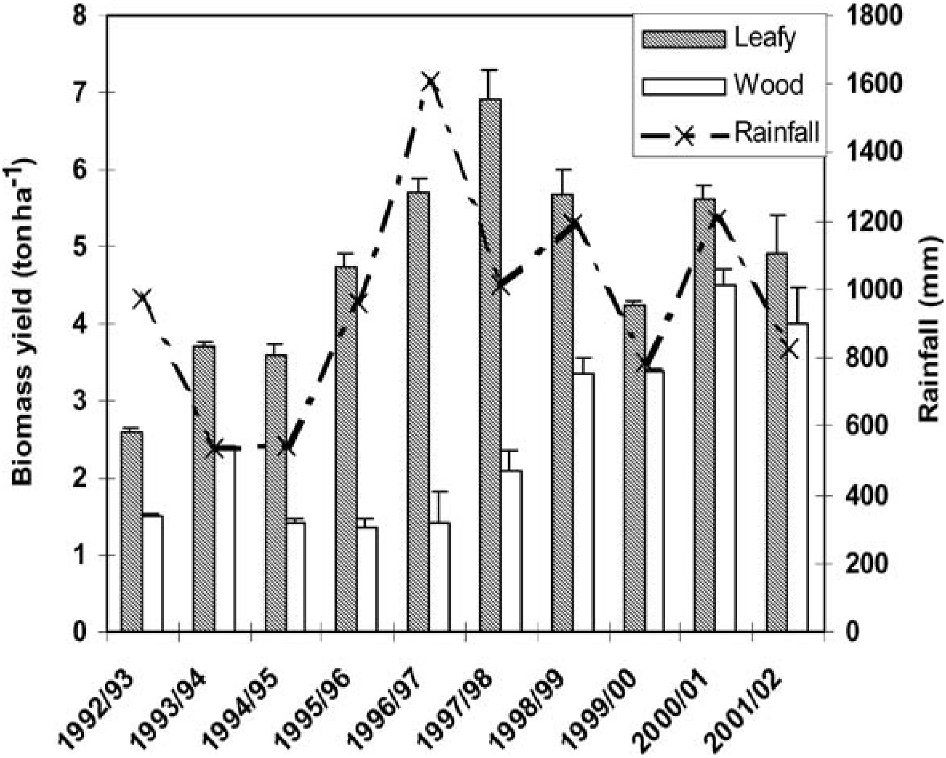

Figure 1. Annual foliage and wood biomass of *Gliricidia sepium* prunings in a maize-gliricidia intercropping system, together with annual rainfall from 1992/93 to 2001/02 seasons (values represent means across three nitrogen fertilizer rates, the vertical bars are S.E.).

has been resumed (but not reported in this paper). Potassium was not applied because it is not considered to be a problem in most soils in Malawi, and the initial soil analysis showed high K levels at the site; even the current national fertilizer recommendation does not include K.

Tree establishment and management

A Retalhaleu provenance of *G. sepium* from Guatemala (OFI seed No. 60/87) was used in view of its superior growth observed in Malawi and elsewhere in southern Africa (Ngulube, 1994). The trees were established from seedling stock in December 1991, without cropping in the first year. The gliricidia plots consisted of four rows of trees planted in every other furrow at a spacing of 0.9 m within tree rows and 1.5 m between tree rows (7400 trees ha^{-1}), to maximize the biomass production. The maize crop was evenly spaced throughout the cropland. Plots measured 6.75 × 5.1 m; each block was separated by 1 m wide paths on two sides. In order to minimize tree root encroachment into adjacent plots or outside the experimental area, iron sheets were installed vertically to 1 m deep around each plot.

The trees were planted in the furrows and the crops on the ridges. This arrangement ensures that no land area is lost to the trees, and that there is no ‘hedge effect’ on the crop. The trees were managed by pruning at 30 cm above ground level during the cropping season to minimize shading and competition for light and water. The gliricidia trees were first pruned in September 1992. In December 1992, the coppice regrowth was harvested and incorporated into the soil and the maize planted. Tree coppices were harvested again in February 1993, and left to grow until September 1993 when the trees were harvested again. The harvesting cycle of September–December–February was repeated continuously from 1992/93 to 1996/97. However, because of the erratic rainfall, the pruning regime was varied from 1997/98 to 2001/02, depending on the onset of the rains. The pruning time were then generally determined as follows: pre-plant pruning in late October to early November (first pruning), late December to early January (second), late February (third) and late August to early September (fourth).

The leaves and small green stems (twigs) were separated and incorporated in to the soil while fresh on the same day that they were pruned. Tree prunings were incorporated by opening the ridges, placing the leafy prunings and reconstituting the ridges thus burying the prunings to a depth of about 15 cm. Wood was not removed in the subsequent harvests (October, January and February cuttings) because the stems were young and tender, and all the prunings were incorporated. Pruning the trees in August/September normally stimulates the production of large amounts of leafy growth rather than the woody biomass produced during the growing season.

The ridges were not shifted to another row under the gliricidia/maize intercropping system on annual basis, unlike traditional practice. Splitting of the ridges when the second and third prunings are applied is not recommended because the maize roots might be cut in the attempt. The incorporation of prunings into ridges coincides with the time of ridge making (land preparation) at the first and second weeding times.

Maize hybrid NSCM 41 was planted on ridges at a spacing of 0.3 m within rows and 0.75 m between rows (44 000 plants ha^{-1}), in both the sole maize as well as the intercropping plots. Two weeks after emergence, the maize seedlings were thinned to one plant per hole. The maize was planted at least two weeks after incorporation of the October prunings. Weeding was done twice by hand during the maize cropping season, as is typical of traditional farming practice.

Soil and plant sampling and analysis

Soil samples were taken at the start of the trial in 1991/92 and when the experiment was terminated in 2001/02 after ten consecutive cropping seasons. In each plot, surface soil (0–20 cm) was randomly collected and bulked from ten auger points, using the Edelman soil augers. Sub-samples were processed and analysed for pH (water), organic C., extractable P and exchangeable Ca, Mg and K, following standard procedures described by Anderson and Ingram (1993), and exchangeable cations were determined using 1N ammonium acetate.

Maize was harvested from the central 5.25 × 4.2 m area of plots in late April of each year. Grain yield was expressed at 13% moisture content. The gliricidia biomass yield was determined separately for each plot. The 'pruning biomass' refers to the twig or foliage (leaves and young stems), and 'total biomass' refers to the whole plant biomass (leafy + wood). Leafy and wood samples were oven dried separately at 75 °C to constant weight for determination of the dry weight. The pruning biomass yield was determined at all harvesting times. The dry plant materials were finely ground and were digested in sulphuric-selenium extractant for total N, P and K analyses following the method described by Temminhoff *et al.* (2000). The decomposition and nutrient release rates of gliricidia prunings and maize stover, and their mixtures have been reported elsewhere (Makumba *et al.*, 2005).

Statistical analysis

All data was subjected to the analyses of variance using GENSTAT (version 4.2, 5th edition), and presentation followed the recommendation of Riley (2001). The data for N-fertilizer and production system for the entire 10 cropping years were analysed over the inorganic P fertilizer treatment (using 2 × 3 randomized block design). In addition, a separate analysis was done for the effects of inorganic P-fertilizer rates and P interaction with N and production system, using a 2 × 3 × 3 randomized complete block design, and the results are presented only for 1998/99 and 1999/2000, when an effect of the residual P treatment was detectable. In all cases of statistical significance the F-test was used, except where otherwise specified. The treatment means were compared using least significant difference (LSD) tests at $p < 0.05$, except where otherwise stated. In the plots with gliricidia/maize intercropping, the mean data on grain yield, tree age, biomass (wood, prunings and total biomass), current year's rainfall and previous season's rainfall were subjected to correlation and multiple regression analyses.

RESULTS

Surface soil chemical properties

The soil properties at the establishment of the trial in 1991/92 and termination in 2001/02 are shown in Table 1. Gliricidia prunings did not significantly affect the soil pH or exchangeable Ca. Fertilizer application did not affect the soil pH, organic C, extractable P or exchangeable Ca. Soil fertility levels were significantly higher under gliricidia/maize intercropping than sole maize ($p < 0.05$), and the levels of Mg and K were significantly increased by N fertilizer application. The mean soil organic C, extractable P, exchangeable Mg and K were maintained at significantly higher levels with gliricidia prunings than in plots without prunings compared to the original soil pH (Table 1). The levels of soil extractable P, exchangeable Mg and K at the end of trial in 2000/01 were significantly higher than at initial plot establishment. There was no evidence of a significant interaction between fertilizer level and pruning applications.

Biomass production in gliricidia and annual rainfall trend

Figure 1 shows the trend in annual prunings (foliage) and woody stem production from gliricidia, together with the amount of rainfall from 1992/93 to 2001/02. The trial experienced two extreme weather conditions i.e. severe drought during the 1994

Table 1. Surface (0–20 cm) soil chemical characteristics and changes in soil nutrient status of the baseline values (at field establishment) compared to status after nine years of continuous cropping under a gliricidia/ maize intercropping system in Makoka.

Production system†	pH (H_2O)	Organic C ($g\,kg^{-1}$)	Extractable P ($mg\,kg^{-1}$)	Exchangeable cations ($cmol_c\,kg^{-1}$) Ca	Mg	K
1991/92 season (Baseline‡)	5.9 (0.17)	8.8 (0.49)	26 (3.76)	4.4 (0.12)	1.6 (0.21)	0.30 (0.05)
2000/01 Season						
Sole maize + 0 kg N ha^{-1}	5.9	8.2	24	3.6	1.0	0.13
Sole maize + 23 kg N ha^{-1}	5.8	7.6	20	4.1	0.8	0.11
Sole maize + 46 kg N ha^{-1}	5.8	7.0	21	4.0	1.1	0.16
Mean	5.8	7.6	22	3.9	1.0	0.13
Gliricidia + 0 kg N ha^{-1}	6.0	9.1	36	4.5	2.4	0.54
Gliricidia + 23 kg N ha^{-1}	6.1	8.9	31	4.3	2.3	0.37
Gliricidia + 46 kg N ha^{-1}	6.1	8.7	33	4.3	2.1	0.52
Mean	6.1	8.9	33	4.4	2.3	0.48
LSD $_{(0.05)}$¶						
Production system	ns§	0.81	6.45	ns	0.37	0.13
N fertilizer rate	ns	ns	ns	ns	0.45	0.16
Prod. Syst. × N Fert. rate	ns	ns	ns	ns	ns	ns
C.V. (%)	12.6	9.3	21.6	22.4	20.3	25.6

†The inorganic fertilizer was all applied at once four weeks after planting.

‡Baseline indicates the initial soil properties at the year of plot establishment in 1992/93 season (soil chemical properties data represents the bulked sample across three replicates). Figures in parenthesis represent the standard errors.

§Not significant.

¶Least significant difference.

and 1995 seasons, and excessive rainfall in 1997. The cropping (wet) season extends from late October or early November until April, with most rainfall occurring between December and February.

In all the seasons, gliricidia produced significantly less woody biomass than foliage (leaf + green stem), because the wood was harvested once at the pre-season cutting in August/September. Pruning biomass was significantly lower in the early years, averaging 2.6 t ha^{-1} y^{-1} (1992/93) to 3.8 t ha^{-1} y^{-1} (1994/95). Pruning biomass yield was maintained at above 4.0 t ha^{-1} (4.75 to 6.8 t ha^{-1} y^{-1}) from 1995/96 to 2001/02. The largest tree biomass (6.8 t ha^{-1} y^{-1}) was harvested in 1997/98, and this was significantly more than that harvested in most other seasons. This large biomass coincided with the season following relatively high rainfall (1600 mm, 1996/97).

Biomass nutrient yield in gliricidia

Table 2 shows the nutrient production by gliricidia prunings during the 1997/98 and 1998/99 seasons. The rates of N fertilizer applied did not affect nutrient biomass production in either year. The time of pruning had variable effects on nutrient biomass, but the trend was not consistent between the soil nutrients measured. The total N ranged from 191 to 302 kg N ha^{-1}; P from 17 to 23 totalled kg P ha^{-1}, Ca from 132 to 192 kg Ca ha^{-1}, and Mg from 76 to 118 kg Mg ha^{-1}. The total nutrients (N, P, K,

Table 2. Biomass nutrient yield (kg ha^{-1}) in *G. sepium* prunings realized from the four cutting regimes during a season of simultaneous fallow intercropping of gliricidia with maize.

		N‡			P			K			Ca			Mg		
Season	TOP†	0	23	46	0	23	46	0	23	46	0	23	46	0	23	46
1997/98	August	38.2	43.3	34.0	2.05	2.30	1.80	16.5	48.8	14.7	29.1	29.7	17.9	19.2	19.5	11.8
	October	129	113	128	8.05	7.10	8.05	65.7	57.9	65.3	28.7	39.5	23.2	18.8	26.0	15.2
	January	59.7	54.5	58.1	3.75	3.45	3.70	30.5	27.8	29.7	32.6	30.7	32.7	21.4	20.2	21.5
	February	75.5	70.2	73.3	4.62	4.28	4.52	37.6	34.8	36.6	42.5	39.5	41.3	28.0	26.0	27.1
	Total	302	281	293	18.5	17.1	18.1	150	169	146	132	139	115	87	92	76
	$LSD_{(0.05)}$															
	TOP		8.49			0.83			4.07			4.78			3.14	
	Fert.§		ns			ns			ns			ns			ns	
	TOP × Fert.		ns			ns			ns			ns			ns	
	CV%		29.4			34.0			26.2			29.4			24.9	
1998/99	August	79.8	85.6	79.0	4.40	4.60	3.70	35.5	37.1	29.7	18.4	14.0	21.0	12.6	14.8	16.0
	October	117	106	128	10.0	8.45	9.80	83.2	68.8	79.1	94.1	87.9	91.2	61.8	57.8	60.0
	January	32.7	30.1	37.2	2.90	2.45	2.85	23.5	20.0	23.0	33.0	33.0	38.1	12.1	11.1	13.8
	February	63.8	59.3	74.8	5.95	5.30	6.00	48.2	43.2	48.7	35.7	33.7	42.1	23.4	22.0	27.7
	Total	293	281	191	23.3	20.8	22.4	190	169	181	181	169	192	110	106	118
	$LSD_{(0.05)}$															
	TOP		11.45			0.74			6.68			6.45			4.244	
	Fert.		ns			ns			ns			ns			ns	
	TOP × Fert.		ns			ns			ns			ns			ns	
	CV%		27.9			25.8			26.8			27.9			17.9	

†TOP: time of pruning.

‡Inorganic N levels (0, 23, 46 kg N/ha) all applied at once four weeks after planting. The mean nutrient fractions in gliricidia leaves were: 40.7 mg N g^{-1}; 2.1 mg P g^{-1}; 16.9 mg K g^{-1}; 20.6 mg Ca g^{-1} and 7.5 mg Mg g^{-1}.

§Fert.: N fertilizer.

¶Not significant.

Ca and Mg) produced in biomass from the prunings obtained at land preparation in October was consistently more than for other pruning times.

Effect of gliricidia prunings and fertilizer on maize grain yield

Table 3 shows the long-term effects of gliricidia as a N source on maize yields, with and without mineral N supplements from 1992/93 to 2001/02. Without fertilizer, the maize yield in sole maize cropping declined steadily from 1994 kg ha^{-1} in the first cropping season (1992/93) to 529 kg ha^{-1} in the fifth cropping season (1996/97). Subsequent yields were only about 1 t ha^{-1} (Table 3). The lowest maize yield from unfertilized sole maize, obtained in 1996/97, coincided with excessive rainfall and associated damage due to lodging. The effects of this damage were not as pronounced in the gliricidia/maize intercropping systems which produced a yield of 3356 kg ha^{-1}. The largest maize yield from the unfertilized gliricidia plot was harvested in the first cropping season (1995/96) 5302 kg ha^{-1}. Yield increases over the unfertilized sole maize ranged from 100% in 1994/95 to > 500% in 1996/97.

The inorganic N fertilizer increased significantly ($p < 0.001$) maize grain yields at half or quarter rates of the N recommendation, compared to the unfertilized sole maize plot (Table 2). Maize yields in the gliricidia/maize treatments were greater than in the sole maize plots in all years ($p < 0.001$), except in the first cropping season (1992/93), when there was 17% yield reduction in gliricidia plots ($p < 0.05$). The generally low yield in the sole maize plot was partly offset by the fertilizer N applied at the rate of 46 kg N ha^{-1}. The greatest N response under gliricidia/maize system was also observed during the first maize season in 1992/93. Afterwards, maize yields from fertilized (half-dose) sole maize plots were similar to those from unfertilized gliricidia plots. However, the effect of fertilizer rate was highly significant on maize grain yield in all years ($p < 0.001$), except 2000/01.

The positive effect of gliricidia application was very highly significant ($p < 0.001$) in all years except for the first cropping season ($p < 0.05$). This coincided with tree establishment. In the second cropping season, maize yields in the gliricidia/maize system were double those of the control plot without fertilizer. In general, the long-term average maize yield was maintained at 3.8 t ha^{-1} under gliricidia/maize intercropping without chemical fertilizer inputs, compared to 1.2 t ha^{-1} from unfertilized sole maize during the 10 cropping seasons (Table 3). The highest maize yield was obtained in 1994/95 under the gliricidia/maize system and ranged from 5.3 t ha^{-1} without chemical fertilizer input to 7.1 t ha^{-1} with a quarter N and 7.5 t ha^{-1} with half the recommended N rates (Table 3). This demonstrates the potential of the gliricidia/maize system and synergy with small fertilizer N doses in favourable years.

The maize yield increases due to gliricidia/maize intercropping were 228% more than that from unfertilized sole maize plots, 78% more in sole maize fertilized with quarter N rate, and 52% more in sole maize fertilized with half N rate over the 10-year period. The sole maize increased from 1.2 to 2.9 t ha^{-1}due to application of 25% N fertilizer, and 3.6 t ha^{-1} at the 50% N rate.

Table 3. Maize grain yield (kg ha^{-1}) in a maize-*Gliricidia* intercropping system during ten consecutive cropping seasons (1992/93 to 2000/01).

Production system	N fertilizer rate (%)†	1992/93‡	1993/94	1994/95	1995/96	1996/97	1997/98	1998/99	1999/00	2000/01	2001/02
Sole maize (no trees)	0	1994	1501	1490	1200	529	1073	1015	804	857	1000
Gliricidia + maize	0	1657	3922	2984	5302	3356	4322	4487	2309	5059	4150
	Mean	1825	2712	2237	3251	1943	2698	2751	1557	2958	2575
Sole maize (no trees)	25	3418	2111	3108	3917	1987	2953	2646	1708	2640	2890
Gliricidia + maize	25	2982	4446	4092	7117	4160	5997	5926	2947	5830	5290
	Mean	3200	3279	3600	5517	3074	4475	4286	2328	4235	4090
Sole maize (no trees)	50	4147	3155	3320	4750	1931	4000	3844	2076	3018	3620
Gliricidia + maize	50	4013	4545	3730	7523	4469	5815	6455	3519	6344	5120
	Mean	4080	3850	3525	6137	3200	4908	5150	2798	4681	4370
LSD$_{(0.05)}$:											
Prod. syst.		198	169	132	172	232	123	212	166	321	530
N fert. rate		242	207	161	211	285	151	248	204	393	649
Prod. syst. × N fert. rate		ns	293	228	232	ns§	214	350	ns	ns	ns
C.V. (%)		11.7	11.8	11.9	5.98	15.3	12.5	6.58	15.8	18.9	13.7

‡The tree establishment was done in December 1991 and first maize crop was planted in 1992/93 cropping season, after tree was about one year old. First tree pruning done in September 1992 and incorporated.

†Inorganic fertilizer N levels (0, 25 and 50% of recommended fertilizer rates correspond to 0, 23 and 46 kg N/ha respectively), all applied at once four weeks after planting.

§ns: not significant.

Table 4. Residual effect of phosphorus and annual N applications on grain yield of maize during 1998/99 and 1999/2000 cropping seasons†

			Grain yield in 1998/99 (kg ha^{-1})†				Grain yield in 1999/00 (kg ha^{-1})			
Production system	N-rates (kg ha^{-1})	P-rates (kg ha^{-1})	0	20	40	Mean	0	20	40	Mean
Sole maize										
	0		700	1101	937	913	653	1053	889	865
	24		1487	2035	2359	1960	1439	1987	2312	1912
	48		2354	2797	3241	2797	2307	2749	3193	2750
	Mean		1514	1978	2179		1466	1930	2131	
Gliricidia + maize										
	0		3779	3794	3591	3721	3802	3818	3614	3745
	24		4892	3605	3285	3927	4916	3629	3308	3951
	48		4279	3912	3727	3973	4303	3936	3751	3897
	Mean		4317	3770	3534		4340	3794	3558	
LSD $_{(0.05)}$:										
	Prod. syst.		306				209			
	N- fertilizer		375				256			
	P-fertilizer		375				256			
	Prod. syst. × N fert.		531				362			
	Prod. syst. × P-fert		531				362			
	N × P fert.		ns				ns			
	Prod. syst. N × P		ns				ns			

†The effect of P on maize yield were not significant during 1992/93 to 2001/02, except for 1998/99 and 1999/00 seasons.

The combination of N fertilizer with the gliricidia/maize system achieved a 30% benefit with the quarter, and 37% for the half N rate, compared to the unfertilized intercropped plot. A significant interaction between inorganic N fertilizer rates and gliricidia prunings was observed at $p < 0.05$ in the 1993/94, 1994/95, 1995/96, 1997/98 and 1998/99 seasons (Table 3).

Residual P effect on maize grain yield

Although the P treatments were discontinued in 1993/94 as P continued to have no significant effect on maize yield, a separate analysis showed that the effect of the initial P application and its interactions with production system was, however, significant in 1998/99 and 1999/2000 (Table 4). There was also a significant interaction between the production system and N, and with P. However, the interaction between N and P was not significant during the entire 10-year period.

In both 1998/99 and 1999/2000, the maize yield from the unfertilized (no P) sole maize was lowest averaging 700 kg ha^{-1} in 1998/99 and 653 kg ha^{-1} in 1999/2000. The application of half the recommended P dosage (20 kg P ha^{-1}) significantly increased maize yield. Sole maize plots fertilized with full P-dose yielded less than that obtained with the half P rate in both years, but the differences were not significant. The effect of P on maize yield was highest in plots supplied with N at the half rate, and yields increased with P-application rate in the fertilized sole maize plot. On the other hand, the trend was different in the gliricidia/maize intercropped plots, indicating that P did not affect maize yield in plots where N was not applied (Table 4). In gliricidia/maize intercropping plots, the maize yield declined in both years with increasing rates of initial P application, despite much higher yields from the intercropped system than the sole maize crop.

Correlation and regression analysis

The annual prunings from gliricidia were positively correlated with maize yield ($r^2 = 45\%$). The weight of gliricidia prunings applied annually correlated with the current season's rainfall for each year ($r^2 = 37\%$) and with the previous season's rainfall ($r^2 = 34\%$), and the number of years after tree establishment, i.e. tree age ($r^2 = 28\%$). The total tree biomass was strongly correlated with age of tree ($r^2 = 83\%$), the weight of prunings harvested (foliage biomass) ($r^2 = 58\%$) and the previous season's rainfall ($r^2 = 44\%$). The tree age also correlated with wood biomass ($r^2 = 69\%$). The regression coefficient of the relationship between tree age, pruning biomass and rainfall was low ($r^2 = 44\%$).

DISCUSSION

The higher nutrient status under the gliricidia/maize system compared to the sole maize cropping is evidence that organic inputs from tree leaf prunings have beneficial effects on soil chemical properties. Several other soil fertility trials in Africa have indicated beneficial effects of organic inputs on soil fertility replenishment (Bekunda *et al.*, 1997; Jones *et al.*, 1996; Wendt *et al.*, 1996). The larger amounts of exchangeable Ca, Mg and K in the topsoil in gliricidia/maize than sole maize plots are evidence of recycling of nutrients from depth by the deep-rooted trees.

The low biomass yield from gliricidia in the second year after establishment (1992/93) was because the trees were still young (Figure 1). This also explains why the maize harvested from gliricidia/maize intercropped plot in the first cropping season was less than that obtained from the sole maize system. The highest gliricidia biomass yield obtained in 1997/98 was attributed to the high rainfall (1605 mm) in the preceding season, which might have enhanced biomass production in gliricidia during the dry season. The highest biomass yield obtained within a season at the first cutting (October/November) contributed the highest nitrogen biomass (Table 2) for the current crop. Pruning carried out in October or early November is the most important cut because the release of N coincides with the time of plant N demand. In a separate biomass transfer experiment with gliricidia at Makoka, it was recently shown that higher yields and N uptake were obtained with a single application of gliricidia prunings in October than when split-applied in December and February (Makumba *et al.*, 2005). An intensive study of the soil N dynamics in the same trial by Ikerra *et al.* (1999) had noted that the prunings applied in October increased the pre-season N, which was highly correlated with the subsequent maize grain yield. The study showed that there was a close association between the inorganic N flush and rainfall, where soil nitrate increased from 6 to 21 kg ha^{-1} in sole maize plots and from 7 to 70 kg ha^{-1} in gliricidia/maize plots, five days after the first rains (21 mm) (Ikerra *et al.,* 1999). On the other hand, Chirwa *et al.* (2006) found that the soil mineral N was greatest in an agroforestry system, and that the application of prunings increased pre-season soil mineral N content, but that it could not be efficiently utilized because maize was too young to act as sink for N early in the season.

The application of gliricidia prunings three times within the maize growing season, was intended to synchronize the N supply with the plant uptake, which is critical for high N use efficiency in the gliricidia/maize system. The foliage biomass yield of gliricidia in this trial ranging from 2.8 to 6.9 t ha^{-1} compared to the average of 4.3 t ha^{-1} reported by Schroth and Zech (1995) in West Africa and 3.6 to 7.3 t ha^{-1} reported in a two-year old gliricidia performance screening trial in Makoka, Malawi (Maghembe and Prins, 1994). The lack of a significant effect of N fertilizer rates on biomass N production in gliricidia suggests that gliricidia was probably able to meet most of its nitrogen requirement through N-fixation, especially since inorganic fertilizer was applied closer to the maize plant on the ridges than to the trees planted in the furrows. The effect of trees on soil N further depends on the soil type, rainfall conditions and rooting systems of the trees and the crop.

The biomass nutrient yield data showed that the trees have the potential to supply nutrients at levels of up to 298 kg N ha^{-1} y^{-1}, 21 kg P ha^{-1} y^{-1} and 170 kg K ha^{-1} y^{-1} (Table 2). Assuming 20% nitrogen use efficiency, the N contributed by gliricidia to maize is equivalent to approximately 60 kg N ha^{-1} of inorganic fertilizer. The recommended N rate in Malawi for the growing of hybrid maize is 96 kg N ha^{-1} (MAIFS, 2004). This indicates that gliricidia alone may not meet all the N demands of maize, and that the crop will therefore respond to small N supplements.

The significant correlation of the previous seasons rainfall with gliricidia biomass produced ($r = 0.55$ for pruning, $r = 0.66$ for total tree biomass) suggests that biomass production of trees in drier areas will be lower than in this trial. The strong association of tree age with foliage biomass ($r = 0.76$) and total biomass ($r = 0.91$) is evidence that gliricidia trees can withstand frequent coppicing without biomass decline for at least 10 years. However, the positive response of gliricidia biomass yield to rainfall and tree age means that tree biomass production in gliricidia may be affected in years following flooding or prolonged drought. It must be pointed out that added N from gliricidia comes at a cost because potential N supply is related to biomass accumulation, which in turn requires sufficient soil water to support growth.

The grain yield of maize in the gliricidia/maize intercropped plots was maintained at high levels (averaging 3.8 t ha^{-1}) without mineral N fertilizer inputs (Table 3). The three-fold increase of maize yield in the gliricidia/maize intercropping system compared to maize without soil amendment during most of the 10 consecutive years of the experiment (Table 3), suggests that with proper management farmers could maintain good maize yields, even when little or no inorganic N fertilizer is available. The low maize yield in the first season (1992/93) in gliricidia/maize intercropping (Table 3) was due to the fact that gliricidia was still juvenile and growing (one year old), therefore producing less nutrient biomass (Figure 1). During years of drought, maize yields from unfertilized gliricidia plots were similar to those from sole maize plots supplied with 50% fertilizer dosage. This indicates that the gliricidia/maize intercropping system demonstrated greater resilience against drought than traditional practices without soil amendments.

During the 10 seasons of continuous maize cropping, the experiment experienced two extreme rainfall conditions, i.e. drought in 1993–94 and excess rainfall in 1996–97. Under these adverse rainfall conditions the gliricidia/maize intercropping system had performed better than the sole maize with or without fertilizer (Table 3). The lowest maize yield harvested in 1996/97 under sole maize was attributed to leaching and water logging due to excessive rainfall and lodging.

The separate effects of prunings and N fertilizer were strongly significant ($p < 0.001$) for the entire period, except in the first season when yields were reduced by intercropping (Table 3). The high correlation of maize yield with pruning biomass ($r = 0.66$) confirmed the positive effect of N from gliricidia prunings on maize. The application of a small dose of inorganic fertilizer N combined with gliricidia prunings had significantly increased (at $p = 0.05$) maize grain yield in five cropping seasons (Table 3), but this effect gradually declined, as more biomass N was contributed from tree prunings, especially in the last three years of the trial.

The addition of 25% N dose in gliricidia/maize system resulted in an additional 30% yield increase, maintaining maize grain yield at more than 5.2 t ha^{-1} across the 10-year period. The significant interaction between gliricidia pruning applications and inorganic N fertilizer confirms there is a positive synergy between pruning and chemical fertilizer. Several long-term experiments in Africa, reviewed by Bekunda *et al.* (1997), provided indirect evidence in support of the combined organic and mineral fertilizer approach to replenish N and C capital. However, the fact that the application of half N rate only increased maize yield by 7% over the quarter N rate, suggests that extra mineral fertilizer N application beyond 25–30% would be superfluous in the gliricidia/maize system. Makumba *et al.* (2005) indicated that combinations of prunings and N mineral fertilizer increased N uptake and maize yield over prunings alone but that the effect was only additive rather than interactive. The low crop response to mineral fertilizer in the gliricidia/maize intercropping, especially in the last two years of the trial, points to the fact that the addition of extra inorganic N might be less important to the crop, when the soil organic N capital has been built-up through sufficient N supplied from the tree prunings.

Although phosphorus fertilizer did not seem to be important at the site as maize responses to P were not significant until after six years of continuous cropping. Fertilizer research in a similar drier region of sub-Saharan Africa indicates that maize responded more to N application than to P (Mayong *et al.*, 2001). However, the significant effect of the residual P fertilizer treatments on maize yield in 1998/99 ($p = 0.011$) and 1999/00 ($p = 0.001$) during the entire period of trial, despite discontinuation of P fertilizer application from 1993/94, is ascribed to differential annual P exports from the soil during harvests without inputs. The significant interaction between P rates and the production system was due to the different response of residual P in sole maize and gliricidia/maize intercropping. The picture that emerged from the residual effect of P on maize yield is complex: P rates increased maize yield in the sole maize but reduced the yield in gliricidia/maize intercropping (Table 4).

This suggests that supplementary P application to the trials could be helpful in the long-term.

The contrasting trend, in the effect of residual P, between the sole and gliricidia/ maize intercropping systems can be explained by: (i) the fact that greater amounts of P might have been lost in the gliricidia/maize intercropped plots than sole maize through greater annual harvests, as the fertilizers had enhanced growth and yield on an annual basis. This may have led to N and P imbalances. (ii) The trend may also indicate that a gliricidia/maize system can enhance P availability compared to sole maize, with little or no fertilizer inputs. The potential of legumes to enhance biologically availability of soil P is often related to their ability to reduce soil losses, and thus increase retention of nutrients in plant-available forms (Snapp, 1998).

Further studies are needed to explain the P-dynamics (P adsorption and availability) under the sole maize and gliricidia/maize systems.

CONCLUSIONS

The potential to improve the soil fertility capital, especially N, using the gliricidia/ maize system has been demonstrated in this study. The trial confirmed that once established, the gliricidia trees can be continuously pruned, and the pruning biomass applied as green manure annually for more than a decade, without any significant decline in biomass production, except following a season of prolonged drought.

The results from the 10-year trial of gliricidia/maize intercropping shows that high levels of maize yield can be achieved, with little or no application of commercial N fertilizer. There was evidence that intercropping maize with gliricidia involving the application of tree prunings to the maize restored the topsoil nutrient capital compared to the traditional practice without soil amendment. Supplemental applications of small quantities of fertilizer can increase the maize yield over gliricidia prunings alone, but maize response to additional N fertilizer will be low after the soil N capital has been built-up by N-rich prunings gliricidia. Therefore, the supplemental N will be more important in the early years of tree establishment, and subsequent applications should be kept at a minimum (e.g. 25–30% of recommended N rate will be worthwhile). There is also some evidence that P may be important for optimum maize production after long years of annual cropping.

It is worthwhile to undertake on-farm research to understand better the performance of gliricidia/maize system under farmer-managed conditions. Researchers should focus on identifying opportunities and designing a range of options to meet increasing labour demands through efficient timing of pruning, enhanced high-yielding potential of crops in low rainfall areas, and improved soil management practices that combine organic and inorganic nutrient sources and enhanced high-quality residues.

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