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Mixed-species legume fallows affect faunal abundance and richness and N cycling compared to single species in maize-fallow rotations

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ABSTRACT

Rotation of nitrogen-fixing woody legumes with maize has been widely promoted to reduce the loss of soil organic matter and decline in soil biological fertility in maize cropping systems in Africa. The objective of this study was to determine the effect of maize-fallow rotations with pure stands, two-species legume mixtures and mixed vegetation fallows on the richness and abundance of soil macrofauna and mineral nitrogen (N) dynamics. Pure stands of sesbania (*Sesbania sesban*), pigeon pea (*Cajanus cajan*), tephrosia (*Tephrosia vogelii*), 1:1 mixtures of sesbania + pigeon pea and sesbania + tephrosia, and a mixed vegetation fallow were compared with a continuously cropped monoculture maize receiving the recommended fertilizer rate, which was used as the control. The legume mixtures did not differ from the respective pure stands in leaf, litter and recycled biomass, soil Ca, Mg and K. Sesbania + pigeon pea mixtures consistently increased richness in soil macrofauna, and abundance of earthworms and millipedes compared with the maize monoculture (control). The nitrate-N, ammonium-N and total mineral N concentration of the till layer soil (upper 20 cm) of pure stands and mixed-species legume plots were comparable with the control plots. Sesbania + pigeon pea mixtures also gave higher maize grain yield compared with the pure stands of legume species and mixed vegetation fallows. It is concluded that maize-legume rotations increase soil macrofaunal richness and abundance compared with continuously cropped maize, and that further research is needed to better understand the interaction effect of macrofauna and mixtures of organic resources from legumes on soil microbial communities and nutrient fluxes in such agro-ecosystems.

1. Introduction

Soil fauna play a significant role in litter decomposition, nutrient mineralization and improvement of soil properties (Hättenschwiler and Gasser, 2005; Lavelle et al., 2003; Ouédraogo et al., 2007). Macrofauna such as earthworms, termites, millipedes and beetles process large amounts of plant material and determine the fate of litter in many ecosystems (Hättenschwiler and Gasser, 2005; Jones, 1990; Rawlins et al., 2006). However, plant community structure has a strong impact on soil faunal communities and their activities (Laossi et al., 2008; Lavelle et al., 2003).

The inclusion of nitrogen-fixing plants in agro-ecosystems has been shown to sustain ecosystem functions and productivity of land (Kahindi et al., 1997; Laossi et al., 2008; Simms and Taylor, 2002). In Africa, the rotation of nitrogen-fixing woody legumes with maize has been widely promoted in order to improve soil fertility (Mafongoya et al., 2006; Sileshi et al., 2008). These are known as legume "improved fallows" to distinguish them from the natural fallows that depend on regeneration of mixed vegetation (Sileshi et al., 2008). Recent research suggests that rotations with mixed-species fallows are preferable in agronomic terms over pure stands due to synergy between above and belowground resource acquisition (Chirwa et al., 2003; Gathumbi et al., 2002). Theoretical predictions also show that greater plant diversity leads to greater resource use and thus greater total community biomass (Tilman et al., 1997). The greater resource use associated with plant diversity would reduce nutrient losses, leading to long-term increases in ecosystem carbon and nutrient stores, which will also increase productivity (Tilman et al., 1997).

Decomposition of litter from a given species changes greatly in the presence of mixed litter incorporating other species (Hättenschwiler and Gasser, 2005). Hence, litter diversity could influence the community structure of macrofauna (Laossi et al., 2008) and ecosystem functions such as litter decomposition and nutrient cycling. Litter diversity could influence community structures and

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ecosystem functions through a variety of litter chemical properties. For example, in temperate forests litter species richness and soil fauna interactively determine rates of decomposition (Hättenschwiler and Gasser, 2005). Besides potential bottom-up control on litter species interactions, experiments with litter-feeding soil fauna suggest top-down consumer control through altered food selection and consumption rate in response to changing litter species composition (Hättenschwiler and Gasser, 2005). Although maize-legume rotations have been widely promoted in Africa (Mafongoya et al., 2006; Sileshi et al., 2008), information is lacking on the effects of mixtures of species on soil fauna communities and the associated ecosystem processes. Interactions between litter diversity and macrofauna also remain largely unknown because of the traditional approach of using litter bags to study decomposition, which excludes macrofauna. Therefore, this study was designed to gain some incite into such interactions. We hypothesized that two-species legume fallows will have more impacts on soil macrofauna communities and soil mineral N than their respective pure stands and continuously cropped maize. We tested this hypothesis by determining the effect of maize-fallow rotations with pure stands, two-species legume mixtures and mixed vegetation fallows on richness and abundance of soil macrofauna and mineral nitrogen (N) dynamics.

2. Materials and methods

2.1. Study site, treatments and experimental design

The study was conducted at Msekera Research Station (13°39′ S, 32°34′ E in Chipata, Zambia) between 1999 and 2007. The mean annual rainfall (averaged over 40 years) at the site is 1000 mm, which occurs during a single rainy season extending from November to April. The soils at the site are Haplic Luvisols (FAO classification) with 61% sand, 11% silt, 28% clay and pH (1:2.5 soil/water suspensions) of 5.3. Before the experiment the top 20 cm soil had 10.20 g kg^{-1} organic carbon, 7.00 mg kg^{-1} total inorganic nitrogen, 2.02 mg kg^{-1} phosphorus, 3.00 $cmol_c$ kg^{-1} calcium, 1.73 $cmol_c$ kg^{-1} magnesium, 1.47 $cmol_c$ kg^{-1} potassium and 0.06 $cmol_c$ kg^{-1} sodium (Kwesiga and Coe, 1994).

The study involved two fallow and cropping cycles on the same site. The treatments were pure stands of sesbania (*Sesbania sesban* (L.) Merrill), pigeon pea (*Cajanus cajan* (L.) Millsp.), tephrosia (*Tephrosia vogelii* Hook f.), 1:1 mixtures of sesbania + pigeon pea and sesbania + tephrosia, and a mixed vegetation fallow. In the mixtures, two-species were planted in alternate rows. The species in the mixture had contrasting growth habits; i.e. sesbania is a deep-rooted perennial tree, while pigeon pea and tephrosia are both relatively shallow-rooted biennial shrubs. The spacing between rows and between plants was 1 × 1 m and the plots were 10 × 10 m. The mixed vegetation fallow consisted of natural regenerations of native legume and grass species. Continuously cropped monoculture maize receiving the recommended fertilizer rate served as the control since it represents a simplified and high-input agro-ecosystem. The continuously cropped maize treatment received the recommended rate of fertilizer consisting of 200 kg ha^{-1} compound fertilizer (N = 100 g kg^{-1}, P = 90 g kg^{-1}, and K = 80 g kg^{-1}) applied at planting and 200 kg ha^{-1} urea (92 kg ha^{-1} N) applied at 4 weeks after planting. Details of the treatments and maize-fallow rotations are shown in Table 1.

The treatments were arranged in a randomized complete block design with three replicates. Weeding was done manually once to help seedling establishment and all weeds were incorporated into the soil. Cumulative litter-fall was estimated using litter traps placed under each legume species. Surface litter was collected twice (in May and October) from three quadrants measuring 2 m^2 in the net plot, dried and weighed. In November 2001 and 2004, after 2 years of growth, trees and natural vegetation fallows were clear cut. Aboveground biomass of trees was measured by separating the biomass into leaves and woody components. These were then weighed fresh and sub-samples were oven dried at 70 °C for 48 h to a constant weight. All leaf and litter biomass was incorporated into the soil. Maize hybrid MM 604 was grown without fertilizer application in all treatments. The spacing within and between rows was 0.30 and 0.75 m, respectively, giving a maize density of *c.* 44,440 plants ha^{-1}. At harvest maize grain yield (moisture content = 13%) were recorded from each of the replicates for each treatment.

Table 1
Treatments and species of legumes used in the fallow-maize rotation

Treatment	Fallow phase	Crop phase		Fallow phase	Crop phase	
	12/1999–10/2001	12/2001–4/2002	12/2002–4/2003	12/2003–10/2005	12/2005–4/2006	12/2006–4/2007
Tv	Fallow	M − F	M − F	Fallow	M − F	M − F
Cc	Fallow	M − F	M − F	Fallow	M − F	M − F
Ss	Fallow	M − F	M − F	Fallow	M − F	M − F
SsCc	Fallow	M − F	M − F	Fallow	M − F	M − F
SsTv	Fallow	M − F	M − F	Fallow	M − F	M − F
M + F	M + F	M + F	M + F	M + F	M + F	M + F
MVF	Fallow	M − F	M − F	Fallow	M − F	M − F

Treatments: Cc = pigeon pea; Ss = sesbania; Tv = tephrosia; SsCc = sesbania + pigeon pea; SsTv = sesbania + tephrosia; TvCc = tephrosia + pigeon pea; MVF = mixed vegetation fallow; M + F = monoculture maize receiving recommended fertilizer; M − F = monoculture maize without fertilizer.

2.2. Sampling soil macrofauna

Macrofauna were sampled using a modification (Lavelle et al., 2003) of the method described by Anderson and Ingram (1993). Sampling took place on four different occasions: (1) February 2004, which is the mid-rainy season and 3 months after planting (MAP) of the fallows; (2) March 2005 (rainy season and 15 MAP of fallow); (3) November 2005 (end of dry season and after clearing fallows); and (4) February 2006 (mid-rainy season and three MAP of the second phase of maize crop). Soil samples were collected using a steel monolith sampler (25 × 25 × 25 cm) placed over a randomly selected spot and driven into the soil to ground level using a metallic mallet. Three monoliths (within 3–5 m of each other) were taken from each of the replicate plots bringing the total number of sampling units per treatment to nine. The soil was removed from the sampler, macrofauna were hand-sorted and separated into higher taxa (family and order). In some taxa such as Coleoptera, where both larvae and adults were encountered, adults + larvae were recorded as total beetles.

2.3. Measurement of soil chemical properties

Soil sampling was conducted during the rainy season of the first fallow (February 2001), at fallow clearing (October 2001) and two times during the cropping phase (February 2002, November 2002), and two times during the second fallow period (February and November 2003) using a metal sampler (4.2 cm diameter pipe) from 0–20, 20–40, 40–60, 60–100, 100–150, to 150–200 cm soil depths for determining soil N. There were three replicates for each treatment and depth. Soil collected from each plot was air-dried and nutrient analyses performed. Ammonium was determined by the salicylate–hypochlorite colorimetric method (Bower and Holm-Hansen, 1980). Nitrate was determined by cadmium reduction (Anderson and Ingram, 1993). For the sake of simplicity we refer to sum of the ammonium-N and nitrate-N as total mineral N. For determination of soil pH, samples were collected in February 2001, October 2001, February 2002 and November 2002. After 2003, soil