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Long-term effects of improved legume fallows on soil invertebrate macrofauna and maize yield in eastern Zambia

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Abstract

Though improved fallows have been widely promoted as low-input technologies suitable for soil fertility replenishment in smallholder agriculture in southern Africa, their interaction with soil invertebrates has not been studied. In the present study we compared the population of soil macrofauna in maize grown in gliricidia (*Gliricidia sepium*), leucaena (*Leucaena leucocephala*), *Leucaena diversifolia*, sesbania (*Sesbania sesban*) and acacia (*Acacia anguistissima*) and continuously cropped monoculture maize. The objectives of the study were to determine (1) the effect of the type and length of fallows on soil macrofauna communities and functional groups, and (2) the long-term effect of legume fallows on maize yield. The number of invertebrate orders per sampling unit was significantly influenced by the type of fallow but not by the length of fallow period. Maize grown in legume fallows had more numbers of invertebrate orders than monoculture maize. Among the soil invertebrate macrofauna, centipede and millipede populations were significantly influenced by fallow type. The density of earthworms varied with both the type and length of fallow practice. Earthworm populations under maize grown in gliricidia fallows were significantly higher than those under fully fertilized monoculture maize. The population densities of other invertebrate orders and functional groups did not significantly differ between maize grown continuously in monoculture and in legume fallows. The highest maize grain yield (3.0–6.0 t ha^{-1}) was recorded in fully fertilized monoculture. Maize grown in gliricidia and leucaena fallows consistently gave 2.0–4.0 t ha^{-1} throughout the study period, while maize grown without fertilizer yielded less than 2 t ha^{-1}. These legumes produced 0.4–2.9 t ha^{-1} of re-sprout biomass annually, which released nutrients contributing to higher maize yields over a long period of time. It is concluded that these legume fallows can improve maize yields in addition to their positive impact on the diversity and functions of soil invertebrates.

Keywords: Agroforestry; Legume fallows; Maize; Macrofauna

1. Introduction

Soil invertebrates are responsible for maintenance of soil physical properties, short term recycling of nutrients, long-term protection of nutrients and organic matter in soil bio-structures. However, the role of soil fauna has been largely ignored by traditional and conventional agriculturists due to limited knowledge on their impact on crop yields in Africa (ICIPE, 1997). Land use practices have strong impacts on soil invertebrate communities and their activities (Lavelle et al., 2003). Theoretical and empirical (Tscharntke and Kruess, 1999; Lavelle et al., 2003) analyses give support to the hypothesis that increased anthropogenic disturbance will affect biodiversity and ecosystem functions such as litter decomposition, nutrient cycling and the natural control of crop pests.

In the last 15 years, improved legume fallows have been widely promoted as low-input technologies suitable for soil fertility improvement and increasing the yields of maize, the staple crop, in smallholder agriculture in southern Africa (Sanchez, 2002). Most of the studies have concentrated on the effect of agroforestry practices on maize yield, which of course is the main concern of farmers. However, another major concern to growers, researchers and policy-makers is the long-term impact of these practices on agroforestry systems through maintaining of a favourable microclimate

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and avoidance of tillage and provision of diverse and abundant organic resources offer the greatest potential to manipulate composition of soil macrofauna. Adequate understanding of plant communities and management practices on soil invertebrates is very important in order to optimize their activity through appropriate design and management of agroforestry systems and other land use systems (Lavelle and Spain, 2001). Whereas soil invertebrates are the major determinants of soil processes and pest management is an integral part of crop production, the potential for manipulating the beneficial soil animals has rarely been considered in designing agroforestry practices in southern Africa. Little attention has also been paid to observing the long-term effects of the introduction of exotic tree species on soil biota.

Maintaining active soil invertebrate communities in soils would considerably improve sustainability of agroforestry practice through regulation of soil process at different scales of time and space. This could result from practices that would maintain plant cover with a diverse plant community in cultivated plots. Although such systems do exist as various forms of agroforestry in southern Africa, their interaction with soil invertebrates have not been investigated. In this study, we compared the population of soil macrofauna after 5, 7, and 12 years of planting maize in monoculture and in legume-improved fallows. The objectives of this study were:

- To determine the effect of the type and length of fallows on soil macrofauna communities and functional groups.
- To determine the long-term effect of legume fallows on maize yield.

2. Materials and methods

2.1. Study sites

The study was undertaken in three separate field experiments (experiments 1–3) established at Msekera Research Station (13°39′S, 32°34′E, altitude 1025 m) in Eastern Province of Zambia. The soils at Msekera were ferric luvisols (FAO classification) characterised by low organic carbon content and macronutrients. The climate of the study area is subtropical with three distinct seasons: the warm wet season (November to April), the cool winter (May to August) and the hot, dry season (September to October). The rainfall averages about 960 mm per year with approximately 85% of the rains falling during December to March. Fig. 1 shows the total annual rainfall received during 1992–2004. The maize growing season starts in November and lasts between 135 and 155 days. The soils at the site are Ustic Rhodustalfs (USDA classification) or Haplic Luvisols (FAO classification) with 61% sand, 11% silt, 28% clay and pH (1:2.5 soil/water suspension) of 5.3. Before the experiment the top 15 cm soil had 10.20 g kg^{-1} organic carbon, 0.70 g kg^{-1} total inorganic nitrogen, 2.02 mg kg^{-1} total phosphorus, 3.00 c mol kg^{-1} calcium, 1.73 c mol kg^{-1} total magnesium, 1.47 c mol kg^{-1} total potassium and 0.06 c mol kg^{-1} sodium (Barrios et al., 1998).

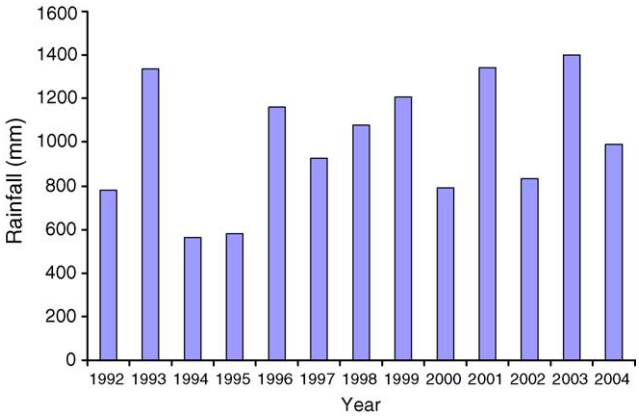

Fig. 1. Total annual rainfall (mm) received during 1992–2003 at Msekera Research Station.

2.2. Treatments and design

In experiment 1, the study focused on the legume fallows of gliricidia (*Gliricidia sepium*), leucaena (*Leucaena leucocephala*) and continuous monoculture maize grown with and without fertilizer. The experiment was established in December 1992 using bare-rooted seedlings in pure stands at a spacing of 1 m × 1 m (10,000 trees ha^{-1}). The fallows were grown for 3 years, and at the end of the fallow period (36 months) the trees were cut, and the leaf and twig biomass was incorporated into the soil with hand hoes. Since then, the re-sprouts were cut back and the biomass was incorporated into the soil three times every year. Maize (hybrid MM604) was planted on the ridges between the tree stumps every year. Continuous monoculture maize crops with and without fertiliser were planted for 13 consecutive years. Sileshi et al. (2005) have described the management of these experiments in detail.

Experiment 2 involved legume fallows of gliricidia, leucaena and continuous monoculture maize grown with and without fertilizer. The experiment was established in 1997 at Msekera Research Station. Bare-rooted seedlings of the legumes were planted in the field in pure stands at a spacing of 1 m × 1 m and the fallows were grown for 3 years. At the end of the fallows, the trees were cut, and the leaf and twigs were incorporated into the soil with hand hoes. Since then, the re-sprouts were cut and the biomass was incorporated into the soil three times every year. Maize hybrid MM604 was planted without fertilizer on the ridges between the tree stumps for three consecutive years. Monoculture maize crops with and without fertiliser were planted for seven consecutive years.

Experiment 3 was planted at Msekera Research Station in December 1999. The treatments were pure sesbania

(*Sesbania sesban*), gliricidia, acacia (*Acacia anguistissima*), *L. diversifolia*, sesbania + gliricidia, sesbania + acacia, sesbania + *L. diversifolia*, monoculture maize with and without fertiliser. Sesbania is a non-coppicing species, and hence after fallow clearance it did not re-sprout. In the mixtures, two species were planted in alternate rows forming a 1:1 row arrangement. The spacing between rows and between plants was 1 m × 1 m (10,000 trees ha^{-1}). Maize hybrid MM 604 was planted on the ridges without fertiliser application in all treatments except the fully fertilised maize. Monoculture maize crops with and without fertiliser were planted for six consecutive years.

In all experiments the plot size was 10 m × 10 m. The treatments were arranged in randomised complete blocks design with four replicates in experiment 1 and three replicates in experiments 2 and 3. The fertilised maize received the recommended rate of 200 kg ha^{-1} compound fertiliser (N = 100 g kg^{-1}, P = 90 g kg^{-1}, and K = 80 g kg^{-1}) at planting and 200 kg ha^{-1} urea at 4 weeks after planting. The spacing within and between rows was 0.30 and 0.75 m, respectively, giving a maize density of about 44,444 plants ha^{-1}. Weeding was done manually, and all weeds were incorporated into the soil. Grain yield was obtained by harvesting all maize plants from a net plot of 49 m^{-2}. The maize was shelled, dried, weighed and grain yield per hectare was calculated at 13% moisture content for each replicate of each treatment. Maize residues (cobs and stalks) were then removed immediately after harvest from each plot as this was the normal farmers' practice.

2.3. Soil sampling and processing

For sampling soil macrofauna, the method described in Anderson and Ingram (1993) was used with a slight modification as suggested by Lavelle et al. (2003). Sampling was conducted in February after 2 months after planting the maize. This is the mid-rainy season. Macrofauna samples were collected from two agricultural practices; improved fallows and monoculture maize grown continuously with and without fertilizer. The improved fallow was stratified according to species, which differ in their quality of organic inputs (Mafongoya et al., 1998). Replicate soil monoliths were taken from each plot within 3–5 m of each other using a metallic monolith (25 cm × 25 cm and 25 cm depth) from all experiments. The number off monoliths taken from each plot was 3 in experiment 1, 2 and 4 in experiment 3. As tree mortality was high in replicate 3 of experiment 3, soil samples were collected only from replicates 1 and 2. The monolith was placed over a randomly selected spot and using a metallic mallet, it was driven into the soil to the ground level. The soil was then removed from the monolith, macrofauna were hand-sorted (Dangerfield, 1997) from each sample and counted. Here macrofauna is defined as an invertebrate group found within soil samples, which has more than 90% of its specimens visible to the naked eye (Lavelle et al., 2003).

To determine the nutrient content of the soil before planting the trees and maize, samples were taken from the top 20 cm in the centre of the net plot of each treatment from four replicates in experiment 1 and three replicates in experiments 2 and 3. Plant litter was gently removed from the soil surface, and soil was collected from each plot, air-dried and nutrient analyses performed as described by Barrios et al. (1998). Leaf samples were collected from the re-sprouts of trees at each pruning in 1996–2000 in experiment 1, freeze–dried and analysed for tissue nutrient content as per the procedures for chemical analysis (AOAC, 1984). Nutrient equivalent, i.e. the nitrogen (N), phosphorus (P) and potassium (K) contents of the re-sprout biomass added to the soil, was worked out based on the tissue N, P, and K concentrations and the annual re-sprout biomass.

2.4. Measurement of bulk density and infiltration

Soil bulk density was measurements at fallow termination (in November 1995) and after 9 years of growing maize in the fallows (November 2003) in experiment 1. Soil samples were taken from each treatment, oven-dried at 105 °C and bulk density was determined using standard methods (Blake and Hartge, 1986). Infiltration and cumulative water intake were measured in October 2003 in experiment 1 using the double ring infiltrometer (Bouwer, 1986). Measurements were made at three locations along the diagonal in the net area of each plot and readings were taken at 5, 10, 15, 20, 30, 45, 60, 90, 120, 150 and 180 min, and the results plotted.

2.5. Data analyses

The invertebrates collected were separated into higher taxa (family and order) as identification to genus or species level was not possible due to lack of taxonomic expertise, the large number of samples collected and difficulties involved in rearing immature stages to adults. The data was expressed as the mean number of orders per sampling unit (i.e. soil monolith) as an indication of richness in invertebrate orders. The numbers of individuals of each taxon per sampling unit were converted into individuals per square meter as an indication of abundance (Lavelle et al., 2003).

The statistical analysis was conducted in two steps. The first step (STEP1) compared the type of practice, i.e. fallows and monoculture maize. For this purpose, data from various tree species were pooled based on their nature as ''coppicing'', ''non-coppicing'' or ''mixed species'' fallows and compared with continuous monoculture maize. The second step (STEP2) involved comparison of fallow length of gliricidia and monoculture maize with and without fertilizer. Gliricidia was selected for this comparison because it was found in all the three experiments. The invertebrate density data were transformed into logarithms to satisfy the requirements of analysis of variance (ANOVA). The generalised linear model (PROC GLM) of the SAS

system (SAS Institute, 2003) was used for analysis to accommodate unbalanced and missing data. Wherever comparison of two populations was necessary, two-sample *t*-test (assuming unequal variance) was conducted. The trends in maize yield with time in experiments 1 and 2 were examined using linear regression.

A principle component analysis (PCA) was conducted using the PROC PRINCOMP of the SAS system (SAS Institute, 2003) to summarize the data on invertebrate abundance by treatment. Raw counts of the invertebrate groups from each sample across replicates were averaged to give a mean number for each treatment, and transformed into square roots for PCA analysis. All variables were then standardised to zero mean and unit variance before analysis.

3. Results

3.1. Effect of type and length of fallows on soil invertebrates

In STEP1 analysis the number of invertebrate orders per sampling unit (order richness) significantly differed among practices (Table 1) and treatments (Table 2) within practices in all experiments. According to Tukey's test, the number of invertebrate orders recorded under maize grown in coppicing fallows and unfertilized monoculture maize was higher than those under fully fertilized monoculture maize in experiments 1 and 2 (Table 1). There was no difference between maize grown in gliricidia and leucaena fallows in the number of invertebrate orders in both experiments (Table 2). In experiment 3, maize grown in mixed-species fallows had significantly larger number of soil invertebrate orders compared with monoculture maize grown with or without fertilizer (Table 1). Maize grown in mixture of *L. diversifolia* and sesbania had significantly larger numbers of invertebrate orders compared with pure fallows of *L. diversifolia*, sesbania and acacia (Table 2). In STEP2 analysis, the number of invertebrate orders per sample was significantly influenced by practice ($F_{2,72} = 25.0$; $P = 0.0001$) but not by the length of fallow period ($F_{2,72} = 2.6$; $P = 0.0800$). The number of orders under maize grown in gliricidia > unfertilized monoculture maize > fully fertilized monoculture maize.

In all experiments fallow practice influenced the populations of millipedes and centipedes (Tables 1 and 2). In experiments 1 and 2, maize grown in coppicing legume fallows had higher densities of centipedes and millipedes compared with monoculture maize. Earthworms and termites were not influence either by the type or the length of practice. There was also no difference in the population densities of other orders including ants, termites, Arachinida, Coleoptera and Lepidoptera among type of practice in experiments 1 and 2. In experiment 3 maize grown in a mixture of a non-coppicing and coppicing legumes had the highest density of centipedes, millipedes and Coleoptera, followed by maize grown in pure fallows of coppicing and non-coppicing legumes. Maize grown continuously in a fertilized monoculture had the lowest density of these invertebrates (Table 2). Populations of Arachinida and Lepidoptera were also higher in maize grown pure gliricidia fallows compared with maize grown in fertilized monoculture (data not presented).

In STEP2 analysis, fallow type significantly influenced the population densities of centipedes ($F_{2,72} = 5.8$; $P = 0.0048$) and millipedes ($F_{2,72} = 9.1$; $P = 0.0003$), while the length of fallow practice did not. The density of earthworms varied with both the type ($F_{2,72} = 3.9$;

Table 1
Effect of length and type of practices on order richness and abundance of selected soil macrofauna at Msekera, eastern Zambia

Length of practice	Type of practice (sample size)[a]	Number of orders	Centipedes	Millipedes	Coleoptera	Total fauna
Ten years (Expt 1)	Coppicing fallow (24)	3.7 a	8.7 a	16.7 ab	50.0	300.0
	Maize without fertilizer (12)	2.8 a	0 b	24.0 a	36.0	818.7
	Maize with fertilizer (12)	1.6 b	5.3 ab	0 b	29.3	222.7
	$F_{2, 40}$	14.2	3.5	4.6	0.8	2.9
	F probability	0.0001	0.041	0.012	0.441	0.069
Five years (Expt 2)	Coppicing fallow (18)	2.8 a	6.2 a	14.2 a	10.7	261.3
	Maize without fertilizer (9)	1.9 ab	0 b	0 b	10.7	122.7
	Maize with fertilizer (9)	1.2 b	0 b	0 b	12.4	65.8
	$F_{2, 29}$	7.6	5.2	9.3	0.5	3.6
	F probability	0.0023	0.012	0.0008	0.640	0.0392
Two years (Expt 3)	Mixed species fallow (23)	4.0 a	9.7 a	4.9	22.3 a	333.1 a
	Coppicing fallow (24)	2.9 ab	4.0 ab	9.3	18.7 ab	206 ab
	Non-coppicing fallow (8)	2.6 ab	8.0 a	8.0	14.0 ab	120.0 b
	Maize without fertilizer (8)	2.0 b	0 b	0	12.0 ab	128.0 b
	Maize with fertilizer (8)	1.8 b	0 b	0	2.0 b	98.0 b
	$F_{4, 60}$	5.2	0.4	2.4	3.1	2.9
	F probability	0.0012	0.015	0.058	0.0212	0.028

Means followed by the same letters in a column do not significantly differ at 5% level according to HSD.
[a] Values in parenthesis indicate the sample size used to derive the estimates of the variables.

Table 2
Order richness and abundance of selected soil macrofauna under maize grown in various tree species fallows and monoculture maize at Msekera

Length of practice	Treatment (sample size)[a]	Number of orders	Centipedes	Millipedes	Coleoptera	Total fauna
Ten years (Expt 1)	Leucaena (12)	3.8 a	10.7 a	26.7 a	64.0	265.3
	Gliricidia (12)	3.7 a	6.7 ab	6.7 ab	36.0	334.7
	Maize without fertilizer (12)	2.8 b	0 b	24.0 ab	36.0	818.7
	Maize with fertilizer (12)	1.6 b	5.3 ab	0 b	29.3	222.7
	$F_{3,\ 39}$	9.3	2.7	5.1	1.3	1.9
	F probability	0.0001	0.059	0.005	0.305	0.151
Five years (Expt 2)	Gliricidia (9)	3.1 a	7.1 a	12.4 ab	19.6	373.3 a
	Leucaena (9)	2.6 ab	5.3 a	16.0 a	1.8	149.3 ab
	Maize without fertilizer (9)	1.9 ab	0 b	0 b	10.7	122.7 ab
	Maize with fertilizer (9)	1.2 b	0 b	0 b	12.4	65.8 b
	$F_{3,\ 28}$	5.5	3.5	6.6	1.2	2.9
	F probability	0.0042	0.028	0.002	0.324	0.055
Two years (Expt 3)	*L. diversifolia* + Sesbania (8)	5.1 a	11.4	4.6	20.6 ab	90.7
	Pure Gliricidia (8)	3.6 ab	2.0	12.0	24.0 ab	184.0
	Gliricidia + Sesbania (8)	3.5 abc	10.0	4.0	28.0 a	422.0
	Acacia + Sesbania (8)	3.4 abc	8.0	6.0	18.0 ab	426.0
	Pure *L. diversifolia* (8)	2.8 bc	4.0	8.0	18.0 ab	230.0
	Pure Sesbania (8)	2.6 bc	8.0	8.0	14.0 ab	120.0
	Pure Acacia (8)	2.5 bc	6.0	8.0	14.0 ab	204.0
	Maize without fertilizer (8)	2.0 bc	0	0	12.0 ab	128.0
	Maize with fertilizer (8)	1.8 c	0	0	2.0 b	98.0
	$F_{8,\ 56}$	3.2	1.8	1.2	2.2	1.7
	F probability	0.0048	0.124	0.299	0.044	0.127

Means followed by the same letters in a column do not significantly differ at 5% level according to HSD.
[a] Values in parenthesis indicate the sample size used to derive the estimates of the variables.

$P = 0.0238$) and length ($F_{2,72} = 3.5$; $P = 0.0366$) of fallow practice. Earthworm populations under maize grown in gliricidia fallows were significantly higher than those under fully fertilized monoculture maize. There was no difference between unfertilized monoculture maize and maize grown in gliricidia. The populations of Coleoptera similarly differed with the type ($F_{2,72} = 3.7$; $P = 0.0307$) and length ($F_{2,72} = 3.3$; $P = 0.0434$) of fallow practice. The densities of earthworms and Coleoptera under maize grown in gliricidia fallow were higher than those under monoculture maize with and without fertilizer. Earthworm and Coleoptera populations were also higher under maize grown in gliricidia fallows established in 1992 compared with those established in 1997 or 1999.

In STEP2 analysis, the density of total macrofauna (all orders combined) significantly differed between fallow type ($F_{2,72} = 6.3$; $P = 0.0031$) and the length of practice ($F_{2,72} = 4.9$; $P = 0.0105$). Their density under gliricidia and monoculture maize without fertilizer was higher compared with monoculture maize with full fertilization. Total macrofauna density was highest under maize grown in gliricidia fallows established in 1992 compared with those established in 1997 or 1999.

The eigenvalues from the PCA indicated that about three principal components provide a good summary of the data. The first three principal components accounted for 70.6% of the total variance, while the remaining five components accounted for less than 30%. The first eigenvector had high positive loadings on Coleoptera (0.49), millipedes (0.47), earthworms (0.46) and centipedes (0.45), while the second had high positive loading on termites (0.67) and Lepidoptera (0.59). The third and fourth components had high positive loading on Arachnida (0.70) and ants (0.80), respectively. It was possible to identify trends on the plot of the first two components (Fig. 2). The plot of the first and second principal component (top) and the first and third components (bottom) strikingly separated treatments that had high overall abundance of soil invertebrates in the right-half of the plot from those with low overall abundance, which are in the left-half of the bottom figure. In the plot of the first and second principal components, fully fertilized monoculture maize in experiment 2 and 3 with overall low abundance of invertebrates is in the bottom left quarter of the plot. The other treatments that had high abundance of earthworms, Coleoptera, centipedes, millipedes and ants are in the bottom-right quarter of the plot. Treatments that had high Lepidoptera and termite abundance are in the top right quarter of the plot, while those with high abundance of Arachnida are in the top right quarter.

3.2. Effect of fallows on soil fertility and maize yield

Gliricidia and leucaena produced about 2 t ha^{-1} of re-sprout biomass annually. The re-sprout biomass produced by gliricidia and leucaena in experiments 1 and 2 are presented in Tables 3 and 4, respectively. Analysis of the nutrient content of the re-sprout biomass in 1996–2000 indicated about 3.19%

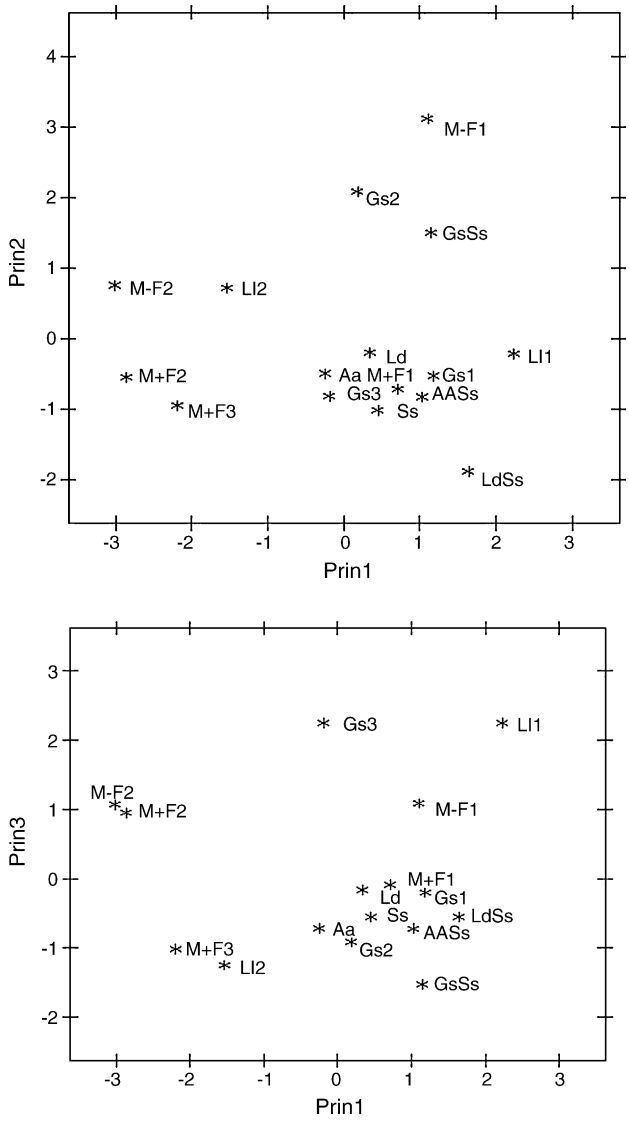

Fig. 2. Principal component plot of the various treatments in experiments 1, 2 and 3. Labels Aa (*Acacia anguistissima*), Gs (*Gliricidia sepium*), Ll (*Leucaena leucocephala*), Ld (*Leucaena diversifolia*), and M + F (fertilized monoculture maize), M–F (unfertilized monoculture maize), Ss (*Sesbania sesban*), identify the treatments within each experiment, and numbers following treatments represent experiment numbers.

(S.E. = 0.06) and 3.32% (S.E. = 0.07) N content in the re-sprout biomass of leucaena and gliricidia, respectively. The K content of the re-sprout biomass of leucaena and gliricidia was 1.48% (S.E. = 0.004) and 1.25% (S.E. = 0.02), respectively, while P content was about 0.18% (S.E. = 0.04) and 0.22% (S.E. = 0.03) of the re-sprout biomass of leucaena and gliricidia, respectively. The re-sprout biomass incorporated was estimated to add to the soil about 57.5 (S.E. = 2.59) and 61.4 (S.E. = 4.01) kg ha^{-1} N annually under leucaena and gliricidia, respectively. In experiment 1, the estimated annual input of P from the re-sprouts was about 3.5 (S.E. = 0.14) and 4.5 (S.E. = 0.30) kg ha^{-1} under leucaena and gliricidia, respectively, while the K input is estimated at 27.4 (S.E. = 1.43) and 23.2 (S.E. = 1.51) kg ha^{-1} under leucaena and gliricidia, respectively. In experiment 2, the re-sprout biomass was estimated to add to the soil about 44.3 (S.E. = 3.00) and 69.14 (S.E. = 12.72) kg ha^{-1} N annually under leucaena and gliricidia, respectively. The estimated annual input of P was about 2.5 (S.E. = 0.16) and 4.6 (S.E. = 0.85) kg ha^{-1} under leucaena and gliricidia, respectively, while the K input is estimated at 20.6 (S.E. = 1.37) and 25.9 (S.E. = 4.76) kg ha^{-1} under leucaena and gliricidia, respectively (Table 4).

The highest and lowest soil bulk density values were recorded under monoculture maize and gliricidia fallow, respectively, in experiment 1 (Table 5). Soil infiltration rate (Fig. 3) and total water intake (Fig. 4) were higher under gliricidia and leucaena compared with monoculture maize grown with or without fertilizer.

Figs. 5 and 6 show the long-term effect fallow practice on maize yield in experiments 1 and 2, respectively. In experiment 3, maize yield was available only for the

Table 3
Coppice biomass (t ha^{-1}), nutrient content (%) and nutrient equivalent (kg ha^{-1}) of the coppice biomass from gliricidia and leucaena incorporated into the soil during the study period in experiment 1 at Msekera, eastern Zambia

Year	Fallow species	Coppice biomass	Neutrient content			Neutrient equivalent		
			N	P	K	N	P	K
1996	Leucaena	0.42	3.44	0.18	1.40	14.56	0.76	5.93
	Gliricidia	0.35	3.32	0.22	1.25	11.69	0.78	4.38
1997	Leucaena	1.39	3.44	0.18	1.40	47.86	2.50	19.48
	Gliricidia	1.32	3.32	0.22	1.25	43.63	2.91	16.34
1998	Leucaena	2.30	3.38	0.20	1.31	67.55	3.94	25.34
	Gliricidia	2.07	3.75	0.34	1.42	77.70	7.09	29.41
1999	Leucaena	2.88	2.74	0.15	1.73	78.77	4.22	49.90
	Gliricidia	2.46	2.89	0.10	1.07	71.21	2.46	26.25
2000	Leucaena	2.90	3.19	0.18	1.48	84.26	4.67	39.15
	Gliricidia	3.27	3.32	0.22	1.25	119.04	7.24	44.59
2001	Leucaena	2.21	3.19	0.18	1.48	70.41	3.90	32.71
	Gliricidia	1.68	3.32	0.22	1.25	55.82	3.72	20.91
2002	Leucaena	2.61	3.19	0.18	1.48	83.12	4.61	38.62
	Gliricidia	3.74	3.32	0.22	1.25	124.16	8.28	46.51
2003	Leucaena	2.54	3.19	0.18	1.48	81.06	4.50	37.66
	Gliricidia	2.61	3.32	0.22	1.25	86.71	5.78	32.48
2004	Leucaena	2.21	3.19	0.18	1.48	70.31	3.90	32.67
	Gliricidia	1.44	3.32	0.22	1.25	47.84	3.19	17.92
Mean	Leucaena	2.09	3.19	0.18	1.48	57.45	3.46	27.37
	Gliricidia	2.14	3.32	0.22	1.25	61.40	4.46	23.21

Table 4
Coppice biomass (t ha^{-1}), nutrient content (%) and nutrient equivalent (kg ha^{-1}) of the coppice biomass from gliricidia and leucaena incorporated into the soil during the study period in experiment 2 at Msekera, eastern Zambia

Year	Fallow species	Coppice biomass	Neutrient equivalent		
			N	P	K
2001	Leucaena	0.71	22.51	1.25	10.46
	Gliricidia	0.61	20.34	1.36	7.62
2002	Leucaena	1.73	54.99	3.05	25.55
	Gliricidia	4.51	149.73	9.99	56.09
2003	Leucaena	1.99	63.32	3.51	29.42
	Gliricidia	2.39	79.28	5.29	29.70
2004	Leucaena	1.14	36.44	2.02	16.93
	Gliricidia	0.82	27.21	1.81	10.19
Mean	Leucaena	1.39	44.32	2.46	20.59
	Gliricidia	2.08	69.14	4.61	25.90

Table 5
Bulk density (g cm^{-3}) of soils under continuous monoculture maize and legume fallows in experiment 1 at Msekera, eastern Zambia

Treatment	November 1995	April 1998	November 2003
Maize without fertilizer	1.54	1.25	1.59
Maize with fertilizer	1.52	1.40	1.56
Leucaena	1.45	1.36	1.47
Gliricidia	1.42	1.30	1.44

2004 crop season, and treatments did not significantly differ ($F_{7,52} = 1.1$; $P = 0.388$). In all three experiments, grain yield was higher than 3 t ha^{-1} in fully fertilized monoculture maize. The poor farmers' practice of growing maize without fertilizer continuously yielded less than 2 t ha^{-1}. Yields from maize grown in gliricidia and leucaena fallows consistently gave yields between 2 and 4 t ha^{-1} over a

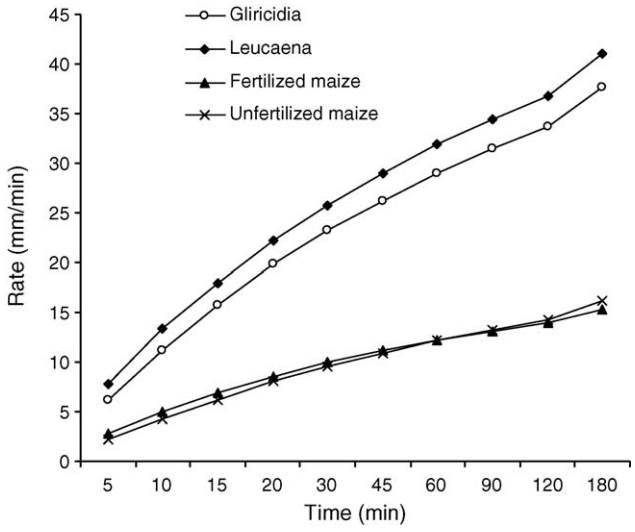

Fig. 3. Cumulative infiltration (mm/min) under legume-improved fallows and monoculture maize in experiment 1 at Msekera.

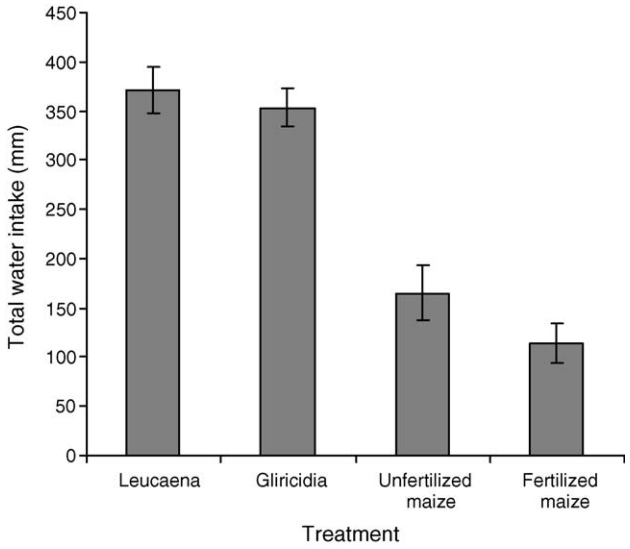

Fig. 4. Total water intake (mm) of soils under legume-improved fallows and monoculture maize in experiment 1 at Msekera. Vertical bars represent standard errors.

long period of time (Figs. 5 and 6). Linear regression indicated a significant decline in grain yield with time when maize was grown continuously without fertilizer ($r^2 = 0.49$; $P = 0.037$; $n = 9$), in gliricidia ($r^2 = 0.56$; $P = 0.021$; $n = 9$) and leucaena ($r^2 = 0.59$; $P = 0.016$; $n = 9$) fallows in experiment 1. However, grain yields from fully fertilize maize did not show any significant decline with time ($r^2 = 0.07$; $P = 0.494$; $n = 9$) in experiment 1. Linear regression also indicated significant decline in grain yield of maize grown continuously with fertilizer ($r^2 = 0.89$; $P = 0.005$; $n = 6$) and without fertilizer ($r^2 = 0.90$; $P = 0.004$; $n = 6$) in experiment 2.

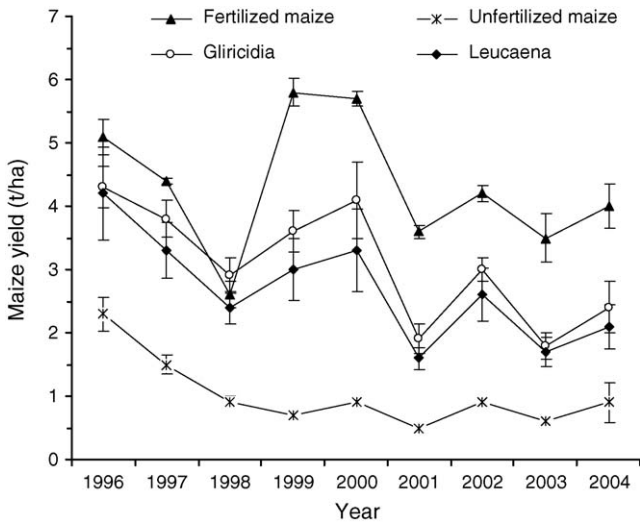

Fig. 5. Grain yield (t ha^{-1}) of maize grown in tree improved fallows and monoculture in experiment 1 at Msekera. Vertical bars represent standard errors.

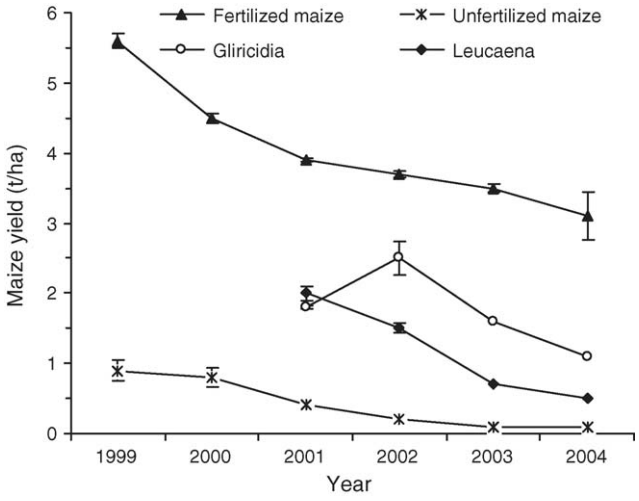

Fig. 6. Grain yield (t ha^{-1}) of maize grown in tree improved fallows and monoculture in experiment 2 at Msekera. Vertical bars represent standard errors.

4. Discussion

The study has shown that the type and length of fallows influence soil invertebrate communities differentially. The majority of the soil invertebrates were less abundant under monoculture maize, which represents agricultural intensification involving continuous cropping and the use of fertilizer. On the other hand, higher abundance of these invertebrates under maize grown in legume fallows is probably because this practice maintains a year round canopy and amelioration of the surface soil temperature and moisture by tree leaf biomass incorporated into the soil. Microclimate factors such as higher soil water content, lower soil temperature, and incident radiation probably favoured the soil invertebrates to thrive under maize grown in legume fallows compared with continuous monoculture maize.

The legume fallows produce large quantities of re-sprout biomass, which serves as a source of food for soil fauna and nutrients for maize crops. Legume species used in agroforestry will affect soil function as they act on the determinants of soil function including climate, edaphic factors and quality of organic matter (Lavelle et al., 2003). The contribution of tree species to stock of soil organic matter is largely controlled by biomass production and later on by litter decomposition mediated by flora and fauna. Recent studies and syntheses (Hole, 1981; Giller et al., 1997; Lavelle et al., 2003; Susilo et al., 2004) show that even where abundance is low, soil invertebrates are significant regulators of nutrient turnover both directly through their feeding activities and indirectly through their influence on soil structure and biological processes.

Soil invertebrates perform important functions related to the growth conditions of plants. For example, termites and earthworms increase soil porosity by tunnelling through the soil (Holt and Lepage, 2000; Lavelle et al., 2003; Susilo et al.,

2004). This is probably why bulk density was lower and infiltration rates were higher in maize grown in gliricidia and leucaena fallows, which had higher densities of this invertebrates than monoculture maize. These invertebrates ingest considerable amounts of soil and dead plant material, thereby contributing to the mixing of organic matter and mineral soils. This improves aggregate stability and increases the surface of organic material so that it is more readily colonized and decomposed by soil microflora (Lavelle et al., 2003). The accumulation of organic matter can increase the water retention capacity of a soil and influence the soil fauna population, in particular, earthworms. Predatory invertebrates including ants, centipedes, beetles, spiders and mites, which are common in the soil may also climb into plant parts and prey on herbivores (Susilo et al., 2004). These may play an important ecological role in reducing pest damage to maize in agroforestry systems as indicated by our earlier research conducted in the study area (Sileshi and Mafongoya, 2003; Sileshi et al., 2005).

Though there was a declining trend in maize yield over time, yields of this crop grown in legume fallows was higher. This is apparently due to improvement of soil physical, chemical and biological properties under the legume fallows. Earlier studies conducted in eastern Zambia (Barrios et al., 1998; Phiri et al., 2003; Chirwa et al., 2004) have shown that, legume fallows can increase soil fertility through maintenance of soil organic matter, biological N fixation, uptake of nutrients from below the reach of crop roots, increased water infiltration and storage, and improved soil physical properties. Tree fallows do not only improve crop productivity by replenishing soil fertility and increasing soil biota, but also by improving soil water status and reducing nutrient losses. Coppicing legumes can promote utilization of residual soil water after maize harvest and help recover soil N below the maize rooting depth during the long dry season. Soil moisture profiles monitored at the end of the dry season have indicated that gliricidia utilized about 40 mm more water, primarily from below 75 cm soil depth, more than the continuous cropped maize. High soil water content in the monoculture maize indicated that N leaching could be a serious problem during the rainy period. Measurements of inorganic N profiles has also confirmed substantial differences in N levels below 75 cm soil depth, with maximum concentrations in the monoculture maize and lower in gliricidia (Mafongoya, unpublished data).

5. Conclusions

This study has shown that continuous cropping of maize in monoculture using inorganic fertilizers reduces invertebrate diversity compared with maize cropping under coppicing or non-coppicing fallows. The study has also shown that legume species such as gliricidia produce large quantities of re-sprout biomass, which decomposes and release N rapidly contributing to higher maize yields over a long period of time. It is concluded that improved fallows of these legumes can maintain maize yields higher than no input practices and sometimes comparable with high input conventional maize monoculture in addition to their long-term positive impact on the diversity and ecosystem functions of soil invertebrates. However, further research is needed on the effect of different lengths of fallow periods, and quantity and quality of organic inputs on soil biota including microfauna and microflora to develop concrete recommendations about improved legume fallows as sustainable practices.

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