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Nitrogen Cycling in Non-N_2-Fixing Tree Legumes: Challenges for Biological Nitrogen Fixation Research in Savanna Ecosystems

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Abstract

Nitrogen mineralization of native organic matter in soil under a miombo woodland was determined *in situ* at Marondera, Zimbabwe. The miombo woodland was dominated by non-N_2-fixing legume species of *Brachystegia* and *Julbernardia*. N mineralization in soil under an arable system was also monitored. Changes in leaf litterfall and N concentration were monitored throughout the year, starting with the beginning of the rainy season (December) to November over three years. Data from studies on biological nitrogen fixation (BNF) of *Cajanus cajan* were used for comparisons of leaf and/or shoot N concentration and nutrient cycling patterns. Cumulative soil N accumulation under natural miombo was more than twice that of the soils under the arable system. There was a significant ($P<0.001$) correlation between soil N accumulation and total N input from tree leaf litter ($R^2 = 0.92$). The leaf N concentrations of some N_2-fixing, non-N_2-fixing and some non-leguminous species are presented. The legumes were also found to contain higher concentrations of not only N but also K, Ca and Mg. The N economy of the miombo ecosystem was considered to be largely dependent on maintenance of a self-renewable nutrient capital, taking advantage of the efficient N capture by the legume trees. Development of soil fertility management options in which N_2-fixing legumes can be used to

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simulate nutrient cycling in the miombo ecosystems is considered a challenge to BNF research. Most of the current BNF research has emphasized on increasing N inputs from N_2-fixation paying, little attention to the capacity of N_2-fixing legumes to capture and recycle nutrients under poor soil fertility environments.

Keywords: miombo, N_2- and non-N_2-fixing legumes, nutrient cycling, soil fertility management

1. Introduction

Legumes (family *Leguminosae*) are a widespread natural resource potentially accessible to all peoples of the world regardless of their social stratum. A wide diversity in the physiognomy and environmental adaptability of legumes has favoured their exploitation in a variety of agricultural systems and under different ecological zones. The *Leguminosae* family is taxonomically classified into three sub-families, namely, *Caesalpinioideae*, *Mimosoideae* and *Papilionoideae* (Allen and Allen, 1981). Over 90% of species in the *Mimosoideae* and *Papilionoideae* sub-families and about 30% in the *Caesalpinioideae* can nodulate and fix atmospheric nitrogen (N_2) through symbiotic association with *Rhizobium* bacteria (Sprent, 1979; de Faria et al., 1989). Because nitrogen is the most limiting nutrient in agriculture (Hauck, 1984; Giller et al., 1997), much biological nitrogen fixation (BNF) research has been aimed at exploiting this resource base. These N_2-fixing species have, therefore, received more attention in soil fertility research than the non-nodulating species. Despite their apparent comparative advantage, however, N_2-fixing legumes have been found to contain only slightly higher shoot N concentrations than their non-nodulating counterparts (Bryan et al., 1996; Giller, 1998). Non-nodulating species have been reported to grow equally well and even outproduce N_2-fixing species on N-limited soils (Bryan et al., 1996). This can be demonstrated in Central and Southern Africa where non-nodulating leguminous tree species of *Brachystegia* and *Julbernardia* (miombo) dominate on the inherently infertile granitic sandy soils (Allen and Allen, 1981; Campbell et al., 1998a). The two species belong to *Caesalpinioideae* sub-family. The question that arises is how these plants have managed to meet their N requirements and sustain productivity within their natural habitats. Most of the smallholder farming areas in Zimbabwe and parts of Southern Africa were derived from these miombo ecosystems. Low and declining soil fertility, particularly N deficiency, have remained a major constraint in these farming systems despite current research efforts (Grant, 1981; Kumwenda et al., 1995; Campbell et al., 1998b).

Current BNF research efforts in Africa and other tropical environments have been mainly focused on improving the functional efficiency of both the microand macro-symbionts in order to maximise N_2-fixation (e.g. Somasegaran and Hoben, 1985; Giller and Wilson, 1991; Mulongoy et al., 1992). Although the potential for BNF to sustain smallholder agriculture has been realised (Giller et al., 1994), productivity and N_2-fixing capacity of these legumes has often been limited by adverse environmental conditions (Giller and Wilson, 1991). Because of high N losses prevailing in these farming systems, agronomists are beginning to question the extent to which the N gain by BNF can replace the removal of N in a cropping cycle (Spencer and Swift, 1992). The inherent capacity of some legumes to efficiently capture and recycle N, even if they are relatively poor N_2-fixers, has received little attention in BNF research. Does the merit of tree-legume use in agro-ecosystems lie in their ability to fix or simply their capacity to recycle N? Can BNF and nutrient cycling under a given legume cropping system be optimised? Although agroforestry research has generated considerable information on nutrient cycling and BNF by tree legumes, more emphasis has been on litter quality and nutrient release patterns (e.g. Cadisch and Giller, 1997). The objective of the study was to examine N cycling patterns in a natural ecosystem dominated by non-N_2-fixing leguminous trees and its implications on soil fertility management in cropping systems in which N_2-fixing are included. The N cycling patterns that have sustained a positive soil N balance within the natural miombo ecosystems in Zimbabwe are explored. Potential role of BNF in the N economy of the farming systems is then discussed in the context of legume productivity and N inputs under predominantly depleted soils. Particular reference is made to pigeonpea [*Cajanus cajan* (L.) Millsp].

2. Materials and Methods

Study sites

The study on N dynamics under the non-N_2-fixing tree species was conducted in a natural miombo woodland at Marondera (18°10'S; 31°30'E) in Zimbabwe. The Marondera site is a 5 ha patch of a "protected" (the woodland has been relatively undisturbed for over 40 years, during which fire and large herbivores have been excluded) savanna woodland situated on the central plateau of Zimbabwe. The natural vegetation is classified as deciduous miombo savanna woodland (Wild and Barbosa, 1967), and is dominated by the non-N_2-fixing leguminous species of *Brachystegia spiciformis* and *Julbernardia globiflora* with a ground cover of a variety of grasses and forbes. Detailed site characteristics are given by Campbell et al. (1988). Pigeonpea (N_2-fixing) studies were conducted at Domboshawa Training Centre (31°09'E; 17°36'S) and in Murewa Communal Area (17°45'S; 31°45'E) (Mapfumo et al., 1998). The arable sites used at Domboshawa and Murewa were both derived from the clearing of miombo (predominantly *Brachystegia* and *Julbernardia* species) for permanent cultivation. All the three sites are in a sub-humid environment and fall under Zimbabwe's Agro-ecological Region II (Vincent and Thomas, 1960). The climate of the study sites is strongly seasonal with over 80% of the mean annual rainfall of between 750–1000 mm falling between November and March. The soils are strongly leached alfisols derived from granitic parent material and are classified as Kandic Paleustalfs (Soil Survey Staff, 1990). The soil textures range from being sandy to sandy loams and the clays are almost entirely 1:1 kaolinite. The nutrient status of the soils is low in both natural and arable systems. The only noticeable difference occur in the top 10 cm of the soil matrix with organic C and soil N contents ranging between 2 and 4% C and 0.12 to 0.20% N in the miombo woodland (Mtambanengwe, 1999) and the Domboshawa sites. The Murewa site has been under continuous cultivation for over 50 years and contain 0.4% C and 0.04% N on average.

Investigation of N dynamics under the non-N_2-fixing miombo trees

The *in situ* N mineralization technique (Anderson and Ingram, 1989) was used to determine the N mineralization potential of native soil organic matter from three different systems throughout the 1995/96 and 96/97 rainy seasons (December to May). These comprised a natural miombo woodland, an arable area and an adjacent area which had been cleared for tillage and amended with miombo leaf litter. Both the arable and the tree leaf litter-amended sites were cleared of miombo in 1992 for soil organic matter studies and had since been under closely monitored land management regimes. No crops were grown under these treatments and any new aboveground biomass was continually removed accompanied by intensive soil disturbance via hoe tillage. Two millimetre stainless steel incubation tubes of 100 mm diameter and 150 mm length were inserted into the ground to a depth of about 10 cm. The tubes were immediately withdrawn and the soil collected in polythene bags (Time 0). The now empty tubes were reinserted into the soil and covered with a perforated plastic cap and left in the field for two weeks after which soil samples were again collected (Time 1). The process was repeated every fortnight for the five months study period. Soils collected at each time were immediately analyzed for extractable NH_4^+-N and NO_3^--N (Keeney and Nelson, 1982), and for soil moisture content. For soil moisture content, the soil was oven-dried at 105°C to a constant weight.

During a twelve-month period (December to November), freshly fallen leaf litter materials (leaflets and petioles) from a woodland site was collected fortnightly for three years. Total monthly litterfall was estimated through the addition of the two sets of collected litter within the same month. The litter collection was extended beyond the rain season in order to capture the magnitude of N input occurring during the dry season. The collected litter was oven-dried at 60°C, weighed and ground to pass through a 1 mm sieve on a Wiley mill. Sub-samples of the ground material were then withdrawn and analyzed for total N (Anderson and Ingram, 1989). The total amount of litter per month was then multiplied by the N concentration in the leaf material for that month to give the possible total N contributions to growing crops at different times of the year.

Comparative studies on N_2-fixing species

The BNF data used was mainly drawn from a study initiated in 1996 to determine the potential contribution of pigeonpea to soil fertility management in smallholder farming systems (Mapfumo, 1998). Additional information was also drawn from some published and unpublished reports. In this study, the effect of different pigeonpea management systems (green manure, forage and seed crop) on subsequent maize crop was being investigated. The pigeonpea was allowed to grow over two seasons with shoot N content being determined at flowering for both the one- and two-year crops at 15 farm locations.

3. Results and Discussion

Soil N input and accumulation

There were no major differences in soil mineral N (NO_3^--N + NH_4^+-N) accumulation for the first eight weeks after the onset of the rainy season. However, between nine and 20 weeks the natural woodland (control) and litter-amended soil had mineralized up to double the amount of available N compared to the arable field (Fig. 1). The leaf litter-amended soil followed the same pattern as the control, suggesting that leaf litter was the main contributor to soil N within the natural miombo ecosystem. According to Campbell et al. (1988), leaves may account for 70% of the annual litterfall. There was a highly significant ($P<0.001$) correlation between soil N mineralization and total N input from miombo leaf litter (R^2 = 0.92). However, there was no correlation between monthly N mineralization and monthly N input ($P<0.05$; R^2 = 0.29). This suggests that addition or removal of litter from the system has no immediate effect on N use by the trees, but may greatly affect N availability in the next season. Decomposition studies in natural systems have shown that N mineralization in the tropics hardly occurs during the dry months of May to October (Mtambanengwe, 1999). The significant correlation

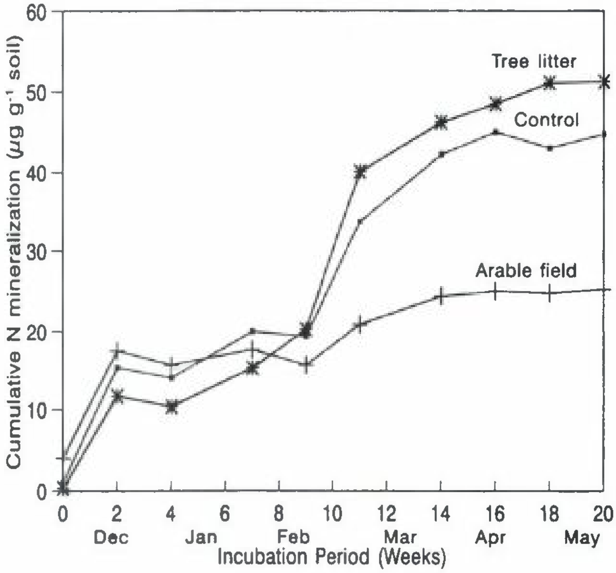

Figure 1. N mineralization of a sandy-loam soil under a natural woodland (control), arable field and miombo leaf litter amended plot.

between N input and soil N accumulation in the control may simply be a reflection of differential N inputs from the previous season's litterfall. Studies in this woodland have shown high rates of litterfall during the dry season due to the deciduous nature of the woodland species and the high water stress experienced by the woodland plants during the same period (Chidumayo and Frost, 1996; F. Mtambanengwe, unpublished). Apparently there is almost a one-season time lag between N input from litterfall and soil N accumulation. Mtambanengwe and Kirchmann (1995) concluded that miombo litter may not be a good source for mineral N within the first 2–3 months after addition. The results suggest that the low N accumulation observed in the arable treatment may be due to the break in N input pattern resulting from litter removal (Fig. 1). Mineralization of native soil organic matter may therefore not be a major contributor to the N economy of miombo ecosystems. This may explain the continuous decline in crop productivity often observed in these miombo-derived agro-ecosystems.

Plant N accumulation

Nitrogen concentration (%N) in the leaf litter increased with the start of the rainy season (Fig. 2a) and started declining with the onset of the dry season

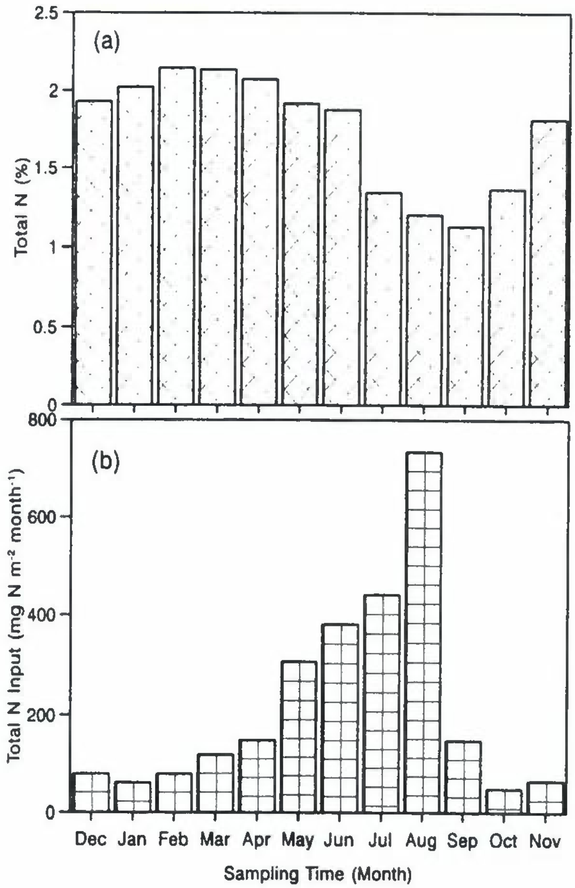

Figure 2. Total nitrogen (% dry weight) of freshly fallen miombo leaf litter (a), and the total N input to the soil system (b) during the course of the year.

(May). Results indicate that there is a sharp decline in %N during the dry months of May to September (Fig. 2a). The leaf N concentrations averaged 2.03% during the rainy season. This value was much higher than that of the non-leguminous *Parinari curatellifolia* (0.73%) and slightly lower than those of the N_2-fixing *Acacia* (2.24%) and perennial *Cajanus* (2.59%) species growing in the same environment (Table 1). This confirms reports of high shoot N concentration in non-N_2-fixing legumes (Giller, 1998). Although some recent work has indicated the possibility of non-nodular N_2-fixation by some members of the leguminosae (Bryan et al., 1996), high shoot N concentration may simply be due to the legumes' capacity to efficiently mobilize and take up N from the soil. This trait is apparently exhibited by both N_2-fixing and non-N_2-fixing

Table 1. Leaf and shoot N concentrations for N_2-fixing and non-fixing tree species grown on granite-derived sandy soil in Zimbabwe

Plant species	%N	Data source
Miombo litter (leaf) [1]	2.03	This study
Miombo litter (leaf) [1]	2.24	Nyathi and Campbell, 1994
Parinari curatellifolia leaf [2]	0.73	Mtambanengwe et al., 1998
Pinus patula [2]	1.30	King and Campbell, 1994
Acacia sieberana leaf [3]	2.24	Mtambanengwe et al., 1998
Cajanus cajan leaf [4]	2.50	P. Mapfumo, unpublished
Cajanus cajan shoot [4]	1.64	P. Mapfumo, unpublished
Cajanus cajan shoot [5]	2.59	P. Mapfumo, unpublished

[1]Non-N_2-fixing legume; [2]non-leguminous; [3]N_2-fixing legume; [4]perennial pigeonpea over one season; [5]perennial pigeonpea grown over two seasons.

Table 2. Potassium, calcium and magnesium (% dry weight) uptake in pigeonpea, cowpea and maize shoots (at flowering) at Domboshawa, Zimbabwe

Plant	Potassium	Calcium	Magnesium
Pigeonpea	0.62	1.26	0.27
Cowpea	2.53	0.93	0.40
Maize	1.13	0.09	0.13

Source: P. Mapfumo, 1998 unpublished.

legumes. In this study, two N_2-fixing legumes, cowpea and pigeonpea, showed a relatively higher K, Ca and Mg uptake compared to maize (Table 2). This may also suggest that legumes are better able to acquire, and hence recycle, these soil nutrients.

Implications for BNF and soil fertility management

The results suggest that the N economy of the miombo ecosystem is largely dependant on maintenance of a self-renewable nutrient capital, taking advantage of the efficient N capture by the legume trees. Leaf litter plays a central role in the N cycling process. This ability by legumes to efficiently capture soil nutrients has not been fully exploited in agricultural systems. BNF research has apparently put much more emphasis on amounts of N_2-fixed. Efficient nutrient capture should also be a basis for legume selection. In this study, the difference in %N between one- and two-year old pigeonpea shoots (Table 1) raises a question of whether this was due to increased N_2-fixation or enhanced N uptake with growth duration. In tropical ecosystems, productivity of N_2-fixing legumes has often been constrained by inherent low soil fertility and other environmental factors resulting in low amounts of N_2-fixed (Sprent, 1979; Giller and Wilson, 1991). However, some legumes have been shown to perform relatively well on depleted soils. In ancient agriculture, lupins (*Lupinus* spp.) have been described as a "wolf believed to destroy or exhaust the fertility of soils", apparently referring to their high nutrient capture (Allen and Allen, 1981). Baylis and Hamblin (1986) reported high P and K mobilization in lupins compared to cereals. Recent studies have shown superior performance of velvet bean (*Mucuna puriens* L.) over other legumes on depleted sandy soils (Muza and Mapfumo, 1998). These studies suggest that legumes may be an important tool in the cycling of nutrients in low input agriculture. The high shoot N concentration in both N_2-fixing and non-N_2-fixing legumes suggests that N_2-fixation per se may not be the best criterion for legume selection in sustainable agriculture. We propose that management of legume residues may play equally the same role in nutrient cycling as that of miombo leaf litter, while BNF is used as a basis for sustenance of legume productivity. The relatively high concentration of basic cations (Table 2) in legumes suggest that BNF may be used as a vehicle for the cycling of other nutrients.

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