

Integrating legumes to improve N cycling on smallholder farms in sub-humid Zimbabwe: resource quality, biophysical and environmental limitations

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Received 1 September 2004; accepted in revised form 26 August 2005

Key words: *Acacia angustissima*, Leaching, N mineralization, Nitrous oxide, Polyphenols, Residue quality, *Sesbania sesban*

Abstract

The release of mineral-N in soil from plant residues is regulated by their ‘quality’ or chemical composition. Legume materials used by farmers in southern Africa are often in the form of litter with N concentration <2%. We investigated the decomposition of *Sesbania sesban* and *Acacia angustissima* litter in the field using litterbags, and N mineralization of a range of legume materials using a leaching tube incubation method in the laboratory. The mass loss of the litter could be described using a modified exponential decay model: $Y = (Y_0 - Q)e^{-kt} + Q$. The relative decomposition constants for *Sesbania* and *Acacia* litter were 0.053 and 0.039 d⁻¹, respectively. The % N mineralized from fresh *Sesbania* prunings was 55% compared with only 27% for the *Sesbania* litter after 120 days of incubation under leaching conditions. During the same period, fresh prunings of *Acacia* released only 12% of the added N while *Acacia* litter released 9%. Despite the large differences in N concentration between *Acacia* prunings and its litter, the total mineralized N was similar, as mineralization from prunings was depressed by the highly active polyphenols. While N supply may be poor, these slow decomposing litter materials are potentially useful for maintaining soil organic matter in smallholder farms. In two field experiments with contrasting soil texture, *Sesbania*, *Acacia* and *Cajanus* produced large amounts of biomass (>5 Mg ha⁻¹) and improved N cycling significantly (>150 kg N ha⁻¹) on the clay loam soil, but adapted poorly on the sandier soil. There was a rapid N accumulation in the topsoil at the beginning of the rains in plots where large amounts of *Sesbania* or *Acacia* biomass had been incorporated. Despite the wide differences in resource quality between these two, there was virtually no difference in N availability in the field as this was, among other factors, confounded by the quantity of N added. A substantial amount of the nitrate was leached to greater than 0.4 m depth within a three-week period. Also, the incidence of pests in the first season, and drought in the second season resulted in poor nitrogen use efficiency. Our measurements of gaseous N losses in the field confirmed that N₂O emissions were <0.5 kg N ha⁻¹. As we had measurements of all major N flows, we were able to construct overall N budgets for the improved fallow – maize rotation systems. These budgets indicated that, in a normal rainfall season with no major pest problems, reducing nitrate leaching would be the single largest challenge to increased N recovery of added organic N in the light textured soils.

Introduction

Incorporation of plant residues in agricultural soils is a useful means to sustain soil organic matter content, and thereby enhance the biological activity, improve physical properties and increase nutrient availability (Kumar and Goh 2000; Palm et al. 2001b). Legume remains and animal manures form a potentially important source of nutrients for crop production in smallholder agriculture in sub-Saharan Africa. The potential of these resources to contribute nutrients, especially N, for other crops is highly dependent on their N release characteristics with respect to demand for uptake by the crops. Decomposition and N release from organic materials in the soil is influenced by several biotic and abiotic factors including the quality of residues (Swift et al. 1979; Cadisch and Giller 1997). High quality materials (high N content, low lignin and polyphenols) are known to decompose quickly and could substitute mineral fertilizers in supplying N for annual crops (Mafongoya et al. 1998). However, the quantity of high quality legume materials on most smallholder farms is pitifully small.

Grain legumes are grown on very small portions of the land on smallholder farms, and though N_2 -fixation rates can be high, overall farm N inputs from biological N_2 -fixation are in some cases as low as $5 \text{ kg farm}^{-1} \text{ year}^{-1}$ as the area planted to legumes is often small (Giller 2001; Mapfumo et al. 2001). It therefore follows that systematic legume-cereal rotations are not feasible because of the disproportionately mismatching areas under the cropping of legumes and cereals. Most farmers grow maize and average crop residue carbon production is often less than $2 \text{ Mg ha}^{-1} \text{ year}^{-1}$. With the exception of the crop roots, a substantial part of these crop residues are eaten by animals and are returned to the fields as manure. As the food chain gets longer, leakages are bound to increase and the overall efficiency of the system is compromised. Under the current system, actual N and C additions on the farms are therefore variable and difficult to quantify, although in general additions are small and fertility of many cultivated fields is declining as evidenced by declining crop productivity (Smaling et al. 1997). In the absence of substantial native soil organic matter, organic fertility management must be

based on adequate repeated residue inputs that balance losses through mineralization and erosion.

Determination of N release from plant residues is often included in decomposition studies. Much research has focused on indicators of chemical quality (N concentrations, C:N ratios, lignin and polyphenol concentrations and computed ratios for the various combinations) as possible predictors for N mineralization or immobilization (Palm and Sanchez 1991; Constantinides and Fownes 1994; Handayanto et al. 1997). There are, however, varied reports in the literature on the relative importance of each of these residue quality parameters. A decision tree, which uses critical values of the different resource quality parameters to quantitatively define high and poor quality organic materials as they relate to their capacity to supply N for crop growth, was developed by Palm et al. (1997; 2001a). Due to retranslocation of nutrients, senesced leaves or litter have lower N and higher C:N ratios, are more lignified and may show decreased mineralization rates compared with the fresh material. Fresh legume prunings (leaves and twigs) are most widely studied for decomposition patterns (e.g. Mafongoya et al. 1998), and relatively little attention has been paid to N mineralization by the litter component.

This paper discusses the capacity of various legumes to cycle N and benefit rotational maize under the different edaphic conditions. The other objective was to investigate decomposition of litter materials in a litterbag experiment, and also to investigate N mineralization of both fresh prunings and litter of the various legume species in a leaching tube incubation experiment. Further, after presenting results of both N mineralization under controlled conditions and data on mineral N profiles in the field with *Sesbania sesban* and *Acacia angustissima*, we show why extrapolation of results from laboratory conditions to the field with improved fallows will remain elusive, as residue quality alone fails to fully account for many of the results from field experiments. Finally, as we had estimated all the major flows of N, we are able to construct detailed N budgets for a case study of an improved fallow-maize rotation system with both *Sesbania* and *Acacia*, compared with continuous maize cultivation.

Materials and methods

Quantifying nitrate leaching and N₂O emissions after improved fallows

Two field experiments were conducted at two sites with different soil texture: The first one was located at the field station of the International Centre for Research in Agroforestry (ICRAF) located at Domboshawa, Zimbabwe (17°35' S latitude, 31°14' E longitude). The soil is a sandy clay loam with 22% clay content, and classified as a Lixisol (World Reference Base for Soil Resources). Two successive maize crops were planted in plots after harvesting two-year old legume improved fallows of (i) *Sesbania sesban*, (ii) *Acacia angustissima*, (iii) *Cajanus cajan*. The fourth treatment was continuous maize without any fertilization. These treatments, on plot sizes of 12 m × 8 m, were replicated three times in a randomized complete block design. After cutting the legumes, all woody plant materials (>5 mm diameter) were removed from the plots for firewood, whereas twigs (<5 mm diameter), leaves and litter were left in the plots for incorporation.

Soils were sampled using augers in sections of 0–20, 20–40, 40–60, 60–90 and 90–120 cm to determine nitrate N dynamics during the cropping phase in all treatments, except *Cajanus*. In each plot soil was collected and bulked from two locations at each sampling time. Subsamples were taken to the laboratory in polythene bags and stored at 4 °C prior to extraction usually within two days of collection. The NO₂-N cadmium reduction method (Keeney and Nelson 1982) was used for soil nitrate-N determination. The quantity of nitrate leached was estimated as the cumulative decrease in the nitrate content of the soil profile between successive sampling events, early in the season when N uptake by maize was still insignificant. The closed soil chamber technique as described by Mathias et al. (1980) was used to estimate gaseous N losses as nitrous oxide in the field. In short, the method involved deploying PVC rings in the field a day before actual measurements were done. On the following day chamber lids were placed on the rings and sealed. Accumulated headspace was then sampled using a syringe at 0, 30 and 60 min after enclosing the

chambers. The gas samples were then analyzed by electron capture gas chromatography.

The second experiment was at a site where the soil was a highly leached coarse-grained sand derived from granite, with no more than 5% clay content to at least 1.2 m depth (Arenosol, FAO classification). The experiment involved a comparison of a range of legumes that included soyabean (*Glycine max*), mucuna (*Mucuna pruriens*), *Crotalaria paulina*, and the agroforestry species as described for the Domboshawa site. This experiment is described in detail by Chikowo et al. (2004a). In both experiments the % N derived from biological N₂-fixation was determined in the legume shoots using the ¹⁵N-natural abundance method (Peoples et al. 1989).

Litter decomposition in litterbags

To further our understanding of the behavior of the organic materials generated, the rate of mass loss of *Sesbania* and *Acacia* litter were assessed by placing 30 g dry weight litter into 25 × 25 cm litterbags with 2 mm mesh size. A total of 21 litterbags were used for each litter type. Seven litterbags of each type were placed in each of the three blocks and the litterbags were buried in the unfertilized maize plots to a depth of 0.15 m. This is the tillage depth normally achieved by farmers using ox-drawn ploughs hence litter is incorporated to this maximum depth. The placement of litterbags was done at the time of establishing the maize crop in the field at Domboshawa. Twigs of varying diameters ranging up to 5 mm constituted approximately 25% of the litter used. Initial chemical properties of these litters are shown in Table 1. One litterbag was retrieved from each block at 1, 3, 5, 8, 12, 17 and 21 weeks after burying, for each of the litter types. At each retrieval time, residues recovered from the litterbags were placed on a 0.5 mm sieve and soil adhering to the litter was carefully cleaned off in a bucket of water. Dry weight was recorded after oven drying at 65 °C for 48 h. Ash-free dry weight of recovered litter retrieved from the soil was obtained following combustion of the litter in a muffle furnace at 550 °C for 3 h. A modified exponential decay model was then fitted to the mass loss data.

Table 1. Chemical composition of legume fresh prunings and senesced litter used in the experiments.

Plant material	% N	% P	% lignin	% polyphenols	PBC	C:N ratio	Lignin:N
Sesbania leaves	3.2	0.28	4.5	1.9	28	14	1.4
Sesbania litter	1.6	0.21	5.4	0.8	20	21	3.4
Acacia leaves	4.8	0.57	7.1	5.7	160	10	1.5
Acacia litter	1.5	0.17	24.4	1.3	29	24	16.2
Soyabean stover	1.7	0.20	12.9	0.6	18	25	7.6
Mucuna litter	1.8	0.31	11.5	3.4	52	24	6.4

‰: (mg per mg dry weight) \times 100; PBC: protein binding capacity, $\mu\text{g BSA mg}^{-1}$ plant sample (BSA = bovine serum albumin).

N mineralization in leaching tube incubations

Decomposition and N mineralization of different legume litters and two fresh prunings were determined in leaching tube incubations (Stanford and Smith 1972). Leaching tube incubations take into account the initial rapid loss of organic and mineral constituents during decomposition and allow periodic leaching from the same tube over time (Sakala et al. 2000). The treatments were fresh prunings of *Sesbania* and *Acacia*, and senesced litter of *Sesbania*, *Acacia*, soyabean, mucuna, and an unamended soil as the control. The soil was a granitic derived sandy soil from a smallholder farm with 4% clay content. To determine total plant N and P, samples of the materials were oven dried at 30–35 °C and ground to pass through a 1 mm sieve. Total N and P were analyzed through complete oxidation by Kjeldahl digestion using sulphuric acid, hydrogen peroxide and selenium digestion mixture (Anderson and Ingram 1993). All the residues were then added at a rate equivalent to 100 mg N of residues kg^{-1} soil.

The leaching tubes were made of plexiglass tubing, and were 28 cm long with an internal diameter of 40 mm. At the base of the tube was a rubber stopper with an opening at the centre where a glass tube was inserted to drain water during leaching. The immediate top of the rubber stopper was covered with rock-wool filter and then a layer of fine sand. After completion of setting up of the experiment tubes were immediately leached with 100 ml of leaching solution (1 mM CaCl_2 ; 1 mM MgSO_4 ; 0.1 mM KH_2PO_4 and 0.9 mM KCl) in 50 ml aliquots (Cassman and Munns 1980). Excess water was removed with a mild suction pump, and then the tubes were incubated in the dark at 24–25 °C.

The tubes were further leached on days 4, 8, 16, 32, 48, 64, 90 and 120. After each leaching, mild

suction was applied to drain excess leaching solution. The leachates were analyzed for $\text{NH}_4\text{-N}$ and $\text{NO}_3\text{-N}$. Net N-mineralization was calculated by subtracting N released from the unamended soil from that released by the residue-amended treatments. Nitrogen mineralization from the plant residues as a function of time (Nmin_t) was calculated from the difference in cumulative amounts of mineral N between soil treated with plant materials and the control at each sampling time divided by the total residue N added.

$$\text{Nmin}_t = \frac{\text{Min N (treat)}_t - \text{Min N (control)}}{\text{Total residue N added}}$$

All the materials used were also analyzed for their lignin and polyphenols contents, as well as the protein binding capacity of the polyphenols. Lignin was determined through acid detergent fibre. Total soluble polyphenols were determined by the Folin-Ciocalteu method (Constantinides and Fownes 1994). This involved extraction of 0.1 g material with 50% methanol in a flask that was placed in a water bath at a temperature of 77–80 °C for 1 h. Protein binding capacity of polyphenols was determined by extracting the material using 50% aqueous methanol at 95 °C. The extract was centrifuged and applied to chromatographic paper, followed by a reaction with bovine serum albumin.

Results and discussion

Biological N_2 -fixation rates and legume productivity

Estimates of biological N_2 -fixation on two field experiments with different texture showed that legumes fixed a large proportion of their accumulated N on both sites, but the actual amounts of the fixed N were very different (Table 2). As

Table 2. Biomass production, biological N₂-fixation, and N input through litter and stover from selected legumes grown on a sandy soil and clay loam soil in Zimbabwe (adapted from Chikowo et al., 2004a, b).

Legume	Leaves/litter (Mg ha ⁻¹)	Recyclable N ^a (kg ha ⁻¹)	% N from N ₂ -fixation	Net N input ^b (kg ha ⁻¹)
Sandy soil				
Soyabean	1.7 (0.11)	28 (2.2)	76	24
<i>Mucuna pruriens</i>	3.9 (0.20)	87 (3.7)	96	106
<i>Crotalaria paulina</i>	0.2	4	46	2
<i>Cajanus cajan</i>	0.4	7	65	4
<i>Sesbania sesban</i>	nd ^c	nd	84	nd
<i>Acacia angustissima</i>	nd	nd	79	nd
Sandy clay loam				
Cowpea	2.5 (0.18)	48(3.6)	58	30
<i>Cajanus cajan</i>	5.3 (0.23)	115 (4.6)	84	103
<i>Sesbania sesban</i>	5.7 (0.30)	152 (5.7)	55	67
<i>Acacia angustissima</i>	9.9 (0.58)	218 (11.6)	56	129

^a Above-ground plant accumulated N (Soil N + N₂-fixed N) returned to the soil in the form of litter and leaves.

^b Amount of N₂-fixed and returned to soil (above ground non-woody components + all root N) – soil derived N exported (woody parts and grain).

^c nd = not determined as these legumes grew poorly on the sandy soil site. values in parenthesis are standard error of means (SEMs).

estimated by the ¹⁵N natural abundance method, all the legumes, except *C. paulina*, derived at least 55% of their N from biological N₂-fixation across the sites. On the sandy site, although N₂-fixation rates were high for these woody legume species, total N fixed was small as these legumes grew poorly and produced little biomass. Soyabean responded well to inoculation with rhizobia and P fertilizer, and cycled comparatively larger quantities of N through its litter and stover when compared with the other legumes (Table 2). Net N input was, however, poor, as soil N was exported through seed harvest. As expected, mucuna had the greatest net N input of 106 kg ha⁻¹ into the system as no N was exported from the field through seed harvest. On the sandy clay loam soil *Sesbania*, *Cajanus* and *Acacia* had comparatively larger net N inputs compared to the same species on the sandy soil due to large biomass accumulated on the soil with less biophysical limitations (Table 2).

Sesbania sesban, *Cajanus cajan*, *Acacia angustissima* are legume species that have resulted in high subsequent maize yields (Mafongoya and Dzwela 1999). *Acacia* is expected to be especially efficient in recycling nutrients as its regrowth capabilities after fallow clearance means that it can be pruned regularly during maize cropping, and the prunings are spread in the field where they act as green manure or mulch. Herbaceous green manure legumes like mucuna grown specifically for soil fertility restoration have not been widely adopted

by farmers in southern Africa (Snapp et al. 1998). The lack of a direct usable product, such as food or fodder, is the principal disincentive that prevents farmers from readily adopting green manuring. Grain legumes have been grown by smallholder farmers in rotations with cereal crops and these can contribute N, but the contributions are variable (from -47 to 137 kg N ha⁻¹) depending on legume type, N partitioning characteristics and rate of biological N₂-fixation (Giller 2001). The benefit of grain legumes to soil fertility largely depend on how their residues are utilized, and grain legumes with large N harvest indices invariably contribute little N to the soil.

Mass loss by litter

The mass loss for both *Sesbania* and *Acacia* litter was rapid during the first 8 weeks after the litterbags had been buried in the soil (Figure 1). When the remaining organic material was plotted logarithmically against time, the resulting lines were non-linear indicating a poor fit to simple first order kinetics ($Y = Y_0 e^{-kt}$). Data were then fitted to a modified single exponential decay model : $Y = (Y_0 - Q) e^{-kt} + Q$, which gave a linear relationship for the plot of $\ln \{(Y - Q)/(Y_0 - Q)\}$ vs. time. 'Q' is the 'quantity' of litter that would remain undecomposed in the litterbags in the long run, and k is the relative decomposition rate. The proportions of recalcitrant material were found to

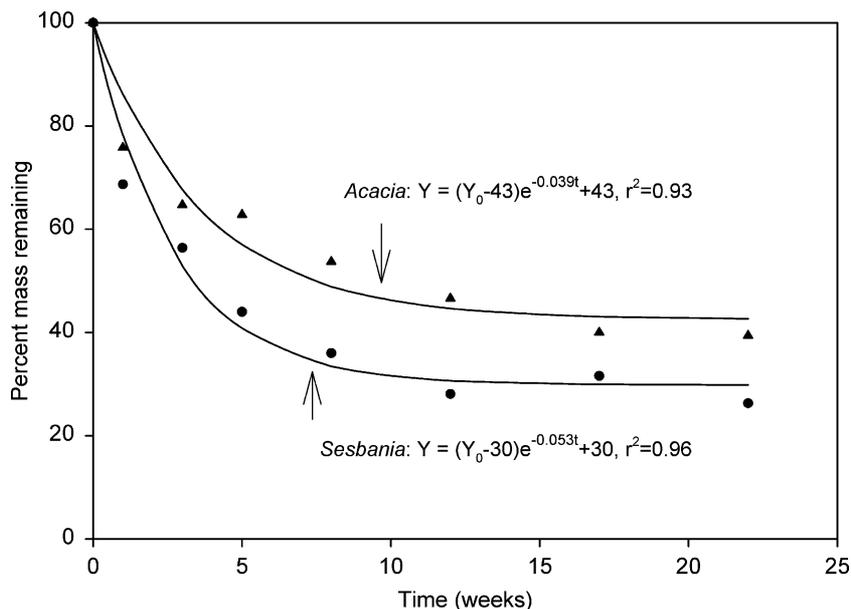


Figure 1. *Acacia* and *Sesbania* litter remaining in litterbags buried in soil on several retrieval times over a 22-week period under sub-humid conditions in the field at Domboshawa, Zimbabwe (see text for explanation of the regression functions).

be 30 and 43% for *Sesbania* and *Acacia*, respectively. The relative decomposition constants for *Sesbania* and *Acacia* litters were estimated to be 0.053 and 0.039 d^{-1} , respectively. These decomposition constants do not have a decomposition meaning solely since some mass loss may be due to material movement through the mesh, as evidenced by the darkened soil on the spots where litterbags had been removed.

At five weeks, about 60% of the *Sesbania* litter had been lost compared with only 40% for *Acacia* litter (Figure 1). The slower mass loss of *Acacia* litter as compared to *Sesbania* litter was probably linked to its higher lignin content (Table 1). About 25% of the litter we used was in the form of small twigs of up to 5 mm diameter, and such material is the more lignified component of the litter that takes longer to decompose or physically be removed from the litterbags with 2 mm mesh size.

Nitrogen mineralization patterns

The chemical composition of the materials used in the N mineralization study varied widely (Table 1). Except for *Acacia* litter, all the materials had lignin concentrations <15%. Total N was

less than 2% for all senesced materials, indicating large variations between fresh and litter materials from the same species. The % N mineralized from high quality *Sesbania* prunings was 55% compared with 27% for the *Sesbania* litter after 120 days of incubation under leaching conditions (Figure 2). During the same period, fresh prunings of *Acacia* released only 12% while its litter released 9% of the added N. Despite the large differences in total N concentration of the *Acacia* prunings and litter, the total mineralized N at the end of the incubation period was similar. The small proportion of N mineralized from the *Acacia* prunings was associated with the high activity of the polyphenols as indicated by the large protein binding capacity (Table 1). Palm and Sanchez (1991) attributed the differences in N release from prunings of various tropical legumes to the presence of polyphenols, and showed that the polyphenol:N ratio was a good predictor of N mineralization. Reactive polyphenols (condensed tannins) bind strongly to proteins in the residues and form complexes that are resistant to microbial attack (Handayanto et al. 1997). The larger polyphenol content and protein-binding capacity of mucuna litter compared with soyabean litter could partly explain why it immobilized N throughout the incubation period in our study.

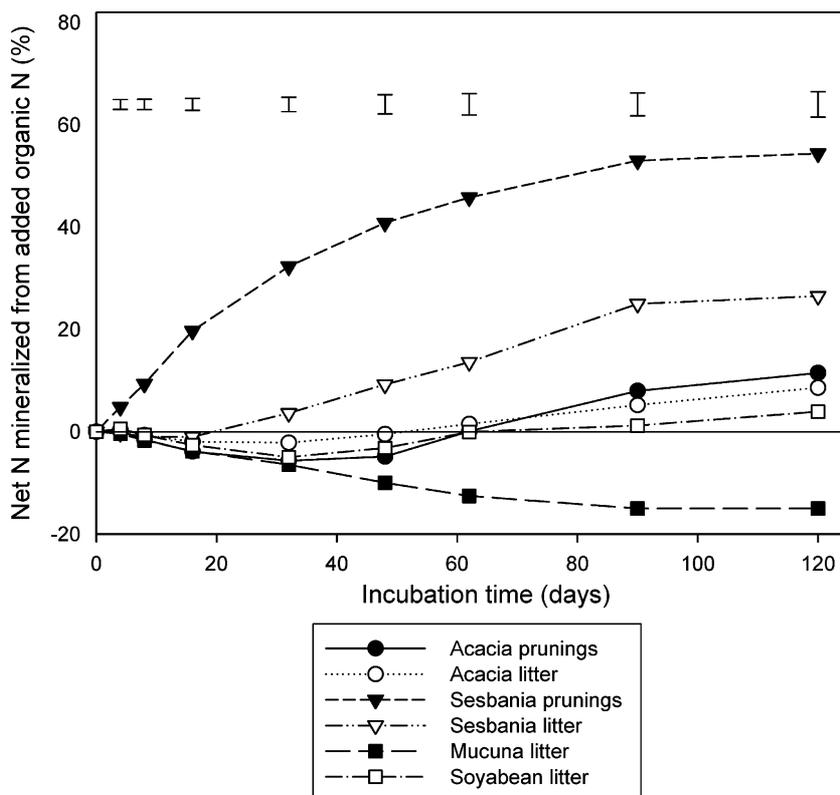


Figure 2. N release by various legume materials in a leaching tube incubation experiment. Bars represent least significant differences.

Net N mineralization from the fresh *Sesbania* prunings was more rapid and resulted in a greater proportion of the N released after 120 days than that from *Sesbania* litter. By contrast there were no obvious differences in N mineralization between prunings or litter of *Acacia*. Most of the senesced litter materials showed N immobilization up to 60 days of incubation, and then slight net mineralization. *Sesbania* litter immobilized N for a 2-week period only and then mineralized N slowly over the next 90 days. Much of the high energy soluble carbon compounds that support microbial activity are translocated from leaves during senescence, prior to abscission and leaf fall, and litter becomes more lignified (Constantinides and Fownes 1994). In a review of decomposition and N release patterns of tree prunings and litter, Mafongoya et al. (1998) showed that litter materials had lower nutrient concentrations compared with green foliage of the same legume species, and this was correlated with slower decomposition rates.

Nitrate leaching and N_2O emissions after the different legumes

Nitrate-N increased substantially in the top 0–0.4 m depth at the beginning of the rains, from 3.2 to 34 kg N ha⁻¹ in *Sesbania*, and from 6.7 to 29 kg N ha⁻¹ in the *Acacia* plots during the period from pre-season sampling to week one (Figure 3). There were no treatment differences in nitrate concentration in soil layers below 0.4 m for the week one samples. These increases in nitrate concentration in topsoil were not sustained as concentrations decreased rapidly only three weeks after planting maize. The decrease in topsoil nitrate concentration was accompanied by a relative increase at depths below 0.4 m. *In situ* production of nitrate at lower depth is unlikely to account for these dramatic increases as the soil contained little organic matter at depths below 0.4 m.

Beyond the third week after planting, the bulk of the nitrate had moved to the 1.0–1.2 m layer or beyond. Poor N recovery following incorporation

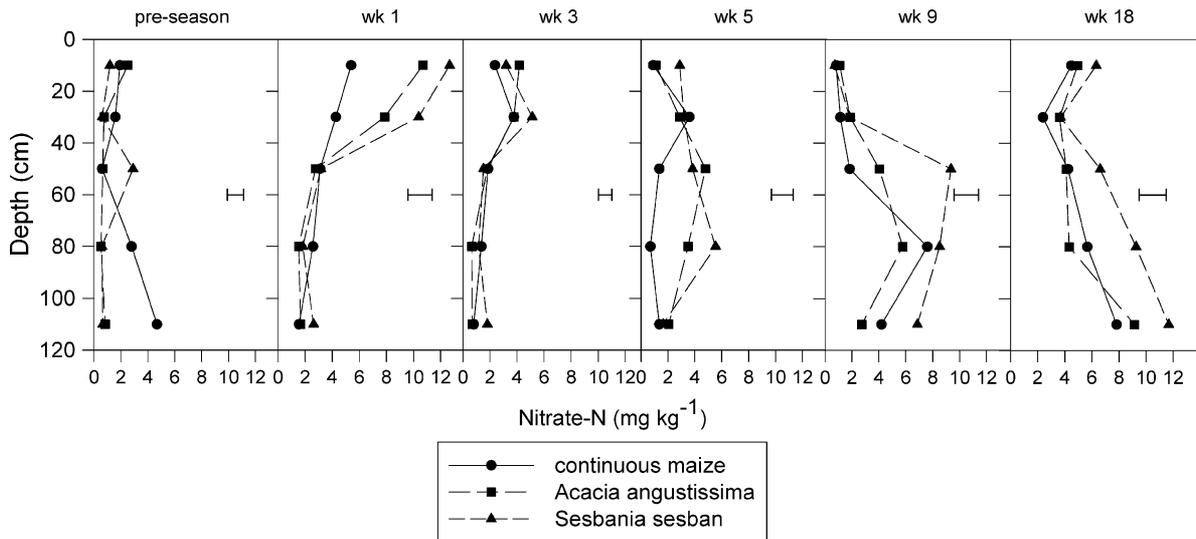


Figure 3. Nitrate-N dynamics following plots that had maize, and 2-year fallows of *Acacia* and *Sesbania*. Each error bar represents LSD ($P < 0.05$) for all depths for the respective sampling dates.

of high quality legume prunings such as *Sesbania* results due to rapid N release and subsequent leaching before crop root systems sufficiently develop (Figure 3). Despite the marked contrast in quality and N release patterns between both prunings and litter of *Sesbania* and *Acacia* in the laboratory incubations described above, this resulted in only slight differences in mineral N contents during the cropping season in the field. This is discussed further below. Using the mass balance approach on soil profile nitrate contents between successive sampling times, Chikowo et al. (2004c) estimated that up to 30 kg N ha^{-1} was leached from the top 0.4 m in the early weeks following planting of maize. None of the materials used in this study demonstrated a perfect synchrony of N release and plant uptake. Mineral N in topsoil following legume tree-improved fallows increases significantly at the start of the rains following a long dry season. Such temporary flushes in mineral N are not directly related to the quality of legume materials as described above, but probably other N sources such as turnover of microbial biomass and labile organic matter.

Nitrous oxide emissions following two-year improved fallows on a sandy clay loam soil indicated that legumes significantly increased N_2O emissions compared to unfertilized maize monoculture, but losses were $<0.5 \text{ kg ha}^{-1}$ for a measurement period of 56 days (Table 3). Under the less-reducing

Table 3. N_2O emissions in a field experiment that involved improved fallows on a sandy loam soil over a 56-day measurement period, Zimbabwe (from Chikowo et al. 2004c).

Treatment	Amount of N added (kg ha^{-1})	Total $\text{N}_2\text{O-N}$ emission (g ha^{-1})
Unfertilized maize	0	60 (12)
<i>Acacia angustissima</i>	218 (11.6)	180 (25)
<i>Sesbania sesban</i>	152 (5.7)	290 (38)
* <i>Sesbania sesban</i> -NT	152 (5.7)	240 (35)

SEM values for amount of N added and $\text{N}_2\text{O-N}$ emissions are given in parenthesis.

**Sesbania sesban*-NT = *Sesbania sesban* plots that were not tilled.

conditions of the open textured soils, a large proportion of the gaseous N could have been lost in the form of nitric oxide (NO). In a study of gaseous N emissions from savanna sandy soils, Scholes et al. (1997) reported that N_2O emissions averaged just 8% of the total N emissions. When denitrification losses were corrected using this factor, maximum amounts of N lost were still only 5 kg ha^{-1} . Though legumes result in increased N_2O emissions, the quantities lost are small and do not contribute significantly to the poor N recovery by crops under organic fertilization that is widely reported in literature (e.g. Mugwira and Mukurumbira 1986; Snapp et al. 1998; Chikowo et al. 2004c).

The nutrient release dilemma of the available organic materials

While nutrient quality explains and predicts N release under controlled conditions (Cadisch and Giller 1997; Handayanto et al. 1997), field environmental factors drive a substantial part of the realities that the farmers face. There are complex factors involved in the N transformations in soils once organic materials are incorporated, and quality parameters as well as the environment will dictate N release. Synchronization of N mineralization and crop demand will be difficult to achieve for many organic resources as either N release precedes plant demand or is too slow. For example, data for nitrate dynamics in the field under maize in sequence with improved fallows showed nitrate profiles of both *Acacia* and *Sesbania* moving well in advance of the crop demand (Figure 3). There was virtually no difference in N availability in *Acacia* or *Sesbania* plots in the field, despite the wide differences in quality that clearly explained the differences in N mineralization patterns in the controlled leaching tube incubation experiment described in section 3.3 above. Specifically, the rapid mineral N accumulation in *Acacia* plots after one week would seem to sharply contradict its N release characteristics as controlled by high lignin content for its litter and the high protein binding capacity of its polyphenols for the prunings. In the field the effects of litter quality and differing N mineralization patterns are confounded by differences in the quantity of N between treatments as well as the duration of exposure of the materials to the environment. In the case of an improved fallow system we report here, at the end of the two years of having the legumes in the plots, there is usually a mixture of plant materials that are at various stages of decomposition and the beginning of rains triggers immediate N mineralization. The resulting N release patterns are, thus, atypical of what would be expected from the chemical composition of the materials. Managing N release in the field under such conditions will remain elusive.

When fresh prunings are used, as in biomass transfer systems, the release of N is in most cases similar to that of litter that has been in the field for a long time. Materials such as *Acacia* prunings that have large amounts active polyphenol would decompose too slowly, again in asynchrony with plant uptake (Figure 2), although accumulated

decomposing litter from the two-year fallow supplies mineral N immediately. Slow decomposing legume materials have the additional advantage of building up and maintaining reasonable soil organic matter contents on sandy soils.

Of the non-legume organic materials, cattle manure is widely used by smallholder farmers as a soil amendment to sustain crop production (Mapfumo and Giller 2001). Cattle graze in large grasslands during the day and manure is collected overnight in cattle pens, thus effectively concentrating nutrients from the large pasture areas. The concentrated nutrients are, however, susceptible to losses (e.g. N loss through volatilization, leaching in pens) and the end product is manure usually mixed with substantial amounts of sand, and with low N and recalcitrant C. Mineralization characteristics of such manure are also not favourable to support high crop yields (Mugwira and Mukurumbira 1986).

Impact of an improved fallow system: a case study

Much is known concerning N supply by a wide range of organic resources and an organic resource database has been developed to aid systematic analysis of these inputs for tropical agriculture (Palm et al. 2001a). Despite the vast documentation of such knowledge, there is a growing challenge to increase crop productivity to levels adequate to sustain human populations in sub Saharan Africa. The resultant increased intensity of land use as populations grow, has led to increased nutrient depletion through crop removal and soil erosion.

Figure 4a summarizes N cycling in an improved fallow system of both *Sesbania* and *Acacia* as related to the specific seasons we carried out our experiment. The combined N uptake by the two maize crops following *Sesbania* fallows was 45 kg ha⁻¹. When the 22 kg N ha⁻¹ used by the unfertilized maize treatment in the two seasons is subtracted from this figure, the N from *Sesbania* prunings and litter recovered by the two subsequent maize crops can be estimated to be 23 kg, representing a N recovery rate of 15% N of that applied. In this experiment, growth of maize and N use efficiency were strongly depressed by cutworm infestation during the first season, and by drought during the second season (Chikowo et al.

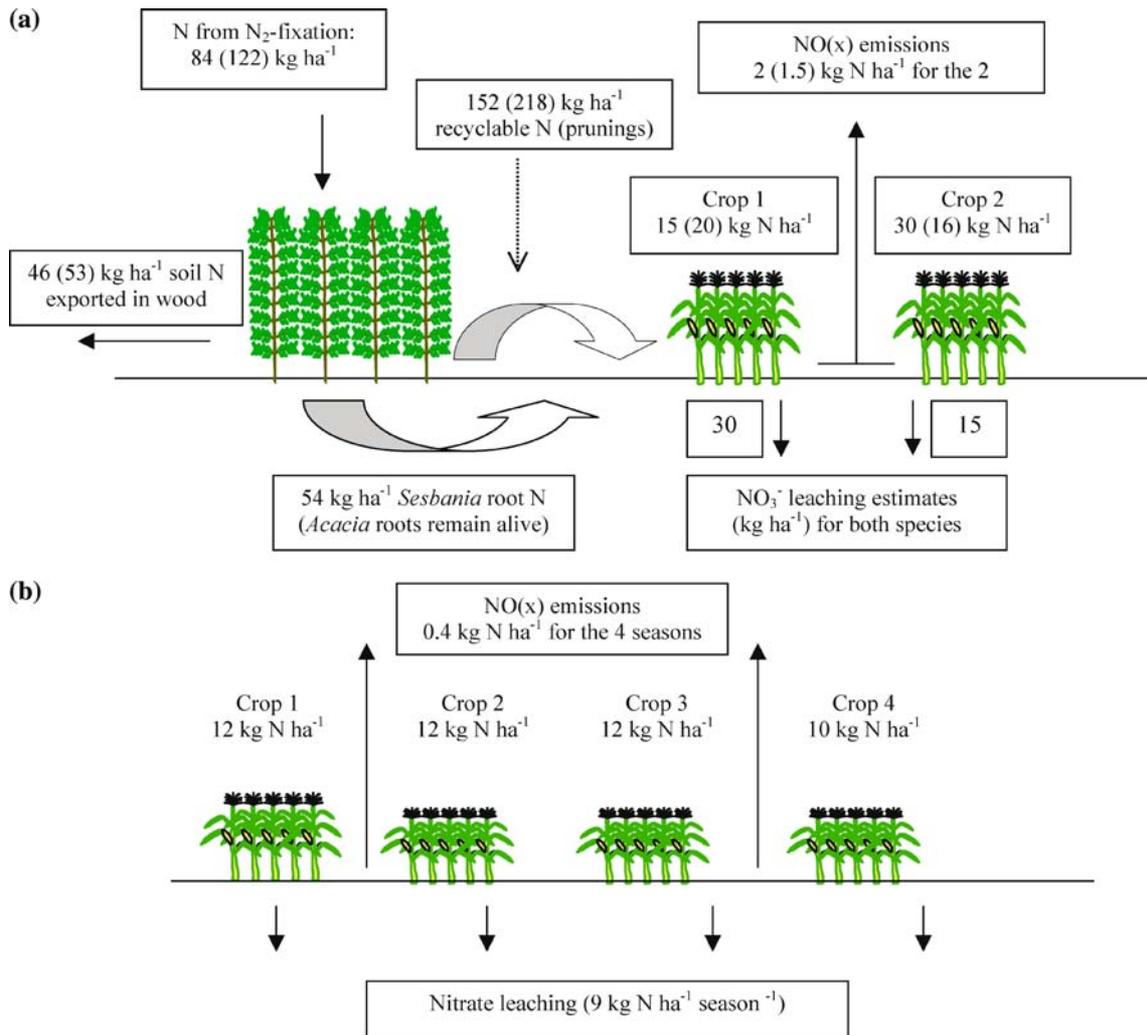


Figure 4. Nitrogen flows in (a) *Sesbania* (*Acacia*)-maize-maize cropping sequence and (b) maize monoculture with no fertilizer application. Figures in brackets for (a) are for *Acacia* N flows. It was assumed that N mineralization from SOM was equal in both cases at 30 kg N ha⁻¹ year⁻¹ (2% of native SOM).

2004b). A similar analysis with *Acacia* shows that of the total of 218 kg ha⁻¹ recycled N, about 122 kg was derived from N₂-fixation. Even after accounting for the soil-sourced N that was exported from the field in woody material (53 kg N ha⁻¹), there was still substantial net N input. *Acacia* root system contained substantially larger N amount than *Sesbania*, but unlike *Sesbania*, most of the roots remain alive after tree harvests as the species has regrowth capabilities. Thus, *Acacia* root N does not translate into an active N input until the trees are completely destroyed. We have already indicated earlier that

there were strikingly similar mineral N profiles early in the season, between *Sesbania* and *Acacia* plots, this despite the contrasting litter qualities. Differences in profile mineral N became significant later in the season, probably due to *Acacia* trees capturing some of the leached N from depth (Figure 3). As was for *Sesbania* plots, maize following *Acacia* was also affected by pests and drought in the first and second seasons, respectively. Improved N cycling was therefore not supported well via maize yields and N uptake in this study. An earlier experiment on the same field resulted in high maize yields following improved

fallows (Mafongoya and Dzwowela, 1999; Table 4). The depressed yields of maize due to pest attack and drought demonstrates the high risks that farmers face as legume technologies are integrated into the farming system.

In continuous cropping systems with little external inputs in Africa, crop production is generally supported through native soil organic matter decomposition until the systems collapse due to soil organic matter reaching critically low concentrations or other soil physical limitations getting more prominent (Smaling et al. 1997). If the decomposition coefficient of SOM is assumed to be 2% (Swift et al. 1979), the soil with 0.06% organic N in the top 0.2 m layer releases about 30 kg N ha⁻¹ year⁻¹. Even with very high N use efficiency, this amount would only support modest crop yields (Figure 4b). With no substantial annual organic material additions (except from weeds), the native soil organic matter decreases and the capacity of soil to supply N gradually decreases, and so will the production intensity that can be supported. We have established that gaseous N emissions are small under unfertilized conditions, and we propose that a substantial proportion of the mineralized N from soil organic matter will be leached as unfertilized maize in a P deficient soil has a poor root system to absorb the N. Though soil losses due to erosion are higher under maize monoculture than following improved fallows, the eroded soil has poor nutrient content and total N losses are thus small.

While the N₂-fixation rate in the legumes is fairly consistent, crop growth and N accumulation are strongly influenced by variability in rainfall during the cropping seasons. It is expected that in the absence of pests and when rainfall is more

evenly distributed, N leaching losses will be smaller and N use efficiency will be larger. Losses of N through erosion will also depend on the rainfall intensity, and its partitioning into infiltration and runoff. N losses due to erosion are small during immediate cropping season after fallow termination, as infiltration rates are large. However, such losses markedly increase in subsequent cropping seasons as the physical effects of improved fallows on water infiltration dynamics disintegrate (Nyamadzawo et al. 2003).

Conclusions

Large proportions of the N accumulated by legumes came from N₂-fixation on both the sandy clay loam and the sandy soil. However, on the sandy site, these were large proportions of small amounts of N and overall N cycling was therefore poor. We have further confirmed that total N content is a poor index to use for N mineralization prediction in some legume prunings like *Acacia* that have highly active polyphenols. The slow release of N due to initial immobilization by a number of senesced legume materials we used means that crop fertilization with such materials alone will not support high productivity. Though N mineralization differences between *Sesbania* and *Acacia* were pronounced in the laboratory experiment, there was virtually no difference in N availability in *Acacia* or *Sesbania* plots in the field, despite the wide resource quality differences. Thus, there remains the challenge to integrate results from litterbag and leaching tube incubation studies to the prediction of N availability in the field. Senesced legume litter materials decompose

Table 4. Maize grain yields (Mg ha⁻¹) for two immediate seasons of cropping following 2-year improved fallows at the same site, Domboshawa, Zimbabwe.

Legume species	Phase 1 ^a		Phase 2 ^b	
	Season 1 1995	Season 2 1996	Season 1 2001	Season 2 2002
<i>Sesbania sesban</i>	4.9	3.7	0.67	1.30
<i>Acacia angustissima</i>	2.9	1.3	0.91	0.58
<i>Cajanus cajan</i>	3.4	3.0	1.20	1.11
Unfertilized maize	1.2	1.3	0.85	0.62
LSD (0.05)	0.4	0.5	0.18	0.14
Rainfall (mm)	672	715	1 218	461

^a Adapted from Mafongoya and Dzwowela (1999).

^b Chikowo et al. 2004b.

slowly, thus, are potentially more useful for maintaining soil organic matter in smallholder farms than the rapidly decomposing fresh prunings. Our measurements of gaseous N losses in the field confirmed that N₂O emissions were small, while substantial amounts of nitrate were leached from the topsoil, driven by the high intensity rainfall and the asynchronous nature in the release of N and its demand by crops. In principle increased N cycling should be associated with increased crop productivity, but we have presented a case in which external biological and environmental factors may nullify the great potential of a promising legume-based farming system.

Acknowledgements

We thank ICRAF for facilitating this work at a long-term experiment at Domboshawa site in Zimbabwe. We are grateful to The Rockefeller Foundation and the EU through the IMPALA project, for financial support, and TSBF through AfNet for funding the first author to attend the AfNet Symposium in Yaounde, Cameroon.

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