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# Impact of *Gliricidia sepium* intercropping on soil organic matter fractions in a maize-based cropping system

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### ABSTRACT

The gliricidia (*Gliricidia sepium*)/maize intercropping system holds promise for increasing productivity in maize-based cropping systems on depleted soils in Southern Africa. The effect of the intercrop on soil properties was investigated to better understand soil processes underlying maize yield response, soil nutrient recaptalization and soil carbon sequestration. Soil organic matter (SOM) fractions, particulate organic matter (POM), POM-carbon, POM-nitrogen, soil nutrient status and underlying soil characteristics were quantified on the 14th year of a gliricidia/maize intercrop established in 1991 on a Ferric Lixisol in southern Malawi. A factorial design compared the intercrop and a sole maize crop at three rates of added inorganic nitrogen (N) and phosphorus (P). Gliricidia leaf biomass was incorporated into the maize three times per year. Soil was sampled to a 20 cm depth, post-harvest to analyze biophysical and chemical characteristics of soil organic matter, POM, POM-C and POM-N, as well as inorganic N, available P, exchangeable K<sup>+</sup> and particle size distribution. The gliricidia/maize intercrop had a significant and positive effect on SOM, POM, and SOM fractions: SOM was 12% higher, POM 40%, POM-C 62%, and POM-N 86% higher in the gliricidia intercrop compared to sole maize, indicating nitrogen enrichment of POM. Nitrogen fertilizer was associated with modest increases in POM, 15% in gliricidia and 27% in sole maize. The impacts of these changes were directed mostly at increasing maize yields and increasing storage of soil nutrients over the short term, while decreasing the proportion of organic matter stored over the long term. Both the gliricidia/maize intercrop and increasing soil clay content were associated with significantly increased soil CEC. The gliricidia intercrop maintained CEC in coarse-textured soils over a 14-year time span, indicating a role for legume trees in intensified cropping of coarse-textured soils.

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### 1. Introduction

Soil organic matter is often the single largest source of nutrients for smallholder farming systems in Southern Africa, as well as storing available moisture, providing energy for soil fauna, and increasing soil aggregate stability (Wander, 2004). Because maize is the staple crop in Malawi, as in the much of southern Africa, food security in the region depends to a large degree on the performance of this crop. How to build soil organic matter capital and maintain soil fertility is a central issue in increasing agricultural productivity in Africa. Therefore it is crucial to examine soil organic matter dynamics to understand soil fertility issues in southern Africa.

The use of nitrogen fertilizers to improve maize production in the landlocked African countries is constrained by the high fertilizer costs, shipping costs and difficult logistics in terms of transport and timeliness (Palm et al., 2001). Price ratios of nitrogen to maize

in Malawi may be double those in Mozambique, which borders Malawi on the east (Mafongoya et al., 2006). Compounding this problem is the low level of fertility and depleted soil organic matter on smallholder farms due to continuous cultivation without adequate soil fertility replenishment.

Several leguminous trees and shrubs such as *Sesbania sesban* (L.) Merr. (*sesbania*), *Tephrosia vogelii* Hook. f. (*tephrosia*), *Gliricidia sepium* (Jacq.) Walp. (*gliricidia*), and *Leucaena leucocephala* (Lam.) (*leucaena*) have been introduced in southern Africa as renewable soil nitrogen (N) and soil organic matter (SOM) sources in maize-based cropping systems (Kwesiga et al., 2003). *Sesbania*, *tephrosia*, and *gliricidia* have been investigated in Malawi and Zambia for soil fertility replenishment (Mafongoya et al., 2006). *Gliricidia* is a promising long-term intercrop in Malawi. It is one of a group of species which tolerates frequent removal of coppice for use as green manure or mulch of crops (Kwesiga et al., 2003). It produces a very high quality green manure, and may contain as much as 4% nitrogen (N) in its leaves (Makumba, 2003).

Maize yield gains with *gliricidia*/maize intercropping have been shown to double in a trial established in 1991 on a Ferric Lixisol

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at Makoka research station in southern Malawi (Akinnifesi et al., 2007). The long-term nature of this trial has allowed researchers to evaluate long-term mining of soil nutrients in the treatments with no added mineral fertilizers or intercrop, and the capacity to build stocks of soil nutrients in the fertilizer and gliricidia treatment combinations. The factorial design has allowed investigation of interactions between mineral fertilizers and gliricidia on soil organic matter and soil fertility, which is important in developing sustainable food production systems in Africa (Sanchez et al., 2007).

Release of nutrients such as nitrogen from soil organic matter depends on mineralization of its biologically active (or labile) fractions (Barrios et al., 1996). Makumba (2003) reported that the maize yield increase associated with N additions from gliricidia and fertilizer in this trial was not associated with total soil organic matter. Labile soil organic matter can be assessed effectively by characterizing the particulate organic matter (POM) fraction. The POM fraction of SOM is typically low-density (usually  $1.4\text{--}2.2\text{ g cm}^{-3}$ ) and/or coarse ( $53\text{--}250\text{ }\mu\text{m}$ ), and commonly derived from biomass additions from the previous year (Wander, 2004). The SOM fractions associated with the silt and clay-sized soil fraction have been characterized as recalcitrant to mineralization processes over the course of decades to centuries. Thus the plant-available nutrients in soil are expected to be mineralized largely from the POM, the sand-sized organic matter fraction. Biochemical composition of plant material also affects rates of decomposition and nutrient availability. Though carbon to nitrogen (C/N) ratios of less than 25 are often assumed to support net nitrogen mineralization in decomposing plant material, some researchers have noted slower rates of mineralization associated with C/N ratios greater than 15 (Springob and Kirchman, 2003).

Soil texture is an important variable in soil fertility studies since it determines in large part the extent to which soil organic matter fractions are accessible to decomposition in soils (Giller et al., 1997). Since plant-available nitrogen is often found in the ammonium form during the dry season in soils with a pronounced dry season, CEC is also a significant factor in soil N fertility. As CEC is largely resident in clay minerals and soil organic matter, a thorough description of soil fertility in maize-based agriculture in areas with a pronounced dry season should include linkages of soil texture and CEC with organic matter and particulate organic matter.

The objectives of this study were (1) to determine whether the gliricidia intercrop significantly increased SOM, POM, and inorganic N, (2) to verify whether the effect of gliricidia interacted with the effect of inorganic N and P fertilizer applications on SOM, POM, and inorganic N, and (3) to determine whether the gliricidia intercrop increased soil's ability to supply plant nutrients beyond those added as inorganic N and P, compared to its effect on more stable SOM in the silt + clay soil fraction.

## 2. Materials and methods

### 2.1. Site description and management

This trial was established in 1991 as a randomized complete block design with three replications to test the factorial combination of two cropping systems, three N fertilizer rates (0, 46, and  $92\text{ kg N ha}^{-1}$ ) and three P fertilizer rates (0, 20, and  $40\text{ kg P ha}^{-1}$ ) (Akinnifesi et al., 2007). The soil at the trial site is classified as a Ferric Lixisol (Ikerra et al., 1999), and is located at the Makoka Research Station (latitude  $15^{\circ}30'S$ , longitude  $35^{\circ}15'E$ ).

The study site is located in Southern Malawi, which lies in the southernmost portion of the eastern Rift Valley. Elevations range from less than 100 m above sea level (asl) in the southern Shire valley to more than 2000 m atop Mount Mulange. Zomba district

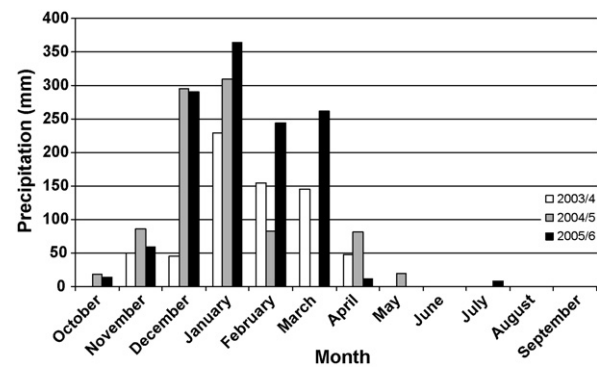


Fig. 1. Monthly precipitation, Makoka Agricultural Research Station, Zomba, Malawi, 2003–2006.

lies mostly between 300 and 1200 m (Benson et al., 2002). Rainfall is unimodal (Fig. 1), with the majority of rains falling between December and April. Rainfall in southern Malawi ranges from 600 to 1600 mm annually. Most of Zomba district receives 800–1200 mm of rainfall annually (Reynolds, 2000).

Soil tests prior to establishment of the trial (0–20 cm) showed a SOM level of  $15.2\text{ g kg}^{-1}$  and a pH of 5.9. Clay content of the soil ranged from 18 to 44%. The mean annual rainfall at the research station between 1991 and 2006 was 935 mm, and ranged from 417 mm in 1994 to 1516 mm in 1997. Monthly rainfall during the growing seasons of 2003–2006 ranged from 11.5 to 363.9 mm and varied widely between cropping seasons (Fig. 1). Nitrogen was applied annually, four weeks after planting. Phosphorus was applied annually as triple super phosphate, except in years 1993–2002, because no P yield effects were demonstrated in the initial years of the trial. Phosphorus applications were resumed in 2002 at the rates listed above (Akinnifesi et al., 2007). The N and P rates used in this trial corresponded to 0, 50, and 100% of the recommended rates (GOM, 2004). As most smallholders in Malawi apply less than the recommended rates of N and P, it is important to examine treatment effects within the range of those typically used.

### 2.2. Establishment and management of gliricidia

Plots measuring  $6.7\text{ m} \times 6.0\text{ m}$  were separated by iron sheets inserted to a 1 m depth to minimize root encroachment. The three replicate blocks were separated by a 1 m path. Planting ridges were established at 75 cm spacing. Gliricidia was planted in alternate ridges (150 cm spacing) and with a 90 cm spacing within the ridge, which results in a gliricidia population of 7400 trees  $\text{ha}^{-1}$ . The trees were pruned to a height of 30 cm in October, December, and February of each year, and the leaves and tender twigs incorporated into the maize ridges, which were rebuilt in October of each year. Biomass was recycled within each treatment plot each year. After the onset of rains both sole maize and gliricidia/maize plots were planted with maize hybrid NSCM 41. The onset of sufficient rains occurred in November in 2005. The maize was seeded at 30 cm intervals in all of the ridges, resulting in a plant population of 44,400 plants  $\text{ha}^{-1}$ . The maize grain was harvested after drying down in the field, usually in May. Sub-samples were taken for moisture determination, and yield and biomass data were expressed as kilograms per hectare on a dry weight basis. A more detailed description of site management may be found in Makumba et al. (2006) and Akinnifesi et al. (2007).

### 2.3. Gliricidia and maize biomass inputs

The gliricidia foliage and maize biomass produced in each treatment plot were incorporated in the same plot. Data on gliricidia

**Table 1**  
Gliricidia and maize biomass additions (dry weight) in selected trials in Malawi, Togo, and Nigeria.

Site	Period (average annum)	Plant type	Treatment <sup>a</sup>	Biomass added (t ha <sup>-1</sup> year <sup>-1</sup> )	Reference
Makoka, Malawi	1993–2003	Gliricidia prunings	Gliricidia intercrop	4.6	Makumba et al. (2006)
	1993–2003	Maize stover	SM + 0	1.7	Makumba et al. (2006)
	1993–2003	Maize stover	SM + 48	5.4	Makumba et al. (2006)
	1993–2003	Maize stover	GM + 48	8.2	Makumba et al. (2006)
Glidji, Togo	1995–1998	Gliricidia prunings	Gliricidia intercrop	2.5	Vanlauwe et al. (2005)
Amoutchou, Togo	1995–1998	Gliricidia prunings	Gliricidia intercrop	5.5	Vanlauwe et al. (2005)
Sarakawa, Togo	1995–1998	Gliricidia prunings	Gliricidia intercrop	4.3	Vanlauwe et al. (2005)
Ibadan, Nigeria	1982–1992	Gliricidia prunings	Gliricidia intercrop	5.7	Kang et al. (1999)
	1982–1992	Maize stover	SM + 0	2.6	Kang et al. (1999)

<sup>a</sup> SM + 0 = sole maize + 0 kg ha<sup>-1</sup> N, SM + 48 = sole maize + 48 kg ha<sup>-1</sup> N, GM + 48 = gliricidia/maize + 48 kg ha<sup>-1</sup> N.

biomass (Table 1) and maize grain yield were reported by Makumba et al. (2007). The average quantity of gliricidia prunings incorporated from 1993 to 2003, given in Makumba et al. (2007), was 4.6 t ha<sup>-1</sup>. This was within the range (2.5–5.7 t ha<sup>-1</sup>) found in the studies by Vanlauwe et al. (2005) and Kang et al. (1999). Maize biomass data were not available, and were calculated from the grain yield data using a harvest index of 0.38 (Tittonell et al., 2005). Data from Vanlauwe et al. (2005), and Kang et al. (1999) are also provided in Table 1 as a comparison from gliricidia/maize intercrop studies in West Africa. The 1.7 t ha<sup>-1</sup> biomass yield for unfertilized sole maize was less than the value reported by Kang et al. (1999), however the rainfall reported for the location in Malawi was correspondingly lower than for the location in Nigeria. The quantity of maize stover calculated for the gliricidia/maize plus 48 kg ha<sup>-1</sup> N treatment was 8.2 t ha<sup>-1</sup> across 1993–2003.

#### 2.4. Soil sampling and analysis

Soil samples (0–20 cm) were taken in July, 2006, composited from six samples per plot using a straight-walled soil probe with 2 cm diameter. The samples were mixed, air-dried, passed through a 2 mm sieve, and stored. A sub-sample of the soil was dried overnight at 40 °C, crushed with an Agvise flail-type grinder and analyzed for organic matter, pH, available phosphorus (P), exchangeable potassium (K), magnesium (Mg), and calcium (Ca) (A & L Great Lakes Laboratories, Fort Wayne, IN). Organic matter was determined by loss on ignition at 360 °C and the data correlated with and reported as Walkley–Black titration. Soil pH was determined in a 1:1 soil to water slurry. Available phosphorus and exchangeable cations were extracted according to Mehlich III (Mehlich, 1984), and analyzed by inductively-coupled plasma spectrometry (ICP) in which the sample was excited in an argon plasma and the elements of interest were detected by a mass spectrometer. The P data were correlated to and reported as Bray P-1 (Bray and Kurtz, 1945). The data for exchangeable cations were correlated to and reported as a 1 N ammonium acetate extraction (McIntosh, 1969). Percent base saturation and CEC were calculated from the results for exchangeable cations.

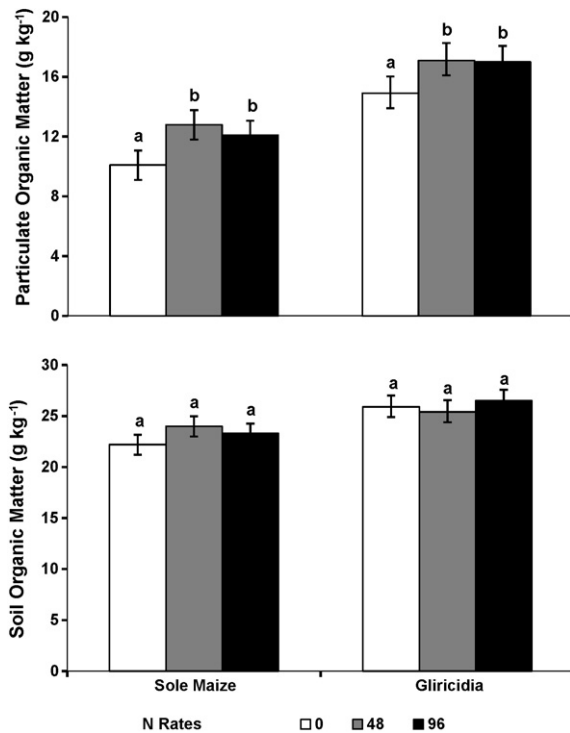
Particle size distribution and particulate organic matter were determined on sub-samples of soil that had not been ground. Particle size distribution of the samples was determined by gravimetric sedimentation after removal of the organic fraction with 30% H<sub>2</sub>O<sub>2</sub> (Gee and Bauder, 1986). SOM fractions and soil nutrients have not been corrected for differing bulk density between treatments, and so have not been transformed to an area basis.

Inorganic N was determined from duplicate 10 g samples of non-incubated soil extracted with 2 N KCl. The extracts were analyzed with a Westco Smartchem analyzer for nitrogen from NH<sub>4</sub><sup>+</sup>, NO<sub>2</sub><sup>-</sup>, and NO<sub>3</sub><sup>-</sup>. Nitrate and nitrite were determined by hydrazine reduction and ammonium was determined with the Berthelot reaction (WestcoScientific, 2007).

POM was separated from the soil samples by size and density fractionation (Cambardella and Elliott, 1993; Wander et al., 1994) and the values presented as a fraction of total soil weight. Quadruplicate 25 g samples of soil were dispersed in 125 mL 0.5 g L<sup>-1</sup> sodium hexametaphosphate for 17 h on a reciprocating shaker at 180 rpm. The dispersed fraction was passed through a 53 μm sieve. The fraction remaining on the screen, containing both sand and POM, was well washed with deionized water, and dried 48 h at 60 °C. The dry sample was carefully transferred into 50 mL plastic conical centrifuge tubes, and 35 mL of sodium polytungstate of density 1.85 Mg/m<sup>3</sup> added. The tubes were capped, and inverted slowly several times to ensure that the suspended material was completely wetted and mixed with the sodium polytungstate. The tubes were then placed in a vertical position and centrifuged at 1000 rpm for 30 min. The POM plus sodium polytungstate was decanted onto a 20 μm mesh nylon filter connected to a vacuum filtration system. The POM remaining on the mesh was rinsed thoroughly with deionized water to remove traces of sodium polytungstate, and dried overnight at 60 °C. Particulate organic matter (POM) was expressed as grams per kilogram of dry soil mass. Sodium polytungstate was recycled according to Six et al. (1999). The weight of POM was recorded for each sample and the quadruplicate samples were combined and ground for 2 min each in a Shatterbox 8515 mill (SPEX SamplePrep, Metuchen, NJ). Carbon and nitrogen were determined on the ground samples by dry combustion in a CHNS analyzer (Costech ECS 4010, Costech Analytical Technologies, Valencia, CA).

#### 2.5. Data analysis

The research design was a randomized complete block with gliricidia intercrop, N rates, and P rates as treatment factors. Analysis of variance was used to test for significant impacts of the three treatment factors on SOM, POM, POM-carbon and POM-nitrogen. The same test was conducted for the impact of the treatment factors on available soil N, Bray P1 phosphorus, exchangeable K<sup>+</sup>, and CEC. Sand and clay content were included in the type 3 analysis in SAS Proc Mixed as covariates (Littell et al., 2006). Where they had no significant impact, the models became simple 3-factor Anovas comparing the effects of added inorganic N, added inorganic P, and cropping system. This permitted textural covariates to be included in the models, and the significance of their impact on SOM fractions to be compared to the impacts of the planned treatments. Interactions of the treatment factors and covariates were also tested within the Anova. The effect of phosphorus rates was included in the analysis above, because it was a planned treatment factor. Because it had little effect on the response variables listed above, few results will be reported. Planned contrasts were carried out for treatments which had similar total N additions, but from inorganic and organic sources. Because variances of exchangeable K<sup>+</sup> were unequal among gliricidia and sole maize, this analysis was



**Fig. 2.** The effect of three fertilizer N rates across sole maize and gliricidia treatments on soil organic matter and particulate organic matter. Error bars represent standard error of treatment means. Columns with the same letter are not significantly different within cropping systems.

conducted using the restricted maximum likelihood method, and different variances specified for the two groups.

Because the soil sampling was done once in 2006, the soil organic matter fractions were a single set of values, though these values were influenced by the treatment and soil texture effects from 1991 to 2006.

### 3. Results

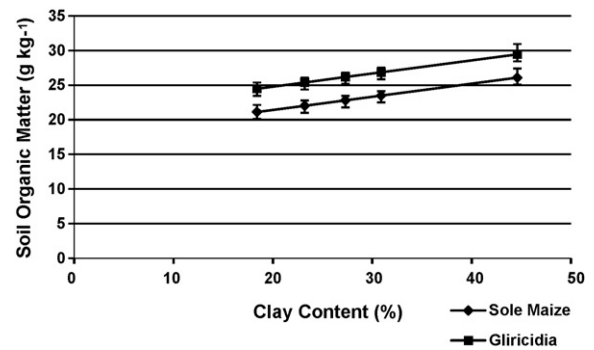
Use of the gliricidia intercrop resulted in significant increases in SOM, POM, POM-C, POM-N, inorganic N, and CEC, as well as a significant decrease in the carbon–nitrogen ratio of POM.

#### 3.1. Soil organic matter

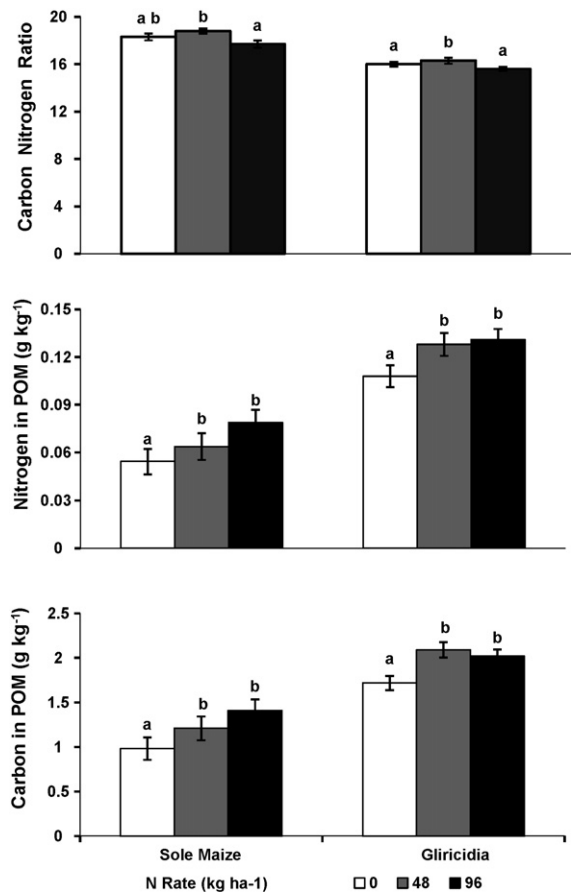
Soil organic matter ranged from 18 to 33 g kg<sup>-1</sup> of total soil mass across all gliricidia, N and P treatments. The gliricidia intercrop and soil clay content significantly increased SOM (Table 1, Fig. 2). The presence of gliricidia increased SOM by 3.4 g kg<sup>-1</sup> beyond the SOM maintained in the sole maize cropping system (Fig. 3) averaged across N and P treatments. The 14% increase in SOM in gliricidia treatments over non-gliricidia treatments was constant across the range of clay content (Fig. 3). The clay content of the soil ranged from 18 to 45%, the average base saturation was 67% and the average pH was 5.6.

#### 3.2. Particulate organic matter

Both the presence of gliricidia and fertilizer N significantly and positively influenced POM (Table 2). The presence of gliricidia increased POM by 37% averaged across N rates (Fig. 2). Fertilizer N added at 48 kg ha<sup>-1</sup> increased POM by 2.5 g kg<sup>-1</sup> over no N additions, averaged across cropping systems.



**Fig. 3.** The effect of clay content and gliricidia on soil organic matter across fertilizer treatments, estimated at endpoints and quartiles of clay content. Error bars represent standard error of treatment means.



**Fig. 4.** The effect of three fertilizer N rates across sole maize and gliricidia treatments on carbon, nitrogen, and C/N ratio in particulate organic matter. Error bars represent standard error of treatment means. Columns with the same letter are not significantly different within cropping systems.

Particulate organic matter made up 50% of SOM in sole maize, averaged across nitrogen treatments, while it reached 63% in the gliricidia cropping system (Fig. 2). The percentage of SOM in the POM fraction was increased 7.5% and by 7.7% by the two added fertilizer treatments, in the sole maize and gliricidia cropping systems, respectively. Thus, POM, the sand-sized fraction of SOM, was greatest in the gliricidia cropping system, while the silt + clay fraction of SOM was greatest in the unfertilized sole maize treatment.

Both gliricidia and fertilizer N significantly increased (Table 2) POM-C and POM-N. Carbon and nitrogen in POM were expressed as mg per kg dry soil, and as a C/N ratio (Fig. 4). The presence of

**Table 2**

Significance of the gliricidia intercrop, N rate, P rate, clay content and sand content on soil organic matter and particulate organic matter of whole soil, on carbon and nitrogen in particulate organic matter, carbon–nitrogen ratio of particulate organic matter, available inorganic nitrogen in soil, and soil CEC.

	SOM	POM	POM-C	POM-N	P-C/N	Inorg. N	CEC
Statistical significance				(Pr > F)			
Cropping system	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	0.0054	0.0017
N	NS	0.0034	0.0026	<0.0001	0.0013	<0.0001	NS
P	NS	NS	NS	NS	0.0399	0.0334	NS
Clay	0.0161	NS	NS	NS	NS	NS	0.0091
N × P	NS	0.0118	NS	NS	NS	NS	NS
Cropping system × sand	NS	NS	NS	NS	NS	0.0232	NS
P × sand	NS	NS	NS	NS	NS	0.0416	NS
Cropping system × clay	NS	NS	NS	NS	NS	NS	0.0049
Planned contrast: (intercrop + N = 0) versus (sole maize + N = 48 kg ha <sup>-1</sup> )			<0.0001	<0.0001			

NS: non-significant (Pr > F) > 0.05.

SOM = soil organic matter, POM = particulate organic matter, POM-C = carbon in POM, POM-N = nitrogen in POM, P-C/N = carbon–nitrogen ratio of POM, Inorg. N = inorganic N, CEC = cation-exchange capacity.

gliricidia increased POM-C by 62% over the sole maize and POM-N by 86%. With 48 kg ha<sup>-1</sup> N fertilizer addition, POM-C was increased 72%, with the intercrop. At the same rate of fertilizer N addition, POM-N increased by 100% (Fig. 4).

POM-C and POM-N values with similar levels of inorganic N + organic N were also contrasted. The POM-C value of the treatment combination gliricidia + 0 added N was 42% greater than sole maize + 48 kg ha<sup>-1</sup> added N ( $p = 0.0001$ ). The POM-N value for the same contrast is associated with a 68% increase in ( $p = <0.0001$ ). Thus, the addition of N through the gliricidia green manure results in enrichment of POM-N, relative to the addition of N through fertilizer.

Nitrogen enrichment of POM was also reflected in the decreased C/N ratios associated with the intercrop. The ratio of C/N in POM varied from 14.6 to 19.6 (Fig. 4) across treatments. The gliricidia, N and P treatments resulted in significant decreases in the C/N ratio of POM (Table 2). The presence of gliricidia was associated with a 14% decrease in C/N ratio compared to sole maize, averaged across N and P treatments (Fig. 4). The 48 and 96 kg ha<sup>-1</sup> rates of N fertilizer were associated with C/N ratios of 17.6 and 16.7 compared to 16.8 for no N fertilizer, averaged across cropping and P treatments.

### 3.3. Macronutrients and CEC

The effect of gliricidia, fertilizer N, and fertilizer P on inorganic N values (NH<sub>4</sub><sup>+</sup> plus NO<sub>2</sub><sup>-</sup> plus NO<sub>3</sub><sup>-</sup>) (Table 3) was positive. Inorganic nitrogen values were expressed as mg N per kg dry soil. Eighty-seven percent of inorganic N was in ammonium form. This ratio was relatively uniform across the three N treatments. Gliricidia increased inorganic N from 7.93 g kg<sup>-1</sup> in sole maize to 12.8 in the intercrop. The effect of high P addition on inorganic N was negative.

Soil phosphorus values were increased by increasing P additions and decreased by the gliricidia intercrop (Table 3). Decreasing soil K values were associated with increasing fertilizer N additions in the sole maize system (Table 3), while the opposite trend was observed in the intercrop. Soils in the gliricidia cropping system maintained CEC between 8.5 and 9 cmol kg<sup>-1</sup> across the range (18–44%) of clay content (Fig. 5), while CEC varied significantly with clay content in the sole maize treatments. Cropping system ( $p = 0.0017$ ), clay content ( $p = 0.0091$ ), and their interaction ( $p = 0.0049$ ) had a significant and positive effect on soil CEC.

## 4. Discussion

The presence of the gliricidia/maize intercrop markedly enhanced the quantity and quality of residues compared to sole maize. This led to moderate gains in soil organic matter and substantial gains in the labile soil C pools which supply crop nutrients,

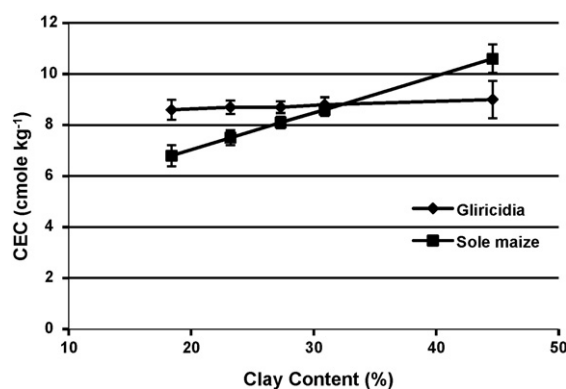


Fig. 5. The effect of gliricidia and clay content across fertilizer rates on cation-exchange capacity, estimated at the endpoints and quartile boundaries of clay content. Error bars represent standard error of treatment means.

as evidenced by particulate organic matter, soil inorganic nitrogen and particulate organic matter nitrogen.

The Lixisol at this long-term trial site is representative of many cereal-farming soils in Africa. Although the base saturation of Lixisols is comparatively high, the CEC and absolute level of plant nutrients is low, which makes recurrent inputs of plant nutrients a pre-condition for continuous cultivation (FAO, 1999). Given the limited natural fertility of these soils, the gliricidia/maize intercrop appears to play an important role in replenishing labile organic matter pools. However, it is important to examine the implications of this impact on food production, soil recapitalization, and carbon sequestration issues important in the region.

After 14 years in the contrasting cropping systems, yields were roughly doubled in the gliricidia treatments (Makumba et al., 2006), compared to the sole maize treatments. However, yield was not correlated with SOM. Particulate organic matter studies were employed to resolve this apparent contradiction in effects on SOM, increased soil N, and yields. Also, though biomass inputs in the gliricidia/maize intercrop with lower rate of N addition averaged almost five times those for the sole maize plots with no N, increases in SOM were modest. Thus, much of the benefit from increased biomass in the intercrop appeared to be diverted into increases in maize yield. This was the major system benefit derived from the gliricidia intercrop.

Soil organic matter values of the three treatments, however, were 50% higher than those when the trial was established demonstrating moderate potential for soil nutrient recapitalization and carbon sequestration. Since bulk density was not measured, quantities of the two carbon fractions could not be calculated at the hectare level. However the combination of a 14% increase in SOM,

**Table 3**  
The effect of cropping system and added N or added P on concentration of plant nutrients in study soils.

	Inorg. N (mg kg <sup>-1</sup> )	Exch. K <sup>+</sup> (mg kg <sup>-1</sup> )	CEC (cmol kg <sup>-1</sup> )
Sole maize			
N = 0	6.2 (3.1) <sup>*</sup>	166 (39.8)	7.75 (0.99)
N = 48	6.6 (3.1)	132 (40.1)	8.82 (0.99)
N = 96	11.0 (2.1)	81.0 (24.9)	8.22 (0.65)
Gliricidia/maize			
N = 0	11.1 (2.3)	96.4 (27.5)	8.01 (0.71)
N = 48	11.5 (2.3)	130 (27.8)	9.08 (0.71)
N = 96	15.8 (1.2)	181 (12.6)	8.48 (0.36)
	Bray P (mg kg <sup>-1</sup> )		
Sole maize			
P = 0	40.4 (12.5)		
P = 20	68.6 (12.5)		
P = 40	87.3 (8.2)		
Gliricidia/maize			
P = 0	31.7 (9.1)		
P = 20	61.6 (9.0)		
P = 40	78.8 (4.7)		

Inorg. N = inorganic N, Exch. K<sup>+</sup> = exchangeable potassium, CEC = cation-exchange capacity, Bray P = available phosphorus with the Bray P1 extract.

<sup>\*</sup> Standard errors of treatment means are in parentheses following the concentrations.

plus the 13% increase in the proportion POM associated with the gliricidia intercrop indicates a preferential build-up of POM, the soil organic fraction relatively more available for decomposition and support of crop production, compared to sole maize. The effect of the intercrop on the proportion of POM was double the effect of fertilizer nitrogen, highlighting the importance of the intercrop in recapitalization of nutrient-mined agricultural landscapes and provision of an available nutrient supply for crops in case of shortfalls of fertilizer nitrogen.

The proportion of SOM in the silt + clay fraction could contribute toward ecosystem benefits in carbon sequestration, as increasing clay contents have been shown to protect soil organic matter from decomposition (Giller et al., 1997). Soil organic matter in the silt + clay fraction was slightly higher in the sole maize cropping system than in the gliricidia intercrop, and higher in unfertilized maize in both cropping systems. This was a minor change in SOM fractions, and as payments for ecosystem services are not yet common, it is also the one from which the smallholder cultivator cannot yet extract individual benefits.

Nutrient addition from organic and inorganic sources all built soil nutrient supplies in our study (Table 3). The gliricidia intercrop was markedly effective at replenishing the POM-N supply, with an 86% increase compared to sole maize, comparable to the effect of the 48 kg ha<sup>-1</sup> rate of fertilizer N (Fig. 4). Vanlauwe et al. (2000) found that N in the POM fraction was significantly related to N uptake by maize in coarse savannah soils. Makumba et al. (2006) associated this gliricidia/maize intercrop with maize yield increases equivalent to those from 50 kg ha<sup>-1</sup> of fertilizer N. Marriott and Wander (2006) have reported similar results in a comparison of organic and conventionally fertilized trials in the U.S. However, the comparatively higher price and logistical difficulties with fertilizer N in landlocked African countries argues for a greater emphasis on organic sources of N in this region.

Makumba et al. (2006) also demonstrated that annual N additions from gliricidia were associated with a lower yield efficiency than fertilizer N in grain production. The enrichment of POM-C and POM-N, however, demonstrates the potential of gliricidia-derived N to provide a hedge against the risk of fertilizer shortfalls in subsequent years.

The data reported here confirm the value of combined gliricidia and N fertilizers as inputs for maize production and soil recapital-

ization, since the combination of the two generated the greatest amount of POM and POM-N in this study. The subsidized fertilizer, however, must be purchased outside the country in a market in which increasing energy costs are expected to drive increasing fertilizer manufacture and transport costs. Nitrogen-fixing crops such as gliricidia may be an especially important source of soil fertility in this context.

Maize residues were mature with very low N concentration, whereas the gliricidia residues were incorporated at vegetative stages and were highly N-enriched (Akinnifesi et al., 2007). The leafy residues may have enabled faster decomposition, which is consistent with the modest SOM increases and increased N found in POM.

The high CO<sub>2</sub> evolution values in the Makumba et al. (2007) study may also be in part due to temporary water-logging from the metal sheets inserted in the soil to prevent root encroachment between plots. Thus soils with subsoil accumulations of clay, such as Lixisols, may have higher losses of N due to temporary saturation of the A horizons during heavy rainfall periods. Because clay content and depth of the A horizon differed across treatment plots, effects from temporary saturation would also have differed across plots, increasing variability in the SOM and POM values.

Particulate organic matter (POM) C/N ratios were decreased from 18.3 to 16 by the gliricidia cropping system. POM C/N ratios were also decreased by N and P additions, but the effect of the gliricidia was far greater than the effect of the N and P additions. This may have important impacts on early-season maize nutrition and yield. Maroko et al. (1998) found a similar effect with a sesbania fallow on both an alfisol and an oxisol, and the Makumba et al. (2007) data imply much higher decomposition rates in the gliricidia treatments. Though C/N ratios in this range are often assumed to result in N mineralization, some researchers have noted reduced rates of N mineralization above a ratio of 15 (Springob and Kirchman, 2003). Therefore, the 12.5% decrease in the C/N ratio of POM may well be biologically, as well as statistically significant.

The highly significant interaction of clay with gliricidia in CEC demonstrated the ability of gliricidia to maintain soil CEC through SOM additions in soils with low clay contents, which has been previously unreported in the literature reporting soil fertility effects of gliricidia. The ability of SOM to maintain CEC and soil fertility in

sandy soils is an important factor in maize-based cropping systems in coarse-textured soils. Oorts et al. (2000) evaluated the effect of several agroforestry species on soil organic matter fractions and the effect of these fractions on the cation-exchange capacity of the soil. They found that the organic inputs from the agroforestry species were associated with an increase in silt-sized particles with the highest charge density of the organic fractions, and noted the promise of these systems for increasing the CEC of weathered soils. Though the CEC increase reported in this study was small, it is operationally important because CEC serves as a conduit for the supply of nutrients for maize in a given year, and lessens the leaching of monovalent cations such as  $K^+$  and  $NH_4^+$  in coarse-textured Lixisols.

The gliricidia intercrop had positive effects on available N and P in the soil, and on CEC, although not on exchangeable  $K^+$ . Nitrogen fertilizer treatments were positively associated with all soil fertility indices in the intercrop, while the shorter term application of fertilizer P had a substantial effect only on soil available P. Akinnifesi et al. (2007) found that gliricidia and the first increment of N and P additions had a synergistic effect on grain yields. The decrease in soil potassium ( $K^+$ ) values associated with increasing N additions in the sole maize system may have been an export effect of higher yields similar to that observed with soil P. Soil  $K^+$  is rarely deficient in Malawian agricultural soils (Snapp, 1998). However, the decrease in exchangeable soil  $K^+$  under intensified maize production, seen in this study may signal a need for eventual use of potash fertilizer for maize production in Malawi.

## 5. Conclusions

This study indicates that the use of the gliricidia intercrop had proportionately greater positive effects on rebuilding of soil fertility capital than on carbon sequestration, though both results are modest compared to impacts on maize yields over the course of 14 years in a semi-arid tropical maize cropping system in southern Africa.

Particulate organic matter pools, which act as a reservoir of crop nutrients, were enhanced by the gliricidia/maize intercrop, which was also associated with a significant decrease in POM C/N ratio, potentially increasing N availability to crops. As production systems are intensified, N-fixing tree intercrops may play an important role in preventing or slowing soil degradation and in maintaining the supply of plant nutrients to maize in intensified cropping systems in the coarse soils typical in this region.

The effect of the intercrop did not interact with the effects of the fertilizer rates, but it did interact with the textural covariates affecting inorganic N and CEC. The maize/gliricidia intercrop maintained CEC in coarse-textured soils. The combination of increases in POM and CEC which both serve as a source and a temporary sink for plant nutrients in this maize-based cropping system supports the use of woody legumes in the intensification of cropping systems on coarse soils.

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