Nitrogen cycling in agroforestry systems of sub-humid Zimbabwe: Closing the loop

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Proefschrift
ter verkrijging van de graad van doctor
op gezag van de rector magnificus
van Wageningen Universiteit,
Prof. dr. ir. L. Speelman
in het openbaar te verdedigen
op dinsdag 23 maart 2004
des namiddags te vier uur in de Aula

Regis Chikowo (2004)

Nitrogen cycling in agroforestry systems of sub-humid Zimbabwe: Closing the loop.

PhD thesis, Wageningen University, Wageningen, The Netherlands
With summaries in English and Dutch.
ISBN: 90-5808-968-X

Abstract

Chikowo, R 2004. Nitrogen cycling in agroforestry systems of sub-humid Zimbabwe: Closing the loop. PhD Thesis, Wageningen University, The Netherlands, 139 pp.

This thesis focuses on nitrogen: its acquisition in cropping systems through biological N_2-fixation and subsoil capture, its release by legume prunings and litter, its use by maize and its loss through leaching and as nitrous oxide gas. The context of the study is improved fallows using leguminous trees/shrubs on a sandy clay loam soil under sub-humid conditions in Zimbabwe.

Two-year legume fallows of *Sesbania Sesban, Acacia angustissima* and *Cajanus cajan* were evaluated for their residual N effects on two subsequent maize crops under minimum and conventional tillage management. The proportion of N_2-fixed in litter was 56, 55, 84 and 58 % for *Acacia, Sesbania*, *Cajanus,* and cowpea, respectively, resulting in inputs of biologically fixed N of 122, 84, 97 and 28 kg N ha^{-1}. Maize growth following the legumes for two subsequent cropping seasons was in most cases not directly related to the N inputs due to pest infestation and drought. On a sandy soil, these legumes adapted poorly and did not improve N cycling.

Soil samples for mineral N determination in profiles were taken at fallow termination and every two weeks during maize cropping with an auger in 0.2 m sections to 1.2 m depth. Pre-season NH_4^+ amounts were > 12 kg N ha^{-1} in the 0-0.2 m layer for treatments that had a large litter layer. There was a flush of NO_3^--N in the *Sesbania* and *Acacia* plots with the first rains. Topsoil NO_3^- had increased to >29 kg N ha^{-1} by the time of establishing the maize crop. NO_3^--N amounts decreased rapidly within three weeks of maize planting to 9 and 11 kg N ha^{-1} for the *Sesbania* and *Acacia* plots, respectively. Total NO_3^--N leaching losses from the 0-0.4 m layer ranged from 29-40 kg ha^{-1} for *Sesbania* and *Acacia* plots within two weeks when 104 mm rainfall was received to an already fully recharged soil profile. NO_3^--N then increased below the 0.4 m depth during early season when the maize had not developed a sufficient root length density to effectively capture nutrients. Nitrous oxide emissions were small, with a peak of 12 g N_2O-N ha^{-1} day^{-1} from *Sesbania* plots and near background fluxes in maize monoculture plots. The decrease of mineral N concentration in the topsoil resulted in reduced N_2O fluxes, despite very high soil moisture conditions. N_2O-N emissions were greatest for *Sesbania* plots with only 0.3 kg ha^{-1} lost in 56 days.

The effects of improved fallows on rainfall partitioning and associated soil loss were investigated using simulated rainfall at 35 mm h^{-1}. Immediately after fallow clearance, infiltration rates were greater than water application rate for the *Acacia* and natural fallow treatments, but steady state infiltration rates were 24 mm h^{-1} in *Sesban* and 5 mm h^{-1} in continuous maize. The estimated runoff losses after 30 minutes of rainfall were 44% from continuous maize compared with 22% from *Sesbania* and none from *Acacia* and natural fallow plots. After one post-fallow crop, water infiltration was still greater than 35 mm h^{-1} in the *Acacia* plots. Steady state infiltration rates after 30 minutes of rainfall were 8 and 5 mm h^{-1} for *Sesbania* and continuous maize systems, respectively. Planted tree fallows increase infiltration rates, but the effect markedly decrease after one year of maize cropping in non-coppicing tree fallows.

In a field litterbag decomposition experiment, the course of the decomposition could be adequately described by the function $Y = (Y0-Q)e^{-kt} + Q$, and the relative decomposition constants for *Sesbania* and *Acacia* litters were 0.053 and 0.039 d^{-1}, respectively. Under laboratory incubation conditions, N mineralized from fresh *Sesbania* prunings was 55% after 120 days compared with 27% only for the *Sesbania* litter. During the same period, fresh prunings of *Acacia* released only 12 % of the added N while *Acacia* litter released 9 %. N mineralization from *Acacia* fresh prunings was depressed by the high protein binding capacity of its polyphenols. Except for *Sesbania* litter, the rest of the senesced legume materials showed N immobilization up to 60 days.

The study showed that *Sesbania, Acacia* and *Cajanus* produced useful amounts of biomass on soils of at least loamy texture and improved N cycling significantly, but adapted poorly in lighter soils. Under conditions of severe texture constraints, mucuna showed robustness but has the disadvantage of having no direct food value. Gaseous N losses after incorporating legume materials were small, and the reduction of NO_3^- leaching is the single largest challenge to increased N recovery in the highly porous soils.

Key words: improved fallows, biological N_2-fixation, nitrogen cycling, nitrate leaching, nitrous oxide emissions, N mineralization -immobilization, granitic sands

Preface

This thesis is one of the many products of research on the IMProved fALlows for Africa project "IMPALA" funded by the European Union. My study in Wageningen University was supported by a grant from the Rockefeller Foundation. I want to sincerely acknowledge these two organizations for the generous funding.

I am particularly grateful to Professor Ken E. Giller, my promoter, for his foresight and unparalleled interest in students and their development. He has been the source of inspiration to me (and undoubtedly also to many of his former students at the University of Zimbabwe and elsewhere). I can openly say that this professor has taught me the practice of science and made me feel competitive and well-equipped to face the future challenges. Ken, it has been an honour for me to be your student.

Many thanks to Dr ir Peter Leffelaar, who accepted to be my co-promoter, and has been teaching me about modeling processes. Unfortunately, I could not include that component of my education in this thesis. To Dr Paul Mapfumo, my supervisor based at the University of Zimbabwe, thanks for those many years we carried out soil fertility research together. I learnt a lot from the daily interactions we had. That at one time we shared the office was special as ideas could be transmitted so efficiently.

After Prof. Giller had left the University of Zimbabwe, Mr Phillip Nyamugafata took over the management of the project. He facilitated all my work and I am thankful for his interest in the success of the research. I also thank George Nyamadzawo who did his Masters degree research on the same project with me. We spent most of the days in the field collecting data and samples together. And the other postgraduate and former graduate students in the Soil Science Department, I have to mention you all by name: Shamie Zingore, Comfort Manyame, Rebecca Zengeni, Chipo Musharo, Rangarirai Mhindu, Kumbirayi Musiiwa, Memory Matokwe and Pardon Muchaonyerwa: thank you all for those good days in the "x-ray room". Many who will read this won't understand why such a room! To Shibu Ebrahim, thanks for the companionship in the 'Attic' room of the Den Nuy building in Wageningen, specifically during the Christmas-New year holidays when I was finalizing the thesis preparation. To my friend, Muyeye Chambwera, it was nice to be together in Wageningen as you were also pursuing your PhD.

A major component of my field work in Zimbabwe was carried out at the field site of International Centre for Research in Agroforestry (ICRAF), and am indebted to Dr Lewis Hove for the smooth facilitation of my work. I would also want to thank Dr Stephen Waddington of CIMMYT for providing funds for me to participate in conferences through the Soil Fertility Network for maize-based farming systems of southern Africa. Dr Arvin Mosier helped with the N_2O analysis and I gratefully thank him for the most helpful advice with this part of my thesis work.

I would want to extend my gratitude to the Plant Production Systems Group secretaries (Ria van Dijk and Charlotte Schilt) for the splendid communication when I was in Harare as we were publishing the papers that constitute this thesis. I got every detail of the many pages they faxed that needed my attention from the journal editors.

And finally special thanks to my wife, Epiphania, for understanding that I had to be away from home. To my nearly three year old son, Tanaka, dad won't abandon you to go to 'college' again. I will be there to see you grow up. It was nice listening to your 'small talk' on the phone on those many evenings I would phone home.

Again, thank you all.

Wageningen, March 2004

I dedicate this work to my mother who passed away a week before I submitted the thesis

Contents

Chapter 1

General Introduction

Background and problem definition

Crop productivity in most of sub-Saharan Africa is on the decline as soils increasingly become depleted of nutrients (Smaling et al., 1997). Ensuring sustainable agriculture requires the implementation of methods to balance nutrients and soil organic matter. In the past, long natural fallow periods regenerated soil fertility but as populations gradually increased, more land had to be brought into cultivation. Currently, either natural fallow periods possible under the circumstances are too short to be effective in restoring soil fertility or continuous cropping is already being practiced. Fertilizer use on such lands is low and soil fertility has been declining rapidly due to the extractive agricultural practices, that also lead to accelerated soil erosion (Vlek, 1990; Stoorvogel et al., 1993). Many areas are marginal and increased land and labour productivity has to come from use of external inputs or improved nutrient cycling. But current economic conditions such as subsidy removal and high inflation are not conducive to high use of external inputs by smallholder farmers. Thus, under these circumstances, organic matter technologies such as green manures, agroforestry systems and animal manures could be important in sustaining crop production (Snapp et al., 1998).

While many soils in sub-Saharan Africa have problems related to acid infertility, the soils in many smallholder farming areas in Zimbabwe are derived from granites and are thus sandy and inherently infertile (Grant, 1981). The soils are characterized by poor clay content, poor organic matter content, have few weatherable minerals and are susceptible to erosion with agricultural use (Thompson and Purves, 1981; Burt et al., 2001). The clay mineralogy is predominantly 1:1, resulting in poor cation exchange capacity, low base status, and low pH (Nyamapfene, 1991). Nitrogen is one of the most limiting nutrients in these soils, and where soil N amendments are available, efficient use will be of paramount importance to make production of crops economically viable and sustainable. Nutrient use efficiency will be invariably low under these biophysical constraints, and substantial external inputs are required to maintain even modest levels of production.

To maintain production farmers have traditionally used small amounts of mineral fertilizers and a variety of locally derived fertilizers, including woodland litter, cattle manure, crop residues and anthill soil (Mugwira et al., 2002; Musvoto et al., 2000). A major issue in the use of these organic materials to meet N requirements of crops is that of ensuring that the release of N from mineralization coincides with the crop's demand and uptake (Swift, 1987). Synchronization of N supply and N demand will lead to increased N use efficiency by minimizing the opportunity for N loss (Woomer and Swift, 1995). The emerging dilemma is on the poor recovery by plants of the added organic N, as there is no single organic material that releases N in perfect synchrony to plant demand (Palm et al., 2001). With mineral fertilizers remaining beyond the reach of many smallholder farmers, one of the biggest challenges in southern Africa is to develop organic matter technologies that are effective within farmer resource constraints to sustain moderate levels of food production.

Nutrient cycling concept and sustainability

Legume trees and shrubs integrated with crops mediate nutrient cycling on farms by increasing the supply and availability of nutrients in the crop root zone and reducing nutrient losses (Rao et al., 1999). Nutrients accumulated by the legumes are returned to the soil either as litterfall, deliberately as prunings in some agroforestry systems and through root senescence. On granite derived soils, N is particularly limiting because of poor organic matter content and its cycling on agricultural fields can be enhanced through legumes with three main components: (1) more gains through biological N_2-fixation (2) decreasing losses through erosion, leaching, denitrification and (3) enhanced internal recycling within the system.

Natural forest ecosystems of the tropics represent self-sustaining and efficient nutrient cycling systems. These are nutrient cycling systems with relatively little loss or gain of the nutrients. In contrast, most agricultural systems represent 'leaky' systems with comparatively high nutrient losses. Even with continuous cropping, the rooting system of annual crop plants require some time to develop and are never as extensive as those of perennial plants, hence annual crop plants are unlikely to be as effective at recovering nutrients from the soils as natural perennial vegetation. There are opportunities to manage agricultural systems in a manner that would reduce nutrient losses, increase gains and ultimately upgrade productivity and sustainability of smallholder farms in Africa.

Improved fallows as an option for sustaining soil fertility

Long natural fallow periods are no longer a viable option due to increased population pressure in most of Africa. Short-term improved fallow technologies involve the rotation of crops with fast growing legume species for soil fertility restoration. The legume fallow and crops are introduced sequentially on the same land unit, thus eliminating the spatial element of competition. Sequential systems with short-duration leguminous trees and shrubs, as exemplified by *Sesbania sesban* rotated with maize, have been found to increase soil fertility significantly in southern Africa. In eastern Zambia, 2-year *Sesbania* fallows resulted in 2-3 fold yield responses of subsequent maize crops (Kwesiga and Beniest, 1998). Despite the large yield response following *Sesbania* fallows, its litter decomposes rapidly as it is rich in N and low in lignin and polyphenols. It is thus unlikely to contribute to long-term enhancement of soil organic matter status of soils (Giller et al., 1997). This is likely to be more so under conventional tillage, and there is scope of modifying decomposition rates with minimum tillage practices. *Acacia angustissima* is another tree legume that has potential for soil fertility restoration. Its litter decomposes more slowly and could be used as an option for building organic matter of sandy soils in the long term (Mafongoya et al., 1997).

It has been shown in many studies that legume fallow technologies improve nutrient cycling through enhanced availability of nutrients resulting from production and decomposition of substantial quantities of biomass, and deep roots of planted trees or shrubs acting as “safety nets” for nutrients, reducing leaching losses (van Noordwijk et al., 1996). More attention should, therefore, be given to inclusion of the natural recycling capacity of perennial leguminous trees in agricultural systems. Legumes that have regrowth capabilities after clearance such as *Acacia angustissima*, will be effective in cycling nutrients in subsequent years once they have established. In this system crops are grown at the same time that the coppicing trees are growing, with frequent cutback of regrowth to reduce shading and excessive competition for soil moisture. The trees are then allowed to grow after the crop has been harvested, until land preparation for the next crop. During this time the trees with an active and widespread root system will capture the nutrients that could have escaped the “safety-net” as a result of high mobility during the rainy cropping phase. In this way, nutrient cycling will be more efficient as substantial biomass is accumulated and nutrients are returned to the surface.

Tillage management and legume fallows

Soil organic matter contents in native soils are usually in a state of dynamic equilibrium where organic matter losses are balanced by organic matter inputs. Conventional tillage practices are largely responsible for soil organic matter decline due to the breaking up of soil aggregates and the exposure of aggregate-protected organic matter to microbial decomposition (Beare et al., 1994; Paustian et al., 1997). Incorporation of residues with tillage operations reduces the size of residue particles and increases the contact with soil particles and biota, thus producing increased breakdown of recently added C (Craswell and Lefroy, 2001). Under no-tillage there is reduced macroaggregate turnover, and increased formation of stable microaggregates in which C is stabilized and sequestered in the long term (Six et al., 2000).

Yields in no-tillage systems are limited due to N shortage, and legume fallows can overcome this constraint. Improved fallows can produce substantial biomass of high quality residues that do not lead to N immobilization, and can provide sufficient soil cover for benefits of no-tillage to be realized. No-till will enhance soil aggregation which is associated with soil C sequestration, improved water infiltration and resistance to soil erosion. The protection of high quality organic residues against microbial attack leads to delayed nutrient release, a scenario that may reduce nutrient loss when fast mineralization occurs before plant roots become established during the early crop phase. The role of legume improved fallows in soil organic matter maintenance is especially important in degraded sandy soils, where the conservation or build up of organic matter and its associated benefits, such as increasing cation exchange capacity are often as important as their role in N supply to crops.

Nitrogen loss pathways

Nitrate leaching

Nitrate leaching is a particular problem on the cultivated agricultural lands and it is often the most important channel of N loss from the field soils (Cameron and Haynes, 1986). Large quantities of high quality tree prunings (e.g. *Sesbania*) at the beginning of the rainy season can result in high rates of mineralization and subsequent large concentration of mineral-N in the soil. This is likely to be at a time when the crop plants are still small and not yet actively taking up nutrients. Mineral N not taken up by plants is susceptible to loss through downward leaching. Cultivation of soil is likely to stimulate mineralization of soil organic N and added organic materials, and can thus result in increased nitrate leaching if followed by large amount of rainfall. Conservation tillage generally results in a greater infiltration capacity because of the presence of surface mulches and the larger number of continuous macropores that are open at the surface (Unger and McCalla, 1980). In this system, initial leaching losses of surface-applied N can therefore be rapid if rainfall occurs soon after N application, as a significant movement of water and solutes will pass through the macropores. Conversely, N that has had time to diffuse into the aggregate micropores will be afforded greater protection from subsequent leaching due to the higher proportion of water flowing in the macropore system (Wild, 1981).

Gaseous N losses

Denitrification is a major biological process through which N from the soil is returned to the atmosphere (Firestone, 1982). The process, which is mediated principally by aerobic bacteria which are capable of anaerobic growth in the presence of N oxides, yields N_2O and N_2 gases. In the absence of O_2, nitrate serve as terminal electron acceptor for respiration electron transport during the oxidation of organic substrate and a more reduced N oxide or N_2 is produced and released into the atmosphere. Under aerobic soil conditions, the N oxide reductase enzymes are present in repressed form and when O_2 is removed from the soil, there are rapid increases in the absolute and relative activities of these enzymes and denitrification commences almost immediately. Following periods of intense rainfall, soils may become saturated with water for brief periods, and during such short periods, intense denitrification occurs (Jarvis et al., 1991). Denitrification can occur even in well-structured aerobic soils due to the occurrence of anaerobic microsites (Firestone, 1982). Anaerobic pockets in soils may often be localized areas of intense respiratory activity where O_2 demand exceeds supply (Leffelaar, 1979; Smith, 1980) rather than resulting from passive anaerobiosis.

Large amounts of readily decomposable organic matter can enhance the potential for denitrification through a general stimulation of microbial respiration, causing rapid O_2 consumption and an acceleration of the onset of anaerobiosis. Rates of denitrification are highly correlated with "available" soil C as evaluated by readily mineralizable C or water soluble organic C (Reddy et al., 1982). Janzen and Schaalje (1992) found that fertilizer N losses were twice as large when green manure plus fertilizer was applied to barley. Chang et al. (1998) showed that annual N_2O emissions increased with manuring rate and this is linked to the increase in easily mineralizable organic C that stimulates microbial biomass. A period under N_2-fixing crop in the field can lead to a significant accumulation of soil N and organic C that could influence soil N transformations, including accelerated soil denitrification (Guixin et al., 1999). It is therefore, a matter of concern that N restored to the soil by a legume fallow or organic fertilization may be subject to loss, when in fact such loss may be minimized through appropriate soil management practices.

Rationale of study

A number of research projects have aimed to optimize the harnessing of N through biological N_2 fixation and appropriate residue management thereafter. There is widespread literature on the inclusion of legumes in cropping systems as an effective method of sustaining soil fertility if conditions necessary for enhanced nodulation and large biomass accumulation are met (e.g McDonagh et al., 1993; Giller et al., 1997). However, the range of reported N recovery rates by crops in sequence with legumes are low and varied, and this may have contributed to poor adoption of some of the technologies. In some cases soil fertility technologies that have performed well elsewhere in the tropics, have been blindly pushed into harsh biophysical environments where they have failed dismally.

The marginal areas of the smallholder farms in Zimbabwe are limited by both bio-physical and socio-economic factors. They are marginal due to inherent infertility particularly on highly leached sandy soils, and induced infertility due to extractive management by resource-poor farmers that results in high runoff and erosion. The challenge is to define the niches where different legume technologies will work, and quantitatively determine the fate of the N applied in the different cropping systems, so as to find ways of improving management and efficiency.

The focus of this project was on monitoring N cycling through tree, shrub and grain legumes, quantifying biological N_2 fixation, and quantifying leaching and nitrous oxide N losses. These were studied in the context of conventional tillage and minimum or no–till practices after improved fallows.

Objectives of the study

The main objective of the study was to assess the contribution of various legumes to the management of N and improve soil fertility on smallholder farms in Zimbabwe. The specific objectives, the integral of which will give answers to the main objective were:

i) to determine nitrogen fixing potential of tree, shrub and grain legumes when grown on research station and under on-farm conditions;

ii) to determine maize response after two-year improved legume fallows and the residual effects in the subsequent seasons;

iii) to monitor mineral N dynamics as influenced by two tillage regimes after the fallow periods and estimate leaching losses;

iv) to study nitrous oxide emissions following improved fallow/no-till practices and continuous maize treatments;

v) to quantify infiltration rates, runoff, soil and nutrient losses following improved fallows;

vi) to investigate N release patterns of legume fresh and senesced materials and to model mineral N movement in soils, and

vii) to construct a complete N balance for an agroforestry system to enable assessment of sustainability of such systems.

Thesis outline

Chapter 2 reports on the productivity of two-year legume tree/shrub improved fallows and the associated N_2-fixation and N contributions to the soil N economy. The residual effects of the legume fallows to two subsequent maize crops are discussed in the context of conventional and minimum tillage.

In Chapter 3 nitrate-N dynamics during the first year of maize cropping following the termination of the legume fallows is described. Maize root development with time down the soil profile is also described in relation to nitrate-N dynamics and potential for uptake. In Chapter 4, nitrous oxide emissions are quantified during the first eight weeks following termination fallows, for the four treatments in which nitrate-N dynamics were also reported in Chapter 3 (unfertilized maize, *A. angustissima,* and *S. sesban* with and without tillage). More data is given on mineral N (nitrate and ammonium) dynamics under maize for the two seasons after improved fallows. This chapter on the fate of mineral N in soil attempts to answer the question of whether mineral N losses through leaching or gaseous N losses following improved fallow systems are the most important.

Chapter 5 reports on the effect of improved fallows on soil and water conservation. A portable rainfall simulator was used and rainfall was applied at an intensity of 35 mm h^{-1} on to plots soon after fallow clearance and then after maize cropping. Estimates of effects of the different management systems to the partitioning of the rainfall in to infiltration or runoff are given. In Chapter 6 an on-farm experiment, in which different soil fertility improvement practices were tested together on sandy soil, is reported. The treatments here included mineral fertilizer use, animal manure, grain legume-maize sequence and a range of legumes for soil fertility restoration. The biophysical constraint that smallholder farmers face on the sandy soils is highlighted and a gloomy picture is presented relating to the limited soil fertility improving technology options that are available to farmers in these environments given their socioeconomic circumstances.

Chapter 7 is based on decomposition studies using litter materials from the experiments described in Chapters 2 and 6. The experiments reported here are the field based decomposition in litterbags using litter of *Sesbania* and *Acacia*, and the leaching tube experiment with treatments that included fresh legume prunings and litter. In Chapter 8, the whole study is synthesized and a complete N cycle for an improved fallow agroforestry system is presented. The study's overall conclusions and recommendations are made.

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CHAPTER 2

Woody legume fallow productivity, biological N_2-fixation and residual benefits to two successive maize crops in Zimbabwe

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This chapter has been accepted for publication as:

Chikowo R, Mapfumo P, Nyamugafata P and Giller K E 2004. Woody legume fallow productivity, biological N_2-fixation and residual benefits to two successive maize crops in Zimbabwe. Plant and Soil (*in press*).

Abstract

Three woody legumes were planted as two-year ‘improved fallows’ to evaluate their residual nitrogen (N) effects on two subsequent maize crops under minimum and conventional tillage management. Maize monoculture and cowpea-maize-maize sequence treatments were included as controls. N_2-fixation was estimated using the ^{15}N natural abundance method to allow the N contribution from the fallows to be partitioned into N_2-fixation and soil N capture. *Acacia angustissima* accumulated the largest amount of both below-ground and above-ground biomass during the 2-year growth period. Using *Hyparrhenia* grass as the reference plant, the proportion of N_2-fixed in litter was 56, 55, 84 and 58 % for *Acacia, Sesbania sesban*, *Cajanus cajan,* and cowpea, respectively, resulting in inputs of biologically fixed N of 122, 84, 96 and 28 kg N ha^{-1}. Maize growth following the legumes for two subsequent cropping seasons was in most cases not directly related to the N inputs. The first year maize crop was severely infested with cutworms (*Agrotis* sp.) in the *Sesbania* and *Acacia* plots, while the second season maize was affected by drought particularly in the *Acacia* plots where there was high moisture demand by the re-growing trees. During the second season, N uptake by maize following *Sesbania* was significantly higher than the rest of the treatments. Conventional tillage resulted in better yields than minimum tillage across all treatments and in both seasons. It can be concluded that (1) improved legume fallow system results in net positive soil N balances, (2) despite large inputs of litter and continued recycling of N during the cropping phase, legume species that re-grow after cutting can result in depressed yields in drought seasons, and (3) tillage is beneficial even after improved legume fallows.

Key words: *Acacia angustissima*, *Cajanus cajan*, conservation tillage, cowpea, maize, N_2-fixation, pest infestation, *Sesbania sesban*

Introduction

Poor soil fertility has been identified as the major cause for poor yields of maize, the main staple food crop in Zimbabwe. Nitrogen and phosphorus (P) deficiencies are widespread, and large responses to mineral fertilizers are common (Grant, 1981; Piha, 1993). As a credible substitute for the expensive mineral fertilizers that most smallholder farmers cannot purchase under the current economic climate, a proposed strategy is to use fast-growing N_2-fixing leguminous trees and shrubs in an ‘improved fallow’ system, in which the legumes are planted on a field and allowed to accumulate N in the biomass over two seasons and rejuvenate soil fertility through litter additions. A maize crop will then follow in the third and subsequent seasons on the same plots. Improved fallows, were hypothesized not only to provide N for the subsequent cereal crops, but also to increase soil organic matter content and hence to improve soil physical conditions and P availability. Other nutrients would also be re-cycled through the tree biomass and returned to the soil during litter decomposition (Sanchez and Palm, 1996).

Sesbania sesban is one of the legume species that has been widely used in agroforestry in southern Africa (Kwesiga and Beniest, 1998; Mafongoya and Dzowela, 1999). A major advantage of the genus *Sesbania* is that most species are tolerant to waterlogging and saline and alkaline conditions. Rhizobia nodulating roots of *Sesbania* spp. are fast-growing strains, and are found in a wide range of African soils (Bala and Giller, 2001). *Cajanus cajan* is another N_2-fixing shrub legume that has potential to restore and sustain fertility in some Zimbabwean soils (Mapfumo et al., 1999). According to Nene and Sheila (1990), the crop has occupied an important place in smallholder farming systems because of its drought tolerance, relatively good performance on poor soils and N_2-fixing ability. The roots can penetrate the soil to more than 2 m depth, although most extensive root development takes place in the upper 60 cm (Reddy, 1990). Its deep rooting system, together with mycorrhizal associations, allows for efficient nutrient capture and cycling. *Cajanus* is nodulated by a wide spectrum of rhizobia strains belonging to the slow-growing and alkali producing cowpea group (*Bradyrhizobium*) as well as the fast-growing rhizobia (Bromfield and Kumar Rao, 1983), and has been successfully grown in many parts of Africa. *Acacia angustissima* is a coppicing legume tree (regrows after cutting) that was introduced to southern Africa from Bolivia, but its N_2-fixation characteristics have been little studied in the region.

The general hypothesis behind this study was that the woody legumes accumulate adequate N over a two-year fallow period and meet a substantial part of the N requirements of at least two subsequent maize crops. The objectives of the study were to (1) quantify the above and belowground biomass of two-year old *Sesbania sesban, Acacia angustissima* and *Cajanus cajan*; (2) estimate the proportion of legume N derived from biological N_2-fixation using the

^{15}N natural abundance method; and (3) assess maize N uptake under conventional and conservation tillage management for two seasons following fallow clearance.

Materials and methods

Site and treatments

The experiment was conducted at Domboshawa (17°35’ S; 31°14’ E), in the experimental fields of the International Centre for Research in Agroforestry (ICRAF), about 30 km north east of Harare. The soil has clay content of 22 %. The mean annual rainfall is 750 mm and occurs during a single rainy season extending from November to April. The 2000/01 season received above normal rainfall of 1 218 mm, but rainfall in the 2001/02 season was below normal, with a total of only 461 mm, 75 % of which was received between December 2001 and January 2002 (Figure 1). The experiment was initially established in November 1991 in a phased entry of fallows to result in 1, 2 and 3-year legume fallow durations by October 1994. In November 1994 the legumes were cleared and the plots were grown with four successive maize crops until May 1997. Detailed results of this phase of the experiment were published already (Mafongoya and Dzowela, 1999).

A new cycle of 2-year legume fallows in the same plots (reported in this paper) began in November 1998 (Figure 2). Six treatments were studied: 2-year fallows of (i) *Sesbania sesban* (ii) *Acacia angustissima* (iii*) Cajanus cajan* (iv) natural grass; and (v) cowpea–maize-maize sequence and (vi) continuous maize cropping. A cowpea-maize-maize treatment (in which two maize crops were planted after a cowpea crop that was planted during the second year of woody legume fallows) was included to capture one of the practices commonly used in cropping sequences by smallholder farmers. In the continuous maize cropping plots, maize had been planted year after year since the beginning of the first phase of the experiment in 1991. *Sesbania* and *Cajanus* were established by transplanting seedlings and direct seeding, respectively, while *Acacia* was established through seedlings during the first fallow cycle and had survived since then through its coppicing ability. This eliminated the need for *Acacia* re-establishment from seedlings after the four years of maize cropping. During the maize cropping phase, the *Acacia* regrowth was cut back after every three weeks at near ground level to reduce competition for light and water with the growing maize crop. Each of the plots was 12 m x 16 m. The three woody legume treatments were replicated nine times, as the original plots with phased entry of fallows were maintained, while the other three treatments were replicated three times.

Determination of fallow biomass

Two-year old fallows of *Sesbania, Acacia* and *Cajanus* were cut at ground level in October 2000. Standing biomass of wood, twigs, leaves and pods was quantified separately on a dry matter basis. After cutting the trees, all woody plant materials (>5 mm diameter) were

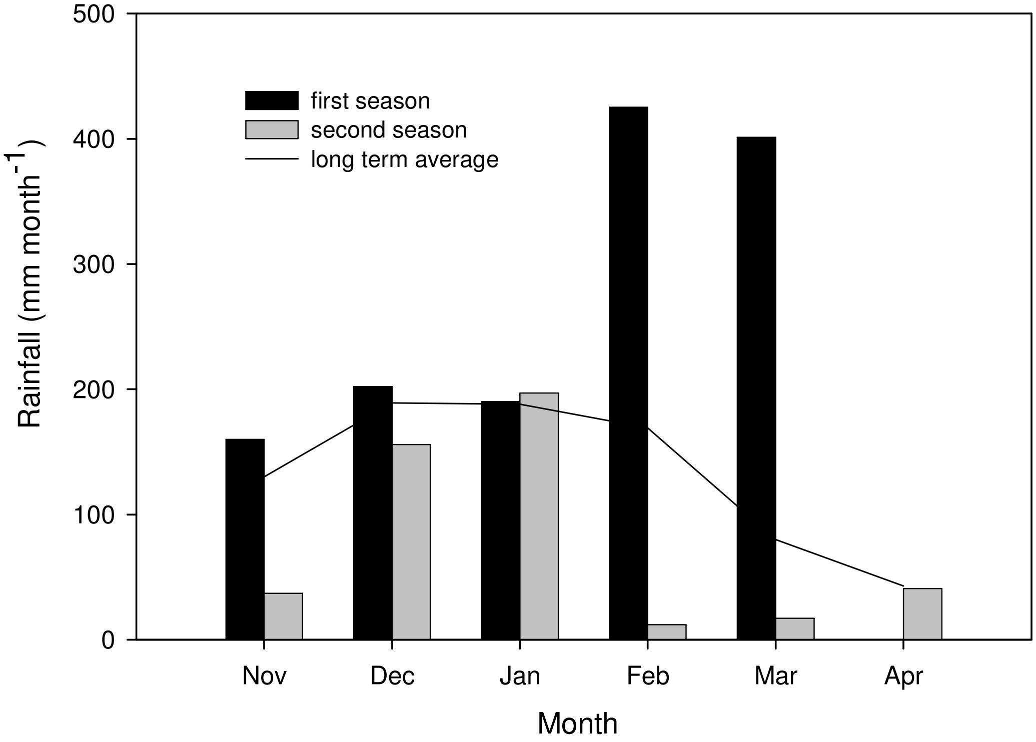

Figure 1. Rainfall distribution during the two immediate post fallow cropping seasons, between November 2000 and April 2002, and long-term average Domboshawa, Zimbabwe.

removed from the plots for firewood, whereas twigs (<5 mm diameter), leaves and litter were left in the plots for incorporation. To determine litter biomass, litter accumulated on the soil surface was collected using 0.5 m x 0.5 m quadrats at five positions in each plot, just before termination of the fallows. For the determination of root biomass, a "representative tree" in each replicate was identified for each species, after which 1 m^2 pits were dug in 0.2 m sections to a depth of 1 m, with the trees at the centre. Roots were recovered from the excavated soil by washing through a 1 mm sieve and drying to constant weight. The root biomass, which was obtained from 0.2 m^3 soil volume, was then expressed as kg ha^{-1} layer^{-1} after taking the tree population into consideration.

Estimation of N_2-fixation

The proportion of plant N derived from fixation by the legume species were estimated using the ^{15}N natural abundance method (Peoples et al., 1989) after two years of tree growth. Maize from unfertilized plots and *Hyparrhenia rufa* grass from adjacent paths were used as non-fixing reference plants. Samples of leaves + thin twigs, twigs < 5 mm, litter collected from the soil surface, and roots were kept separate. The biomass of *Acacia* regrowth was also determined at each pruning every four weeks during the following two cropping seasons.

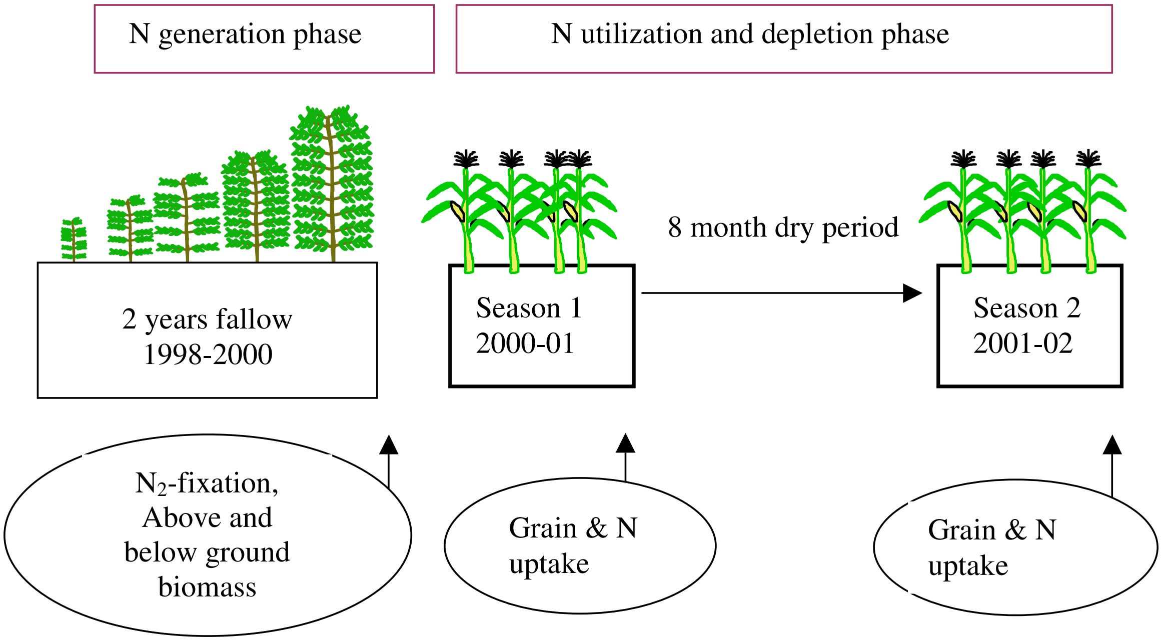

Figure 2. The cropping pattern from establishment of legume fallows to the end of the second maize crop covering a four-year period: 1998-2002. The graph is not drawn to real time scale.

Hyparrhenia grass was collected at the time of harvesting the fallows, while maize stover was collected at the end of the first cropping season after the fallows from the continuous maize plots. Samples were placed in paper bags, oven dried at 60 °C for 48 hours and ground to pass through a 1 mm sieve. The samples were analyzed for %N and ^{15}N using a 20-20 stable isotope mass spectrometer, coupled to a CN auto-analyzer and $\delta^{15}N$ was computed as:

$$\delta^{15}N\ (^{o}/_{oo}) \; = \; 1000 \;\times\; \frac{(\text{atom\% }^{15}N\text{ sample} - 0.3663)}{0.3663}$$

as the natural abundance ^{15}N of the air is a constant 0.3663 atom % ^{15}N (Hogberg, 1997). The proportion of legume N derived from N_2-fixation was then calculated as:

$$\%\ N_2\text{-fixation} \; = \; 100 \;\times\; \frac{\delta^{15}N\text{ (reference crop)} - \delta^{15}N\text{ (legume N)}}{\delta^{15}N\text{ (reference crop)} - B}$$

where $\delta^{15}N$ (reference crop) was obtained from a non-fixing reference plant grown in the same soil as the legumes. B is $\delta^{15}N$ of the same nodulated N_2-fixing plant when grown with N_2 as the sole source of N, a measure of isotopic fractionation during N_2-fixation. B values were obtained from the literature (Boddey et al., 2000; Gathumbi et al., 2002; Peoples et al., 1989).

First maize crop (2000-2001 season)

Before planting maize, all the plots were divided lengthwise into conventional tillage (T) and no-tillage (NT) sub-plots. In conventional tillage, soil was inverted and plant materials incorporated into the soil through an ox-drawn plough to a depth of 0.2 m, whereas only planting holes were opened for seed placement for the no-till subplots. The legume roots were left in the soil to decompose in both cultivated and uncultivated sub-plots. The plots were further subdivided into plus or minus fertilizer (+F or –F) sub-subplots, to result in 4 management systems per plot (T+F; T-F; NT+F; and NT-F). The main plots were 16 m x 12 m, the two subplots were 8 m x 12 m and the sub-subplots were 8 m x 6 m. The fertilized sub-subplots received 12 kg N ha^{-1}, 9 kg P ha^{-1} and 20 kg K ha^{-1} in form of a soluble compound fertilizer incorporated into the soil. All the plots were then sown with maize at 0.9 m inter-row and 0.3 m within row spacing. A top dressing of 40 kg N ha^{-1} as ammonium nitrate was applied at 6 weeks after crop emergence (WAE) to the fertilized sub-sub plots. Dry matter accumulation and N uptake were monitored by destructive maize harvests at 4, 8, 12 WAE and at maturity on a net plot. Four maize plants were sampled per plot by cutting at ground level. At each of these sampling times, alternate maize plants were sampled from rows next to the border row, and cut at soil level. At the final maturity harvest, maize grain and above ground biomass yield was obtained from an area of 10.8 m^2 comprising three middle rows of 4 m lengths.

Second maize crop (2001-2002 season)

Residual fertility was assessed on another maize crop in the second year after termination of the fallows. This time, all plots were fertilized with 18 kg P ha^{-1} and 40 kg K ha^{-1} basal fertilizer, as single superphosphate and muriate of potash, respectively. Crop management was similar to that of the first year, except that only 20 kg N ha^{-1} was applied to the +F subplots as top dressing at 4 WAE. The other complement of the fertilizer split could not be applied later on because of moisture stress. Maize biomass accumulation and N uptake were determined at 8 WAE, and at final harvest, following the procedure described above for the first year maize crop. All plant samples were oven dried at 65 ^{o}C for dry matter determination. Samples were later ground to pass through 2 mm mesh for N analysis. Maize N uptake was calculated by multiplying the maize tissue N concentration by the corresponding dry matter yields. Maize yield (grain and stover) and the associated N uptake were analyzed by ANOVA (GENSTAT, 1997) and means were compared at probability $P<0.05$.

Table 1. Aboveground biomass and litter (fine twigs and senesced leaves) (Mg ha^{-1}) from two-year old legume fallows and annual cowpea at Domboshawa field experiment, Zimbabwe.

Legume species	Plant material				
	Woody (>5 mm)	Twigs (<5 mm)	Fresh leaves	Litter (fine twigs + leaves)	Pods/seed
A. angustissima	15.2 (1.10)	1.02 (0.21)	0.43 (0.05)	9.49 (0.58)	nd
S. sesban	8.91 (1.03)	2.28 (0.17)	0.21 (0.02)	5.52 (0.30)	0.19 (0.02)
C. cajan	3.80 (0.36)	1.40 (0.12)	0.19 (0.02)	5.07 (0.23)	0.34 (0.03)
Cowpea	0	0	0	2.5 (0.18)	0.87 (0.08)
P	<0.01	<0.01	<0.05	<0.01	<0.01

Standard error of means (SEM) values are presented in parenthesis: nd = not determined

Results

Fallow productivity

Most of the standing biomass at the end of the fallow period was woody for all the three species (Table 1). *Acacia* had the largest biomass of both litter and woody material, whereas fresh leaves, which normally have highest N concentration among the components that remain in the field after harvest, constituted a small fraction of the total biomass at fallow termination across all legume species. Total above ground biomass as well as litter followed the order *Acacia* > *Sesbania* > *Cajanu*s > cowpea. Among the three improved fallow species, *Cajanus* yielded the greatest amount of seed (0.34 Mg ha^{-1}), while cowpea, which was grown primarily as a food legume, produced 0.87 Mg ha^{-1} grain (Table 1). As was the case for the woody components, seed was harvested and taken-off the field.

Root biomass was significantly different for the three woody legume species (*P*<0.01) in the top 0.6 m. *Acacia* had the largest root biomass at all depths (Figure 3). While there was an exponential reduction in root biomass with depth for *Sesbania* and *Cajanus*, *Acacia* root biomass decreased less dramatically. *Acacia* showed vigorous re-growth soon after cutting, suggesting that most of the roots remained active after cutting, and thus may not contribute

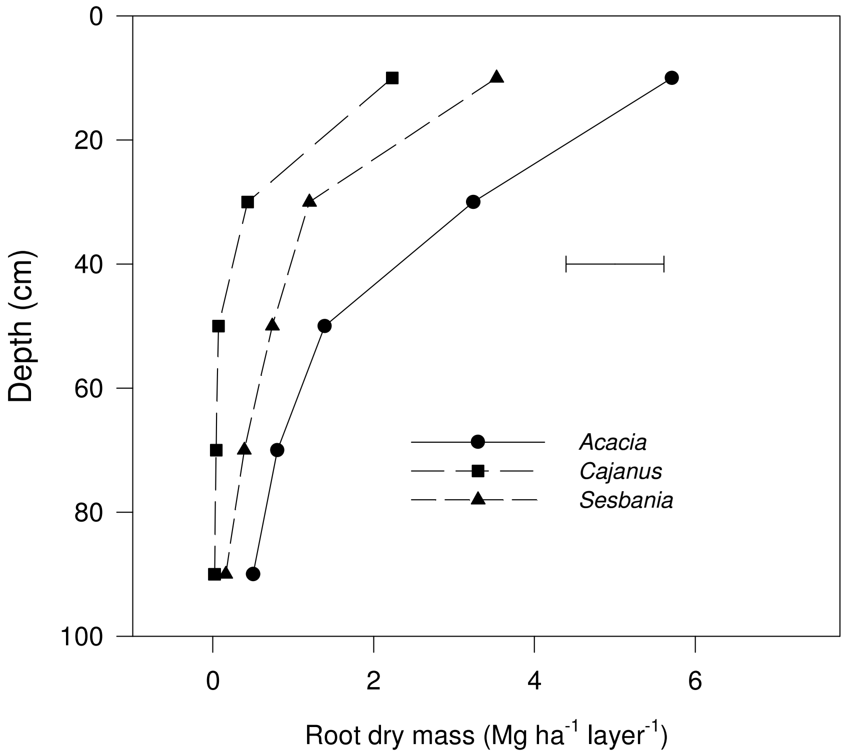

Figure 3. Root biomass as a function of depth for two year-old legume species at Domboshawa, October 2000. The horizontal error bar represents pooled LSD (P<0.05) for comparison of root biomass of the three legume species at the various depths.

substantially to nutrient and soil organic input below ground. The roots from all the three tree species had low N concentrations (<1 %). Total root N content in the top one metre depth was 27, 54, and 104 kg N ha^{-1}, for *Cajanus*, *Sesbania and Acacia*, respectively. Of the total root biomass in the top 1 m, *Acacia* had 48 % of its root biomass in the 0-0.2 m depth, *Sesbania* had 62 %, and *Cajanus* had 79 % within the same depth. There was an increase in finer roots with depth for all the three species, but these did not contribute much to root biomass. The coppicing *Acacia* had a dense fine root system in the 0-20 cm layer.

N_2-fixation by legumes

The $\delta^{15}N$ signatures of non-N_2-fixing controls were 1.08 and 3.01 for maize and *Hyparrhenia* grass, respectively (Table 2). All the four legumes had significantly lower $\delta^{15}N$ values than the non-fixing controls. There were large differences in the $\delta^{15}N$ signatures of the different N input components of the fallow system. The lowest $\delta^{15}N$ signatures were found to be associated with the twigs for all the three woody species, with *Sesbania* twigs having the

Table 2. Estimates of % N derived from N_2-fixation by *Acacia, Cajanus, Sesbania* and cowpea, as determined by the ^{15}N natural abundance method using unfertilized maize and *Hyparrhenia* grass as reference plants.

Legume species	Plant part	*B*-value[a]	$\delta\ ^{15}N$ ($^{o}/_{oo}$)	N_2–fixation estimate (%) maize	N_2–fixation estimate (%) *Hyparrhenia*
A. angustissima	Leaves	-1.50[b]	0.81	11	48
	Regrowth*		0.80	10	49
	Twigs		-0.58	64	79
	Litter		0.46	24	56
	Roots		0.42	25	57
S. sesban	Leaves	-1.76[c]	0.95	5	42
	Twigs		-0.66	56	73
	Litter		0.39	23	55
	Roots		0.46	20	53
C. cajan	Leaves	-0.90[d]	-0.05	54	76
	Twigs		-0.47	73	86
	Litter		-0.29	68	84
	Roots		-0.02	50	80
Cowpea	Residues	-1.66[e]	0.32	28	58
Non-N_2 fixing controls					
Maize			1.08		
Hyparrhenia grass			3.01		

*leafy material harvested from coppicing *Acacia* during the cropping season

[a] δ value obtained from the same plant grown on N-free sand nutrient solution mixture and hence plant relying solely on N from N_2-fixation

[b] Our estimate, no data readily available

[c] Gathumbi et al. (2002)

[d] Peoples et al. (1989)

[e] Boddey et al. (2000)

most dilution. All the $\delta^{15}N$ signatures for *Cajanus* plant parts were negative. The $\delta^{15}N$ values for *Acacia* leaves harvested at fallow termination and those of leaves harvested from the regrowth material at the end of the first cropping season, were remarkably similar (Table 2).

The proportions of N_2-fixed in plant litter (using *Hyparrhenia* grass as reference plant) were 56, 55, 84, and 58 % for *Acacia, Sesbania, Cajanus* and cowpea respectively. Litter was the component that had the greatest N input to the soil, as it was the largest component returned to the soil (Table 1). Considering fresh leaves alone, *Cajanus* fixed 76 % of its N, *Acacia* 48 %, and *Sesbania* fixed 42 %. Estimates of N_2-fixation were lower in all cases when maize was used as the non-N_2-fixing reference plant. The disparity in calculated values using the two reference plants was very wide, for example 11% and 48% for *Acacia* leaves using maize and *Hyparrhenia*, respectively (Table 2). For the three woody species, there was generally a high proportion of N derived from N_2-fixation in the twigs.

N contribution by the legumes

Total recyclable N contained in fresh prunings and litter was highest for *Acacia* with 218 kg N ha^{-1} during the two-year fallow period. *Sesbania* and *Cajanus* recycled 152 and 115 kg N ha^{-1}, respectively, largely through litter (Table 3). As wood was removed, the estimated net N contribution by the legumes to the soil N economy was calculated using % N_2-fixation for litter and fresh prunings from Table 2, and their respective fallow N yield data for the different fallow components from Table 1. Total fixed N (estimated using *Hyparrhenia* as reference plant) contained in the non-woody components of the above ground biomass plus litter was highest for *Acacia* with 122 kg N ha^{-1} during the two-year fallow period. *Cajanus, Sesbania* and cowpea fixed 97, 84 and 28 kg N ha^{-1}, respectively (Table 3). *Acacia* also accumulated the highest amount of soil N (96 kg N ha^{-1}), and was followed by *Sesbania* (68 kg N ha^{-1}). *Cajanus*, which had the highest N_2-fixation rate, sourced only 18 kg N ha^{-1} from the soil (Table 3).

Total soil N amounts exported from the field in wood and grain ranged between 11 and 53 kg N ha^{-1}. Of the woody species, *Cajanus* exported the least amount of soil N (14 kg N ha^{-1}) in the harvested wood plus seed, while *Acacia* had the highest extraction from the system through the large volume of the woody component (Table 3). Cowpea grain yield was 0.87 Mg ha^{-1}, which contained 27 kg N ha^{-1}. With 58 % N_2-fixation, 11 kg of this N was derived from the soil and exported through seed harvest. The rest of the cowpea residue N was recycled. All the four legume systems resulted in net positive N balances that ranged between 17 and 82 kg N ha^{-1}. The unfertilized maize had total annual N offtake of 14 kg ha^{-1} through stover and grain (Table 3).

The above net N balance estimates exclude below-ground N additions. When root N contribution is considered for the top 1 m depth, *Cajanus* derived additional 21 kg N ha^{-1} from biological N_2-fixation, *Sesbania* derived 29 kg N ha^{-1} and *Acacia* derived 60 kg N ha^{-1}. However, most of the *Acacia* root N would remain in the organic form as the roots remain

Table 3. Estimates of net N contribution by two year-old legume tree fallows, cowpea and unfertilized maize to the overall soil N economy at Domboshawa. Recyclable N is the sum of means of total N in non-woody above ground components (twigs, litter, and fresh leaves).

Legume species	Recyclable N (kg ha^{-1})	% N from N_2-fixation[a]	N source (kg ha^{-1})		Soil N exported in wood/grain[b]	Net N addition (kg ha^{-1})[c]
			N_2-fixation	Soil		
A. angustissima	218 (11.6)	56	122	96	53	69 (+60)
S. sesban	152 (5.7)	55	84	68	46	38 (+29)
C. cajan	115 (4.6)	84	97	18	14	82 (+21)
Cowpea	48 (3.6)	58	28	20	11	17 (+13)
Maize[d]	0	0	0	14	14	-14

SEM values for total aboveground recyclable N are given in parenthesis

[a] N_2-fixation for plant litter, which was the greatest N input component to the system

[b] Total woody biomass N + grain N – N derived from N_2-fixation in woody biomass and grain

[c] Amount of N_2-fixed and returned to soil through above ground non-woody components – soil derived N exported through woody parts and grain. Values in parenthesis are additional amounts of N_2-fixed in roots.

[d] Unfertilized maize with stover removed from field

active after fallow clearance. We estimate that total below-ground N for cowpea would constitute at least 30 % of the total above-ground N accumulated by cowpea, and that additional N from biological N_2-fixation through roots would be 13 kg N ha^{-1} (Table 3).

Maize yields and N uptake

During the first season, the cowpea-maize rotation plots had the highest grain yields across all the four management practices (Figure 4). When the soil was tilled, *Sesbania* had the lowest maize yields, while under minimum tillage maize in the grass fallow treatment had the lowest yields, < 500 kg ha^{-1}dry matter. As expected, fertilized subplots had better N uptake compared with unfertilized maize (Figure 5). Despite the large amount of recyclable N that was applied through *Sesbania* litter (152 kg N ha^{-1}), the maize yields were among the lowest and comparable to the continuous unfertilized maize treatment. No tillage resulted in significantly lower dry matter accumulation and N uptake. The no-till grass fallow had the lowest N uptake and final maize grain yields that were as low as 400 kg ha^{-1}dry matter. Application of 40 kg N ha^{-1} as topdressing resulted in general increased N uptake across most treatments except for *Sesbania*, and to a lesser extent, *Acacia.*

The second season crop was adversely affected by low rainfall (Figure 1). *Sesbania* resulted in significantly higher N uptake under minimum tillage when compared with other treatments (Figure 5). At final maize harvest, *Sesbania* gave significantly higher N uptake for all the four management systems, while maize in *Acacia* plots failed due to serious moisture stress. There was poor partitioning of crop N to grain. Maize grain yields were significantly affected by tillage management, fertilization and land use systems ($P < 0.05$). While conventional tillage significantly increased N uptake for most of the treatments, it had no effect on N uptake by maize for the *Sesbania* treatment.

Discussion

Above and below-ground biomass production

Among the three agroforestry species, *Acacia* accumulated the greatest biomass of woody and litter components. The large litter biomass as compared with fresh leaves on the standing trees for all the three species at the end of the 2-year fallow period (Table 1) is remarkable as it has implications on the quality of the dominant source of N. Senesced litter of these species has a low N concentration (< 2 % N), and is known to immobilize N in the short term (Giller and Cadisch, 1997; Palm et al., 2001; Sakala et al., 2000). However, the dynamics of N mineralization are not easy to explain at the onset of the rainy season, as the leafy materials were shed at different times during the two-year fallow period, and a large component could immediately mineralize once incorporated into the soil as the soil is rewetted at the start of the rains.

There were large differences in root biomass of the three woody legumes and the decline in root biomass with depth was rapid (Figure 3). This is consistent with observations of Ruhigwa et al. (1992), who found large differences in rooting of four species. The comparatively large root biomass of *Acacia* compared with either *Sesbania* or *Cajanus* was expected. *Acacia* had a more extensive root system, as the trees were not two years old as they were established some eight years before the other two species, and the trees had survived since then through their coppicing ability. There was a dense network of fine roots in *Acacia* plots in the 0-0.2 m layer. In a study of the effects of pruning on root distribution, Hairiah et al. (1992) reported that many tree species respond to decreased pruning height by increasing the number of branch roots originating at the stem base and the first 0.1 m of the tap root. This has the effect of increasing the number of superficial tree roots in the maize-rooting zone, thus leading to undesirable competition for water and nutrients. In our study, *Acacia* trees were cut at near ground level and subsequent cut backs of the coppice material was done as close to the soil surface as possible in an effort to maximize plant material for N recycling. While frequent pruning probably supported a shallower fine root system, it may also have led to significant death and release of N from a component of the fine roots, thereby contributing to N supply

Although root biomass decreased rapidly with depth, other reports have shown that the root length density of these species remain > 0.1 cm cm^{-3} to depths of 1.5 m. van

Noordwijk (1989) reported that root length densities of about 0.1 cm cm^{-3} in the subsoil are sufficient for utilizing virtually all available mineral N. Low soil nitrate under *Sesbania, Acacia* and *Cajanus* at 2 years after tree establishment, when compared with either the continuous maize plots or cowpea plots at this site was attributed to the subsoil capture by roots (Chikowo et al., 2003). Although root length densities of these species were not determined in this study, observations in the pits during root biomass determination indicated dense fine root networks, especially for *Acacia*. These fine roots will give the trees greater capacity for water and nutrient uptake.

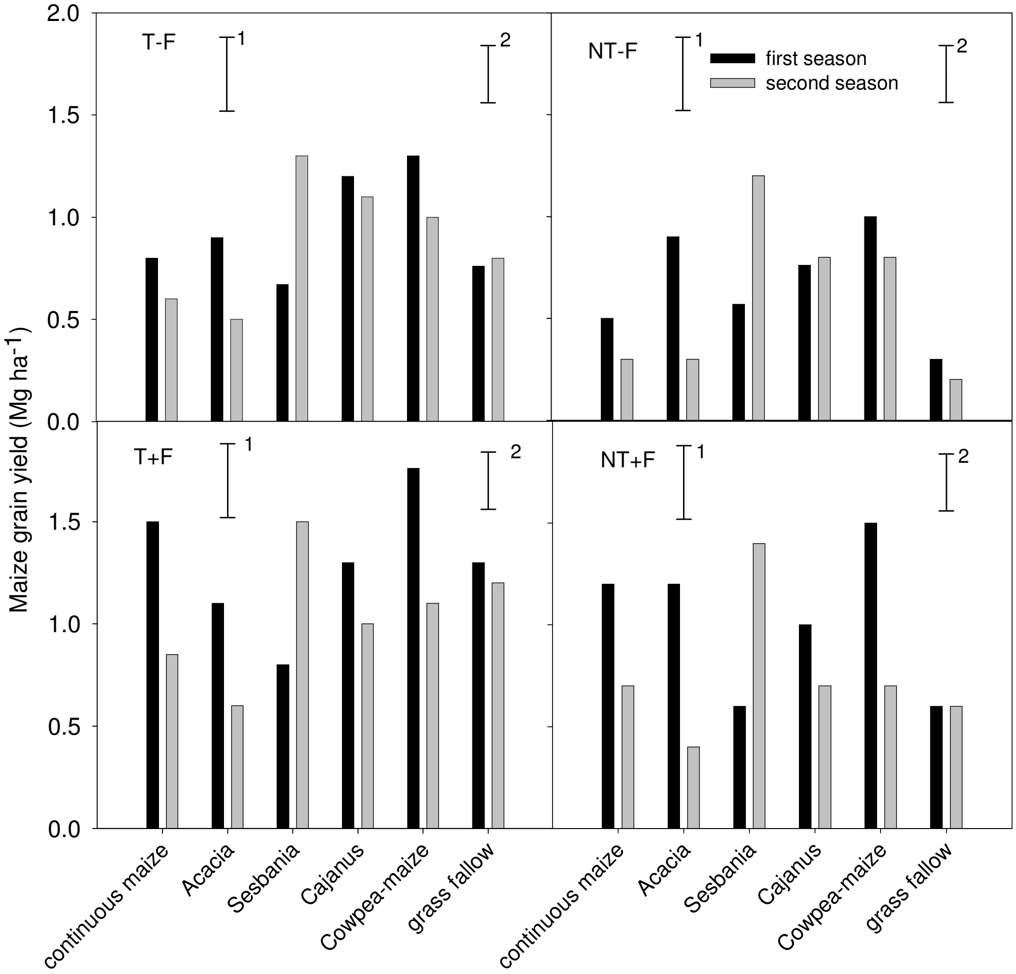

Figure 4. Grain yield of maize crops as influenced by tillage management and N fertilization in various land use systems, for two seasons following termination of fallows. Error bars represent LSD ($P<0.05$) for comparison of treatments within a management practice: 1 = season 1; 2 = season 2. See materials and methods for description of T (tillage) and F (fertilizer treatments).

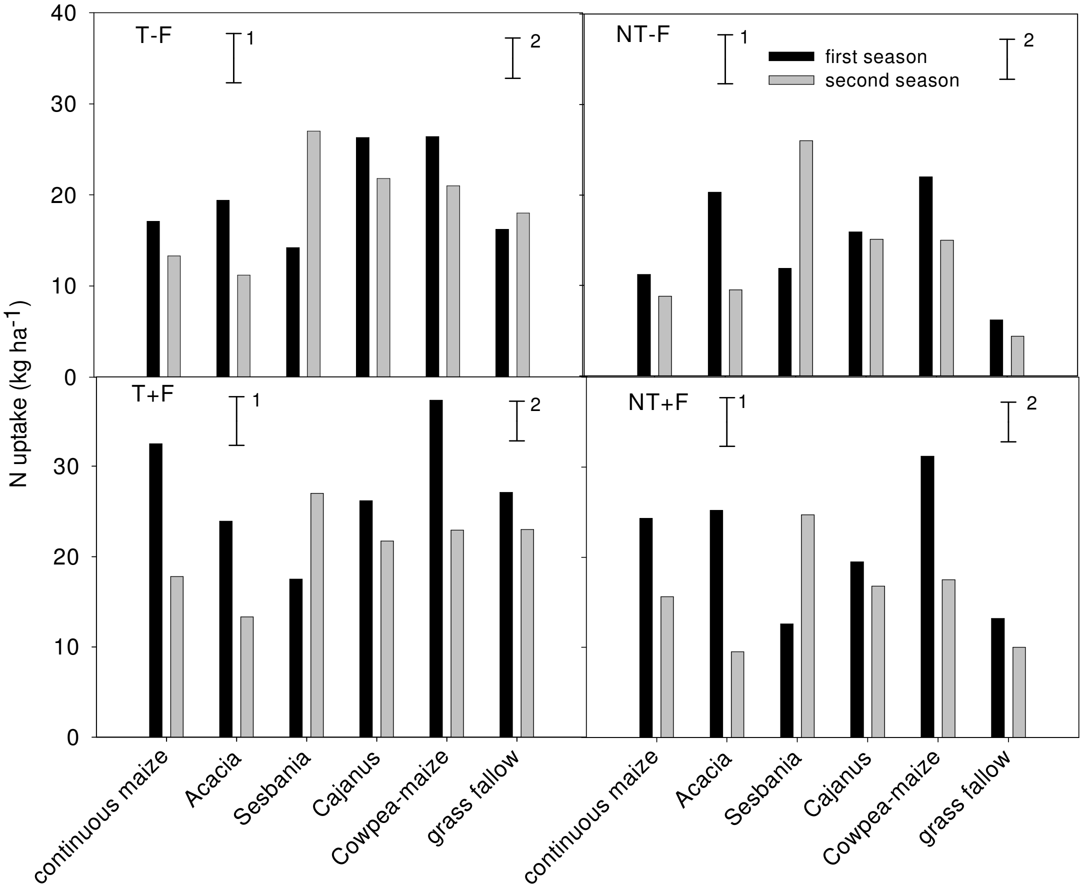

Figure 5 Total N uptake by maize as influenced by tillage management and N fertilization in various land use systems, for two seasons following termination of fallows. Error bars represent LSD (P<0.05) for comparison of treatments within a management practice: 1 = season 1; 2 = season 2

Estimates of N_2-fixation and N additions

Nitrogen input from the legume fallow to the cropping system may come from both N_2-fixation and capture of N from the soil profile, both of which are contributions that are not possible when the tree is not present. Estimates of N_2-fixation using the natural ^{15}N abundance method, with *Hyparrhenia* as the reference crop, revealed that the legumes fixed at least half of the N they accumulated. *Acacia* fixed about 122 kg N ha^{-1} of its recyclable N, but also extracted a considerable amount of N from the soil. Its large woody biomass resulted in large quantities of soil N being exported from the field, resulting in smaller net N additions when compared with *Cajanus*. Despite recycling about half as much N as *Acacia*, *Cajanus* had the greatest net N balance. This was because N_2-fixation was very high (84%), resulting in less soil N being exported through wood. Net N input is a function of the rate of fixation as well as N export from the field (Giller, 2001). On the basis of monolith sampling we estimated that the below-ground contribution of N varied between 13 kg N ha^{-1} for cowpea to 60 kg N ha^{-1} for *Acacia angustissima*, although in this case much of the root biomass remains alive and cannot be considered as a net input of N (Table 3).

Although net N input for *Sesbania* and *Acacia* was less than that for *Cajanus*, the overall amount of N cycled was substantially greater. These species extracted a substantial amount of the N they accumulated through sub-soil capture when compared with *Cajanus* (Table 3). This more efficient sourcing of soil N is likely to have resulted in their lower dependency on N_2-fixation for accumulation of the comparatively large amounts of their N, compared with *Cajanus*. The N recycled through subsoil capture became concentrated and available to the plants during the cropping phase. Thus, though the net N addition may indicate system sustainability, it may not reflect well the potential the different systems have in supplying N during the next cropping phase. Nitrogen sourcing through subsoil capture could be an equally useful way of supplying N in the topsoil in legume fallow–maize cropping sequences in the short term. Total N recycled is therefore more useful in predicting immediate N supply to the following maize crop, rather than N balance values. Litter was only collected at the end of the two-year fallow phase, and we probably underestimated litter N inputs as some of the litter may have already decomposed during the fallow period.

Our N_2-fixation estimates based on *Hyparrhenia* as a reference plant, are consistent with findings elsewhere. Yoneyama et al. (1990) estimated that between 60 and 100% of the N in the leaves of N_2-fixing trees growing in Thailand was derived from N_2-fixation. Peoples et al. (1996) reported that 65% of N in the *Cajanus* regrowth and between 78-86% of N in *Sesbania* were from N_2-fixation. Above-ground N inputs under *Sesbania* fallows amounted to 71-95 kg N ha^{-1} for 2 year fallows and the surface metre of soil contained a root biomass of 3 Mg root dry matter ha^{-1}, which contained 21-25 kg N ha^{-1} (Torquebiau and Kwesiga, 1996).

In western Kenya, *Sesbania* fixed about 60% of its N, amounting to 70 kg N ha^{-1} in a 6-month period and recovered 54 kg N ha^{-1} from the soil (Gathumbi et al., 2002).

Our estimates of N_2-fixation could have been compromised by the low ^{15}N enrichment of the soil N pool. Reference plant $\delta^{15}N$ values were low, 3.01 and 1.08 $^{o}/_{oo}$ for *Hyparrhenia* and maize, respectively. Ledgard and Peoples (1988) and Shearer and Kohl (1986) suggested that enrichments of soil $\delta^{15}N$ of at least $6^{o}/_{oo}$ were required for application of the ^{15}N natural abundance method. Contrary to this, Unkovich et al. (1994) concluded that values as low as $2^{o}/_{oo}$ could be used as N_2-fixation estimates were more dependent on the $\delta^{15}N$ values of the legume than on the reference plant. Gathumbi et al. (2002) suggested that plant available soil N ^{15}N signatures should preferentially be > 5 $^{o}/_{oo}$ for use in tree-based fallow systems. In this study it was also clear that the choice of appropriate reference plant was critical to the application of the method as use of maize as a reference plant would clearly underestimate N_2-fixation, as suggested from previous research outlined above. Additionally, if maize was used as reference plant, then *Acacia* and *Sesbania* would have accumulated 167 and 120 kg N ha^{-1} from the soil, which is greater than the total mineral N that was available in the soil profiles (Chikowo et al., 2003). Despite these problems, the natural abundance method appears to be the best choice for measuring N_2-fixation by trees in the field as it enables estimates of N_2-fixation in mature trees already growing in the field by using non-fixing neighbouring shrubs or weeds as reference plants (Boddey et al., 2000).

The ^{15}N signatures of the different plant parts of all the agroforestry species were found to vary enormously, with twigs consistently having the most depletion (Table 2). That woody plant parts are less enriched in ^{15}N than leaves has been widely reported (Boddey et al., 2000; Shearer and Kohl, 1986) and a plausible explanation is due to the internal cycling of plant N. Nitrogen from soil is first translocated to leaves and then retranslocated to twigs and branches, and exported N has a tendency to become depleted in ^{15}N (Shearer and Kohl, 1986). The seasonal relocation and recycling of N within the N_2-fixing trees is one of the challenges in the application of ^{15}N methodologies to perennial trees.

Maize N uptake and yields

During the first season, N uptake was highest following *Sesbania* during early growth, but this was not maintained for the rest of the season. By the 8th WAE, maize following *Sesbania* had lower cumulative N uptake, and maize plants showed acute N and P deficiency, despite high mineral N in the soil profile (data not presented), and supply of P fertilizer. Investigation of the root systems revealed that the poor growth was caused by cutworm (*Agrotis* sp.) infestation that destroyed most of the maize root system, thus resulting in restricted nutrient uptake. The poor maize growth resulted in mineral N building up in the respective profiles and subsequent leaching to deeper horizons. The same pest also affected other treatments at a later stage, especially *Acacia*, and this resulted in lower yields than were expected, from a system with such high N input. This was one of the unexpected effects of improved fallows, and this limit the usefulness of the technology for soil fertility improvement.

In contrast to the first season results, maize yielded more in the *Sesbania* plots during the second season while maize had the lowest yields in the *Acacia* plots. The increased maize N uptake in the *Sesbania* treatment during the second season can presumably be attributed to supply of nutrients that were spared the previous season when there was poor nutrient uptake due to pest infestation, and new mineral N linked to delayed release of part of the litter N. There are several reports of increased maize yields for at least two seasons after *Sesbania* fallows (e.g. Kwesiga and Coe, 1994; Mafongoya and Dzowela, 1999), but reports of problems related to pest infestation following improved fallows are scarce. While it was clear that legume fallows increased N availability and could possibly be useful for building soil N capital in African farming systems (Giller et al., 1997), the question of serious pest incidence on subsequent cereal crops needs to be addressed in the context of the target farmers, as potential for adoption will seriously be threatened by such effects.

During the first season, maize yields in *Acacia* plots were depressed because of cutworm damage, but yields were even lower during the second season due to drought (Figure 4). *Acacia* is one of the improved fallow species that will coppice and produce additional high N leafy biomass that can be pruned and become an additional source of nitrogen to the growing maize crop. The rainfall during the 2001-2002 season was below normal (Figure 1), and this resulted in serious moisture stress to the growing maize crop. Despite frequent cutting back (every 3 weeks) to reduce competition, *Acacia* with its widespread rooting system, was also drawing water from the same limited soil moisture pool. Consequently, maize in the *Acacia* treatment was affected by increased moisture stress and wilted. Final maize grain yields were barely 500 kg ha^{-1}dry matter, despite the additional nitrogen input through prunings. It was clear that soil moisture became the most limiting factor for maize growth. By providing root barriers next to hedgerows of *Leucaena leucocephala*, Singh et al. (1989) demonstrated that the positive effects of trees on the annual food crops due to additional prunings are normally offset by the negative effects due to competition for water in the semi-arid environment.

This result poses a number of challenges with regard to management of ‘coppicing’ fallows in environments or seasons where rainfall is limiting. To reduce the competition for soil moisture, more frequent prunings are required, but this increases labour demands on the farmer. The high water use by the coppicing *Acacia* fallows that resulted in maize being more moisture stressed shows that the additional N from the fresh biomass has a considerable cost. The lower limits of rainfall and soil water storage that are sufficient to support both the regrowth of *Acacia* as well as maize are not known. The significant maize yield reduction observed for *Acacia* in this experiment is in agreement with other studies in the semi-arid tropics (e.g. Danso and Morgan, 1993). Other than moisture competition, the yield loss could be due to competition for various growth resources such as light and nutrients.

Though greater N recycling is reasonable in principle, it was not supported well via maize yields and N uptake in this study. The rotation of cowpea with maize, in which litter from cowpea was incorporated into the soil, generally resulted in stable maize yields for the two seasons, even though total N input was the least of the four legume systems. Just as in the continuous maize plots, there were no problems with pests and diseases in the maize crop following cowpea. Cowpea is used in a non-systematic way by smallholder farmers as an intercrop in maize fields.

Conclusions

Biological N_2-fixation and soil N capture by roots were equally important in cycling N for *Sesbania* and *Acacia*. Soil N capture was less important for *Cajanus* as its N_2-fixation was very high. *Acacia* recycled the greatest N input, but led to subsequent maize crops being affected by the combined effects of the unexpected cutworms and drought over the two-cropping seasons. The benefits of tree fallows on soil fertility in this work depended on tree species and season. The adoption of improved fallows would therefore, depend on the balance of the farmers' perceptions of the risk involved by foregoing two maize cropping seasons, possible financial returns (particularly when additional labour would be required in managing the coppicing fallows to reduce competition for nutrient and water resources), and the availability of other soil fertility options. In the semiarid tropics, where water is often limiting, coppicing fallows are likely not to be successful because of competition of trees with crops for water. Despite the large organic matter inputs from the legume fallows, tillage was necessary to give good maize response to the added legume N.

Acknowledgements

We thank the European Union for financial support through the IMProved fALlows for Africa project. The Rockefeller foundation supported the first author's study at Wageningen University. We are grateful to ICRAF for the use of the Domboshawa site, and we thank Jon Fear of Imperial College at Wye for the ^{15}N analysis.

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CHAPTER 3

Nitrate-N dynamics following improved fallows and maize root development in a Zimbabwean sandy clay loam

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This chapter has been published as:

Chikowo R, Mapfumo P, Nyamugafata P, Nyamadzawo G and Giller K E 2003. Nitrate-N dynamics following improved fallows and maize root development in a Zimbabwean sandy clay loam. Agroforestry Systems 59: 187-195.

Abstract

Improved or planted fallows using fast-growing leguminous trees are capable of accumulating large amounts of N through biological N_2-fixation and subsoil N capture. During the fallow phase, the cycling of nutrients is largely efficient. However, there are few estimates of the fate of added N during the cropping phase, after the 'safety net' of fallow-tree roots is removed. Nitrate-N at the end of the fallow phase, which is pre-season to the subsequent crop, was monitored in seven land use systems in successive 20-cm soil layers to 120 cm depth at Domboshawa, Zimbabwe in October 2000. Thereafter, nitrate-N dynamics was monitored during cropping phase until April 2001 at 2-week intervals in plots that had previously 2-year planted fallows of *Acacia angustissima* and *Sesbania sesban*, and in a continuous maize control. Pre-season nitrate concentrations below 60 cm soil depth were <3 kg N ha^{-1} $layer^{-1}$ for *S. sesban, A. angustissima, Cajanus cajan* and natural woodland compared with the maize control, which had >10 kg N ha^{-1} $layer^{-1}$. There was a flush of NO_3-N in the *S. sesbania* and *A. angustissima* plots with the first rains. Topsoil NO_3-N had increased to >29 kg N ha^{-1} by the time of establishing the maize crop. This increase in NO_3-N in the topsoil was not sustained as concentrations decreased rapidly due to leaching. Nitrate then accumulated below 40 cm, early in the season when maize (*Zea mays* L.) root length density was still low (<0.1 cm cm^{-3}) and inadequate to effectively intercept the nitrate. It is concluded that under light soil and high rainfall conditions, there is an inherent problem in managing NO_3-N originating from mineralization of organic materials as it accumulates at the beginning of the season, well ahead of peak demand by crops, and is susceptible to leaching before the crop root system develops.

Key words: Leaching, N_2-fixation, N mineralization, Nutrient cycling, Root length density, Subsoil nutrients

Introduction

One of the tenets of integrating trees with crops is that their deep root systems can potentially intercept nutrients leaching down the soil profile and capture nutrients accumulated below the rooting depth of annual crops (van Noordwijk et al. 1996). A review by Giller et al. (1997) documented the role of biological N_2- fixation in building up of soil N, particularly in N-depleted soils. In improved tree fallow–crop rotation systems, trees and crops occupy the fields at different times. During the fallow phase, nutrient cycling is largely efficient as nutrients taken up by trees from below the rooting zone of annual crops are transferred to the soil surface in the form of leaf litter (Schroth 1995; Hartemink et al. 1996; Buresh and Tian 1997). It is important to determine the fate of these nutrients when the 'safety net' offered by the fallow-tree roots during the fallow phase is removed. Many studies have confirmed that the recovery of organic nitrogen is lower than that of mineral nitrogen (Read et al. 1985; Mafongoya and Nair 1997), and this has been attributed to the slow decomposition of residues, lack of synchrony in N mineralization and crop uptake, and loss of nitrogen through leaching, volatilisation and immobilization (Palm 1995).

In southern Africa, a maize crop is normally grown in sequence with improved or planted fallows (Kwesiga and Coe 1994). The extent to which maize roots explore the soil and capture the nitrogen depends on the distribution of nitrogen in the profile and root length density (van Noordwijk 1989). Few studies have investigated the spatial root distribution of maize with time in order to explain the likelihood of successful nutrient capture. Information on this is important especially where nitrate is mineralized *in situ* and management cannot determine its placement, as is normally the case in improved fallow systems.

The objectives of this study were: (1) to compare NO_3-N in the soil profile following 2-year planted fallows of *Acacia angustissima*, *Sesbania sesban* and *Cajanus cajan*, annual cowpea (*Vigna unguculata*), and 2-year grass fallow with that in continuous maize (*Zea mays* L.) cropping and a natural miombo ecosystem; (2) to monitor NO_3-N dynamics and estimate leaching losses under maize following 2-year fallows of *A. angustissima* and *S. sesban*; (3) to determine the effects of tillage and no-tillage on NO_3-N dynamics after *S. sesban* fallows; and (4) to study the spatial distribution of maize roots during the first eight weeks after crop emergence, and how this affects the use of soil NO_3-N.

Materials and methods

Mineral N determination at fallow termination

A field experiment established in November 1998 at Domboshawa, 30 km northeast of Harare, Zimbabwe involved evaluation of 2-year planted fallows of *S. sesban, C. cajan* and *A. angustissima*, grass fallow, and annual cowpea for their effects on a subsequent maize crop compared with an unfertilized continuous maize. The experimental site was a sandy clay loam texture (ustalf), with 22% clay and 73% sand for the 0 to 20 cm layer. The cation exchange capacity of the soil was 2.1 $\text{cmol}_c\ \text{kg}^{-1}$ and pH (0.01 M $CaCl_2$) 4.9 and organic C was 0.78%. The fallows were harvested in October 2000, and aboveground and litter biomass was determined. Biomass additions as litter and standing foliage at harvest were 9.5, 5.5 and 5.1 t ha^{-1} for *A. angustissima, S. sesban,* and *C. cajan*, recycling about 220, 155 and 115 kg N ha^{-1}, respectively. *A. angustissima* was allowed to coppice during the cropping phase and the coppice growth returned to soil. Soon after harvesting the fallows, soils were sampled in 20 cm sections to a depth of 120 cm, on 28 October 2000 (pre-season sampling, PSS), from these treatments. Sampling was also done from a miombo woodland adjacent to the experiment. In each plot, soils were collected and bulked from two locations for each depth. Sub-samples were immediately taken to the laboratory and stored at 4°C until nitrate was extracted, usually within 2 days of collection.

NO_3-N dynamics under maize

Except the miombo woodland, all the plots were subdivided into two subplots for imposing two tillage treatments (conventional tillage and no-tillage) and cropped with maize. Tillage was executed using an ox-drawn plough to a depth of 20 cm, while for no-tillage only planting holes were made for seed placement. For detailed monitoring of NO_3-N four contrasting treatments were selected: continuous maize on tilled plots without fertilizer, maize with conventional tillage after *A. angustissima* and *S. sesban* fallows, and maize with no tillage after *S. sesban* fallow (S. s*esban*–NT). *Sesbania sesban* represented the rapidly decomposing high quality litter, whereas *A. angustissima* represented slower decomposing low quality organic materials (Mafongoya et al., 1997). The unfertilized maize treatment was included as a control while *S. sesban*–NT treatment was included to investigate the effect of tillage on NO_3-N dynamics. Soils were sampled using augers in sections of 0–20, 20–40, 40–60, 60–90, and 90–120 cm. Maize was planted on 30 November 2000. Soils for monitoring NO_3-N dynamics were sampled on six occasions at 1, 3, 5, 7, 9 and 11 weeks after planting maize. The last sampling was at maize physiological maturity on 5 April 2001, about 10 days after the termination of rains (Figure 1).

Nitrate analysis

Nitrate from field moist soils was extracted using 0.5 M KCl solution. Sub samples of the soils were dried at 105 °C for 24 hours to determine the dry soil weight. All results are expressed on an oven dry soil basis. The NO_2-N cadmium reduction method (Keeney and Nelson 1982) was used for nitrate determination. The NO_2-N was determined colourimetrically at an absorbance of 543 nm. Respective bulk densities of the different soil layers were then used to convert NO_3-N concentrations from mg kg^{-1} to kg N ha^{-1}. The apparent leaching loss from the time of maize planting to harvest was calculated as the cumulative decrease in the NO_3-N content of the soil profile between successive sampling events.

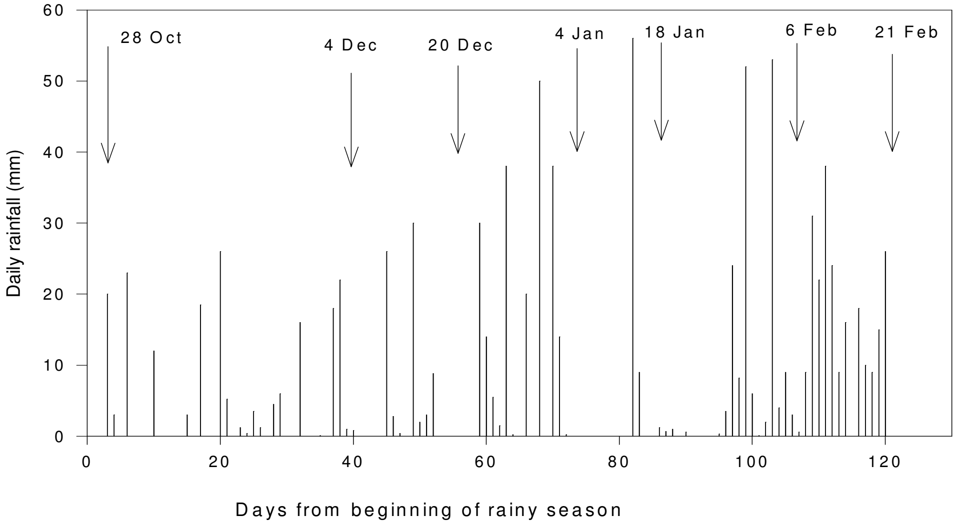

Figure 1. Rainfall distribution during the study period from October 27, 2000 to February 23, 2001 at Domboshawa, Zimbabwe. Vertical bars indicate the dates when soil sampling was carried out for nitrate-N measurement.

Maize root development

A satellite maize plot was established outside the main experiment for studying maize root development by destructive sampling. Maize was planted at 90 cm inter-row distance and 30 cm intra-row spacing. The plots were kept weed free by periodical uprooting of emerging weeds to avoid weed competition and weed roots interfering with maize root measurements. This ensured reduction in overestimation errors due to inclusion of non-maize roots mixed with maize roots. The crop received a basal application of 25 kg N, 18 kg P and 30 kg K ha^{-1} and a topdressing of 40 kg N ha^{-1} at 4 weeks after emergence.

Maize root development was monitored at 2-week intervals (2, 4, 6 and 8 weeks after emergence, WAE). Sufficiently wide pits to have adequate working space were dug out for root sampling. The distance from the plant to middle of the inter-row space was divided into two zones of 22.5 cm width each (zone 1, 0–22.5 cm; zone 2, 22.5–45 cm) (Figure 2). Four replicate monoliths from each of the zones were excavated in 20 cm sections, progressively increasing to 100 cm depth over time. The excavated soil (6750 cm^3 volume) of each monolith was soaked in water in a large bucket for about an hour for soil aggregate breakdown and, later poured onto a 0.5 mm sieve to trap roots. The trapped roots mixed with soil in the sieve were washed under a steady flow of water from a tap to separate the roots.

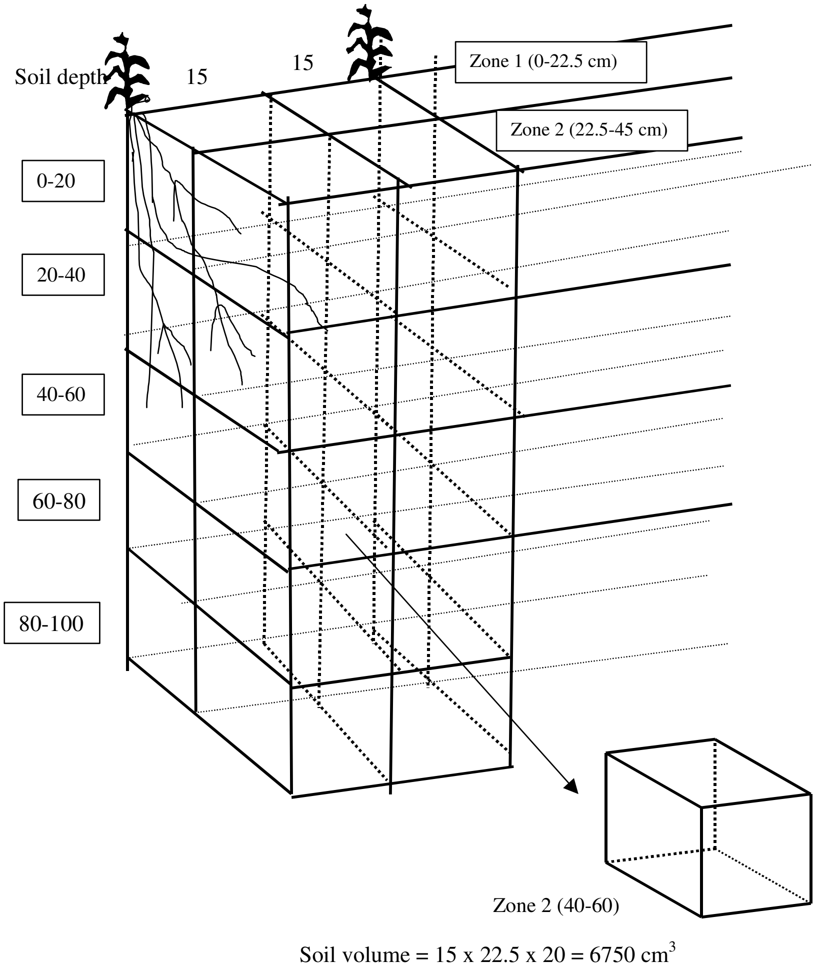

Figure 2. Scheme for root sampling used for monitoring maize root distribution in the study.

Root length measurements

Root length was determined using the line intercept method (Newman 1966). To improve contrast, the roots were stained with 0.1% saffranin red. They were then spread out with random orientation in a thin layer of water on a transparent acetate folio, and a glass plate with 1 cm grid size (D) was placed on top. The horizontal and vertical interceptions of the roots with grid lines were counted and added together (N). Root length and root length density were then calculated as:

$$\text{Root length, L (cm)} \quad = \quad \Pi ND / 4 \quad \text{(Tennant 1975)}$$

$$\text{Root length density, Lrv (cm cm}^{-3}) \quad = \quad \frac{\text{Root length (cm)}}{\text{Soil volume (cm}^3)}$$

Results

The daily rainfall pattern during the 2000–01 season from October 28 to the termination of the rains is shown in Figure 1. The arrows indicate the sampling occasions for nitrate within the season.

Pre-season soil NO_3-N

Nitrate-N in the soils sampled before the rains on 28 October 2000 differed significantly among the treatments ($P<0.05$) (Figure 3). Pre-season NO_3-N concentration in the 0–20 cm layer was greatest in plots that had cowpea and *A. angustissima* in the previous season, which amounted to 6.8 kg N ha^{-1}. The adjacent unmanaged miombo woodland, which had 2.6 kg N ha^{-1} in the 0–20 cm, had the lowest NO_3-N concentration in almost all layers. A distinct bulge in soil nitrate was present starting at 60 to 80 cm layer in the continuous maize treatment, and at 80 to 90 cm depth in the cowpea–maize rotation treatment (Figure 3). The continuous maize treatment had the greatest accumulation of 12 kg N ha^{-1} of nitrate-N at 100–120 depth compared with 2.1 kg N ha^{-1} for S. s*esban* and 2.6 kg N ha^{-1} for *A. angustissima* treatments at the same depth.

Dynamics of NO_3-N

There was a flush in NO_3-N in the S. s*esban* and *A. angustissima* plots at one week after planting (wk 1) in the two top 20 cm layers (Figure 4). Topsoil NO_3-N increased from 3.2 to 34 kg N ha^{-1} in the *S. sesban* and from 6.7 to 29 kg N ha^{-1} for *A. angustissima* fallows during the period from pre-season sampling to week 1. At this time, the *S. sesban*–NT plots showed comparatively low amounts of NO_3-N, which were of similar magnitude to that in the continuous maize control. There were no treatment differences in NO_3-N concentration in soil layers below 40 cm for the week 1 samples (Figure 4). The increase in NO_3-N observed for the *A. angustissima* and *S. sesban* treatments was not sustained as concentrations decreased rapidly. Topsoil NO_3-N decreased to 8.6 kg N ha^{-1} and 11.2 kg N ha^{-1} for the *S. sesban* and *A. angustissima* plots, respectively, by 20 December, only 3 weeks after planting maize. The decrease in topsoil NO_3-N was accompanied by a relative increase in NO_3-N at depths below 40 cm. A noticeable bulge in NO_3-N had built up by the third week after incorporating the litter, with the control always lagging behind (Figure 4). There was clear evidence of nitrate movement down the profile as the bulge became more pronounced with depth and time. Beyond the third week after planting, both *S. sesban* and *S. sesban*–NT plots had more NO_3-N in the profile compared with either the *A. angustissima* or the maize control plots. The exception was after 11 weeks when *A. angustissima* plots apparently had the highest amount of nitrate in the 40 to 100 cm depth zone (Figure 4). By this time the bulk of the NO_3-N for the *Sesbania* plots had moved to the 100 to 120 cm layer or beyond. There was only one storm between January 4 and 18 (Figure 1). This resulted in little movement of nitrate in the profiles between week 5 and week 7. After the end of this long mid season dry spell, there was significant accumulation of NO_3-N in the deeper layers by the 9th week (Table 1c).

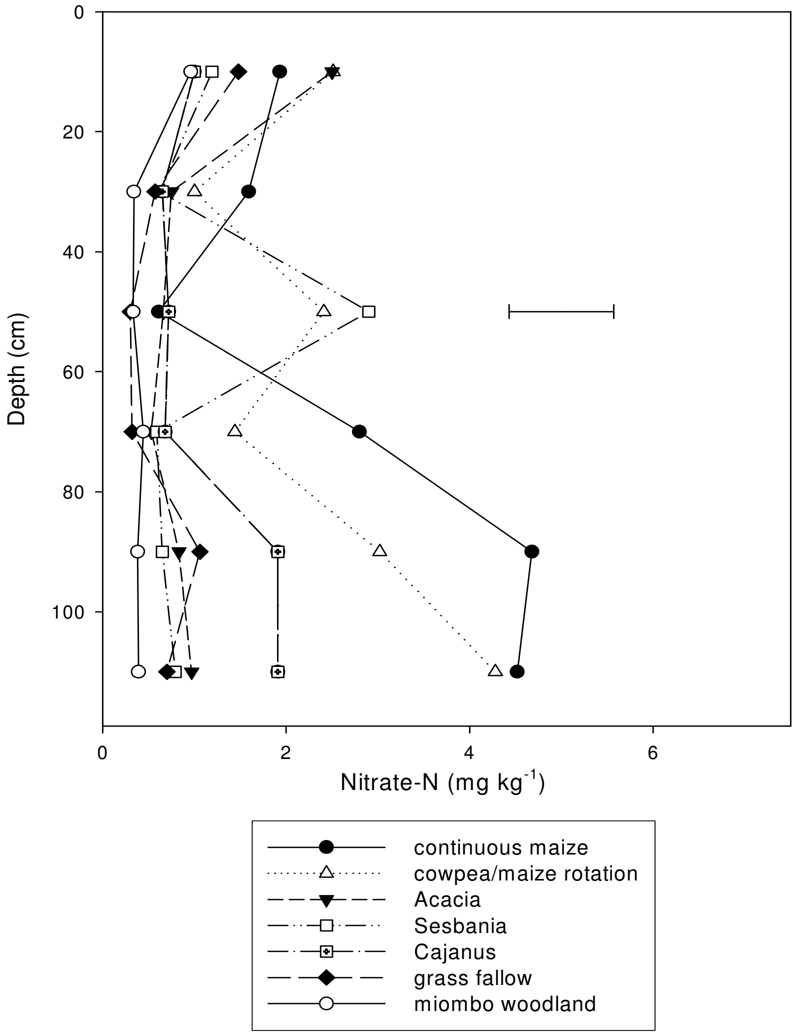

Figure 3. Nitrate-N in plots that had continuous maize, cowpea–maize rotation, grass fallow, miombo woodland and following cutting of 2-year *Acacia angustissima*, *Sesbania sesban*, and *Cajanus cajan* improved fallows. Error bar represents *LSD* ($P < 0.05$) at each depth.

Root length densities

Maize roots were largely confined to the top 20 cm of the zone closest to the maize plants (zone 1) during the first 4 weeks after emergence (Table 2). The root lengths of maize recovered were significantly greater at 0–20 cm than the rest of the depths. As from six weeks after emergence, mineral N in the zone furthest from the plants (zone 2) was as accessible to the roots as that in zone 1 since root length densities were comparable. Root length densities at depth greater than 60 cm were small, and were still less than 0.1 cm cm^{-3} by the eighth week after crop emergence, yet most of the nitrate now stayed in these deeper layers.

Discussion and conclusions

Accumulation of nitrate-N below the 80-cm depth for continuous maize and cowpea-maize rotation treatments and its absence in the tree-fallow treatments observed in this study is consistent with findings elsewhere. Hartemink et al. (1996) reported that *S. sesban* and *Calliandra calothyrsus* reduced soil nitrate in the top 2 m by up to 200 kg N ha^{-1} one year after establishment. In western Kenya, *S. sesban* roots penetrated to below 4 m, and were able to use soil water and capture N that leached to lower depths, below the rooting zone of maize (Mekonnen et al. 1997). Trees with deep roots intercept nitrate leaching down the soil profile and 'capture' nutrients accumulated in the subsoil below the rooting depth of maize (van Noordwijk et al. 1996). Nutrients taken up by trees from below the rooting zone of annual crops will become an input to subsequent crops when they are transferred to surface soil in the form of leaf litter, roots and prunings of tree leaves and branches (Schroth 1995).

Nitrate-N dynamics were followed in detail in only four of the treatments. Soon after the first rains of the season, soil nitrate concentrations increased in all the treatments. The re-wetting of the dry soil resulted in a flush of nitrate due to rapid mineralization of N from the residues and from the soil organic matter, known as the 'Birch effect' (Birch 1964). This was evident from the accumulated nitrate in the top 40 cm of the soil at week 1 sampling for the tilled plots of *S. sesban* and *A. angustissima* (Figure 4). High amounts of nitrate in the tilled *S. sesban* plots as opposed to the low amounts in the *S.* sesban–NT plots at this stage in the season presumably resulted from rapid release of N stimulated by tillage (Table 1a). However, at this time of the season, most of the NO_3-N was susceptible to leaching, as maize roots were not yet sufficiently developed to absorb and intercept the leaching nutrients. The lag time in N mineralization noticed for *S. sesban*–NT treatment was only temporary as nitrate concentrations increased by the third week after planting maize. However, this delay may improve N capture by maize, as this N may become available when the crop root system has comparatively developed better to intercept the NO_3-N.

This study has reconfirmed the rapid flush of mineral N at the onset of rains after a pronounced dry season. However, this flush seems to be of short duration as the concentration of mineral N dropped within two weeks. This reduction is probably due to leaching and denitrification losses as plant N uptake can clearly be discounted on account of poor N uptake by maize early in the season. In semi-arid tropical dryland agriculture, leaching losses depend on the coincidence of heavy rainfall with the application of N or organic matter mineralization. Kamukondiwa and Bergstrom (1994) working on a sandy soil in Zimbabwe reported N leaching losses of 17–39 kg ha^{-1} in a single season.

Table 1. Differences in soil NO_3-N concentration between successive sampling dates at different soil depths for continuous maize and tree-fallow–maize sequences during the 2000/2001 rainy season, at Domboshawa, Zimbabwe.

(a) Pre-season (28 October) to Week 1 (4 December)

Soil depth (cm)	Treatments			
	Continuous maize	*Acacia*	*Sesbania*	*Sesbania* (NT)
	--------------------------NO_3-N (mg kg^{-1})---------------------------			
0–20	+3.47	+8.21	+11.48	+4.29
20–40	+2.68	+7.12	+9.77	+3.90
40–60	+2.50	+2.11	+0.26	+0.88
60–90	–0.22	+1.00	+1.25	+2.64
90–120	–3.52	+0.82	+1.97	+1.23

(b) Week1 (4 December) to Week 3 (20 December)

	Control	*Acacia*	*Sesbania*	*Sesbania* (NT)
0–20	–3.02	–6.54	–9.47	–0.76
20–40	–0.51	–4.09	–5.26	+0.34
40–60	–1.25	–0.97	–1.63	+0.31
60–90	–1.21	–0.86	–0.66	–1.07
90–120	–0.60	–0.96	–0.82	+0.22

(c) Week 7 (18 January) to Week 9 (6 February)

	Control	*Acacia*	*Sesbania*	*Sesbania* (NT)
0–20	+0.21	–0.66	–0.55	–1.39
20–40	–0.77	+0.14	–2.32	–4.68
40–60	–2.24	–0.61	+3.12	+2.46
60–90	+4.71	+2.85	+6.61	+6.80
90–120	+2.78	+1.72	+5.78	+9.31

Table 2. Root length density (cm cm^{-3}) of maize measured at different soil depths and two distances from maize plant at different weeks after crop emergence (WAE), in a sandy clay loam soil at Domboshawa, Zimbabwe.

Sampling time	Soil depth (cm)	Zone 1 (0–22.5 cm)*	Zone 2 (22.5–45.0 cm)
2 WAE	0–20	0.140	0.005
	20–40	0.000	0.000
	40–60	0.000	0.000
4 WAE	0–20	0.440	0.080
	20–40	0.003	0.000
	40–60	0.000	0.000
	0–20	0.760	0.481
6 WAE	20–40	0.133	0.112
	40–60	0.170	0.160
	60–80	0.000	0.000
	0–20	0.606	0.740
8 WAE	20–40	0.328	0.111
	40–60	0.160	0.077
	60–80	0.018	0.032
	80–100	0.005	0.000

* Zone 1 (0–22.5 cm) refers to the distance from the maize row to midway towards the center of the inter-row spacing, as illustrated in Figure 2.

Root length densities for maize were less than 0.1 cm cm^{-3} in all layers except for the top 20 cm layer, during the first 4 WAE. This could have exposed the nitrate to leaching. van Noordwijk (1989) reported that a root length density of at least 0.1 cm cm^{-3} in the subsoil is required to sufficiently utilize the available nitrogen. By the ninth week after planting maize, there was severe depletion of NO_3-N in the 0–40 cm depth, and evidence of accumulation in deeper soil layers (Figure 4) where maize root length densities were still less than 0.1 cm cm^{-3}. Soil nitrate increase in deep layers during maize cropping, was a result of a ‘leaky’ system in the absence of deeper-rooted trees. Except *A. angustissima* which coppiced and continuously recycled nutrients through the prunings, other trees were non-coppicing species. It therefore seems the closed nutrient cycle that was established during the fallow phase had disintegrated within a few weeks of cropping, and the systems reverted back to a ‘leaky’ one (Nair 1993). There is a frequently raised question concerning the management of N fertilizers during the growing season: at what stage of maize growth can N fertilizers be applied by broadcasting instead of localized application to save labour? The spatial root length density distribution from this work suggests that NO_3-N generated in the topsoil six weeks after crop

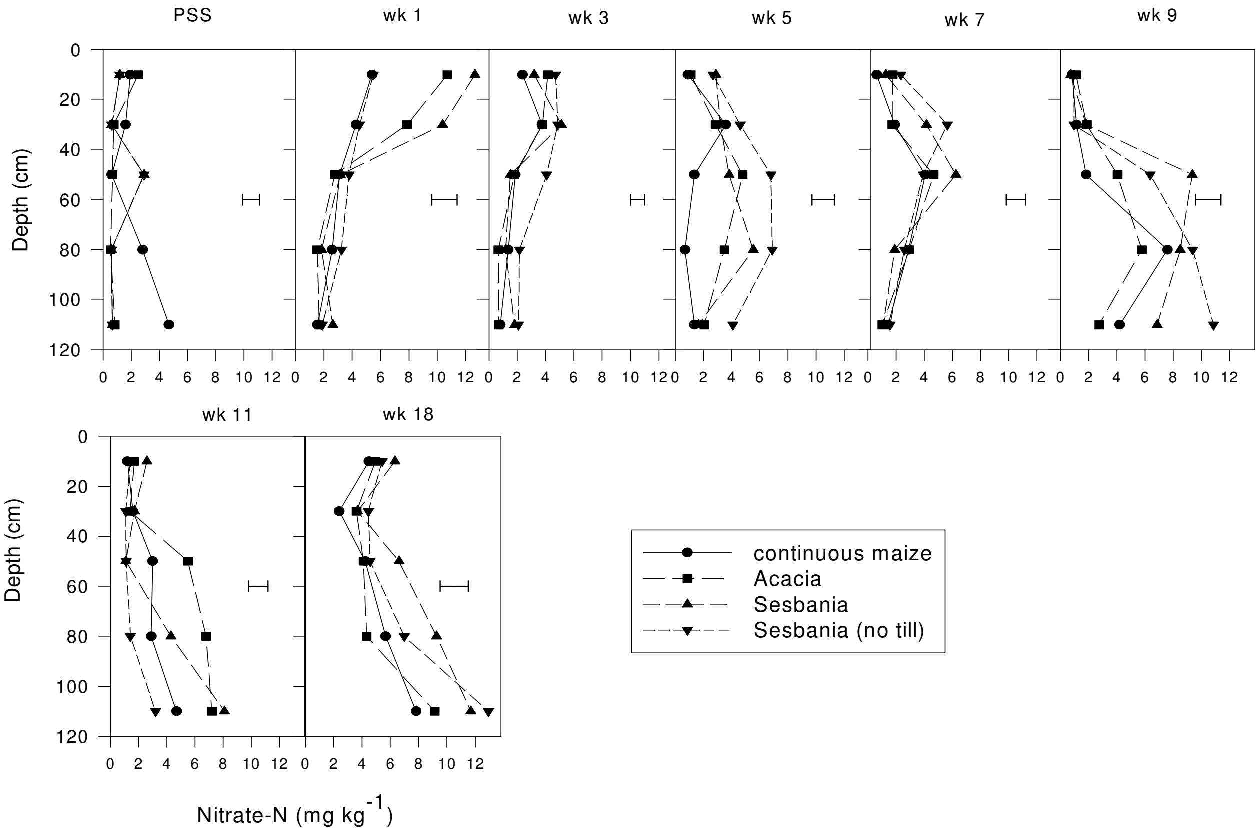

Figure 4. Nitrate-N at different soil depths during maize cropping following 2-year *Acacia angustissima* and *Sesbania sesban* improved fallows and in continuous maize. PSS = preseason sampling and wk = weeks after emergence. Error bars represent *LSD* ($P < 0.05$) at each depth for the respective sampling dates.

emergence can be efficiently utilized by maize crop, as root density would be sufficiently large in the topsoil. Thus, spot application of fertilizer N six weeks after crop emergence may not necessarily result in increased fertilizer recovery.

This work has, however, shown an inherent problem in the efficient use of nitrogen originating from mineralization of organic materials as it normally accumulates at the beginning of the season, well before the root systems of annual crops are adequately developed. This has strong implications on N management under smallholder systems for which N supplies are limited in quantity and often available only in the form of organics. Reducing the time gap between harvest of fallows and the subsequent crop by sowing the crop immediately after the onset of rains would partly solve the dilemma. Planted fallows using tree species that coppice could be another strategy to reduce nitrate leaching and improve N use efficiency in fallow–crop rotation systems.

Acknowledgements

We gratefully acknowledge ICRAF–Zimbabwe team for allowing us to use the long-term experiment at Domboshawa to make the measurements we have reported in this paper. The work is an output of the 'Improved Fallows for Africa Project' funded by the European Union.

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CHAPTER 4

Mineral N dynamics, leaching and nitrous oxide losses under maize following two-year improved fallows on a sandy loam soil in Zimbabwe

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This chapter has been accepted for publication as:

Chikowo R, Mapfumo P, Nyamugafata P, and Giller K E 2004. Mineral N dynamics, leaching and nitrous oxide losses under maize following two-year improved fallows on a sandy loam soil in Zimbabwe. Plant and Soil (*in press*).

Abstract.

The fate of the added N on a sandy loam soil was determined in an improved fallow - maize sequence field experiment in Zimbabwe. Pre-season mineral N was determined in 20 cm sections to 120 cm depth by soil auguring in seven land use systems. Thereafter, sequential soil auguring was done at two-week intervals in plots that previously had 2-year fallows of *Acacia angustissima*, *Sesbania sesban* and unfertilized maize to determine mineral N dynamics. Using the static chamber technique, N_2O fluxes were also determined in the same plots. Pre-season NH_4-N concentrations were > 12 kg N ha^{-1} in the 0-20 cm layer for treatments that had a pronounced litter layer. NO_3-N concentrations below 60 cm depth were <3 kg N ha^{-1} $layer^{-1}$ for *Sesban, Acacia, Cajanus cajan* and natural woodland compared with > 10 kg N ha^{-1} $layer^{-1}$ in the control plots where maize had been cultivated each year. There was a flush of NO_3-N in the *Sesbania* and *Acacia* plots with the first rains. Topsoil NO_3-N had increased to >29 kg N ha^{-1} by the time of establishing the maize crop. This increase in NO_3-N in the topsoil was not sustained as concentrations decreased rapidly within three weeks of maize planting, to amounts of 8.6 kg N ha^{-1} and 11.2 kg N ha^{-1} for the *Sesbania* and *Acacia* plots, respectively. Total NO_3-N leaching losses from the 0-40 cm layer ranged from 29-40 kg ha^{-1} for *Sesbania* and *Acacia* plots within two weeks when 104 mm rainfall was received to an already fully recharged soil profile. Nitrate then accumulated below the 40 cm depth during early season when the maize had not developed a sufficient root length density to effectively capture nutrients. At one week after planting maize, N_2O fluxes of 12.3 g N_2O-N ha^{-1} day^{-1} from *Sesbania* plots were about twice as high as those from *Acacia*, and about seven times the 1.6 g N_2O-N ha^{-1} day^{-1} from maize monoculture. This was at the time when mineral N was at its peak in the topsoil. The unfertilized maize showed consistently low N_2O emissions, which never exceeded 2 g N_2O-N ha^{-1} day^{-1} for all the eight sampling dates. The decrease of mineral N concentration in the topsoil resulted in reduced N_2O fluxes, despite very high soil moisture conditions. Total N_2O-N emissions were greatest for *Sesbania* plots with 0.3 kg ha^{-1} lost in 56 days. We conclude that, under high rainfall conditions, there is an inherent problem in managing mineral N originating from mineralization of organic materials as it accumulates at the onset of rains, and is susceptible to leaching before the crop root system develops. We did not quantify nitric oxide and N_2 gas emissions, but it is unlikely that total gaseous N losses would be significant and contribute to poor N recovery that has been widely reported.

Key words: maize, leaching, improved fallows, nitrous oxide, subsoil capture, synchrony

Introduction

Nitrogen supply to cereal crops is one of the major constraints to agricultural productivity in southern Africa, and improved fallows where legume trees and crops occupy the fields at different times, is one of the technologies tht offers promise (Kwesiga and Coe, 1994; Mafongoya and Dzowela, 1999). The legumes accumulate abundant N during the fallow period through biological N_2-fixation (Giller and Cadisch, 1995; Mapfumo et al., 1999), and through deep soil N recovery from below the rooting zone of annual crops through extensive rooting systems (Hartemink et al., 1996; Mekkonen et al., 1997). As a result, during the fallow phase the cycling of N is largely efficient. In this study, the fate of the added N after the 'safety net' of the tree root system is removed during the cropping phase was examined. Nitrogen losses are likely to be high under high rainfall events of the tropics, especially on light textured soils. Recovery of added N in the form of organic residues by the first crop has been widely reported to be within a range of 10-30 % (Mafongoya and Nair, 1997; Giller and Cadisch, 1995; Palm et al., 2001). Mineral N frequently accumulates during the onset of rains following a long dry season (Birch, 1964). This is the time when abundant nitrate in the soil is most untimely, and large leaching losses are inevitable (Addiscott, 2000). As the rains continue, the accumulation of soil NO_3-N is usually followed by a rapid decrease in topsoil NO_3-N due to a combination of plant uptake, denitrification, immobilization, and leaching (Cameron and Haynes, 1986).

Formation of nitrous oxide (N_2O), a greenhouse gas that contributes to the destruction of the earth's protective ozone layer, primarily results from nitrification and denitrification as an intermediate in the reaction sequences of both processes (Firestone, 1982; Firestone and Davidson, 1989; Kroeze et al., 1999). Although information concerning the utilization of N from legume prunings applied to agricultural soils by crops is now available (Mafongoya and Dzowela, 1999; Palm et al., 2001), the impacts of improved fallows with legumes on soil N_2O fluxes are largely unknown. As N_2O release from agricultural soils is associated with fertilizer use (Bouwman, 1996), it would be reasonable to expect increased N_2O emissions with increased N inputs from N_2-fixing legumes. Studies under temperate conditions have shown that greater emissions follow incorporation of residues with low C:N ratios, such as those of legumes, than after cereal straw addition (Kaiser et al., 1998; Baggs et al., 2000).

There are currently no data on the role of N_2 fixing trees on soil emissions of trace gases in Zimbabwe, and remarkably little information from the tropics in general (Palm et al., 2002). Field measurements of N_2O emissions are therefore important, but these estimates are complicated by the diffuse nature and the large spatial variability of N_2O emissions (Kaiser et al., 1998; Rover et al. 1999) and also their marked temporal variability (Christensen, 1983; Flessa et al., 2002). Short periods of very high flux rates on 'hot spots' are characteristic, and can make up a substantial part of the total annual loss (Mogge et al., 1999; Rover et al., 1999).

The overall objective of this study was to determine whether emissions of N_2O from soils after improved fallows were of sufficient magnitude to offset the N derived from biological N_2-fixation, and whether tillage management could regulate and reduce mineral N leaching and gaseous N emissions. Specifically, the objectives of this study were (1) to monitor mineral N dynamics and estimate leaching losses during maize cropping following two years of *Sesbania sesban* and *Acacia angustissima* fallows, and maize monoculture (2) and to estimate N_2O emissions in the same treatments.

Materials and methods

Experimental site and its history

The study was conducted on a long-term field experiment at Domboshawa, about 30 km north-east of Harare, Zimbabwe (17°35' S; 31°14' E). The soil is a sandy loam with 22 % clay, 5% silt and 73 % sand; CEC of 2.1 $cmol_c\ kg^{-1}$ and organic C and total N of 0.6 and 0.05 %, respectively, for the continuously cultivated maize monoculture plots. The soil, classified as a Lixisol (World Resource Reference Base), is N deficient and crops respond strongly to mineral N fertilization. Coarse textured soils of this nature are widespread in Africa, making this study widely relevant. The site had gone through a first legume improved fallow phase of different durations (introduced in a phased-entry) and subsequent 4 years of maize cropping from 1991 to 1998, as summarized in Table 1. Detailed results of this phase of the experiment were published already (Mafongoya and Dzowela, 1999). In 1998 a second improved fallow phase of 2 years duration was established in the same plots, and 2 years of maize cropping then followed, from November 2000. We report here data that was collected during the two seasons of maize cropping between year 2000 and 2002. The mean annual rainfall is 750 mm and occurs during a single rainy season extending from November to April. Rainfall was above average during the 2000/01 season with 1218 mm, and was below average, amounting to only 461 mm in the 2001/02 season (Figure 1).

Treatments and experimental design

The experiment was established in November 1998, using a randomized complete block design with six treatments and three replications. The treatments were: (i) continuous maize; (ii) maize-cowpea-maize-maize sequence iii) natural grass fallow; and three woody leguminous species: iv) *Acacia angustissima* (v) *Sesbania sesban* and (vi) *Cajanus cajan.* In November 1998, the legume fallow species were established on 16 x 12 m plots. *Sesbania* was established from 3-month old seedlings while *Cajanus* was established by direct seeding. *Acacia* was established through coppicing of the trees from the previous fallow cycle (Mafongoya and Dzowela, 1999).

Table 1. The management history of the experimental site prior to our measurements after the second fallow cycle at Domboshawa, Zimbabwe.

	Treatments					
Year	Phased entry of legume fallows* (*Sesbania, Acacia, Cajanus*)			Cowpea-maize rotation	Continuous maize	Grass fallow
1991/92	maize	maize	fallow	cowpea	maize	grass
1992/93	maize	fallow	fallow	maize	maize	grass
1993/94	fallow	fallow	fallow	cowpea	maize	grass
1994/98	←		4 years of maize cropping		→	
1998/2000		Second fallow cycle – 2 years		maize	maize	grass
				cowpea	maize	grass
2000/2002	←		2 years of maize cropping		→	

*At the end of 1994 there were plots with 1, 2, and 3 years old fallows of all the 3 legume species

In the natural fallow, natural vegetation was allowed to regenerate. The legumes and natural vegetation grew for 2 seasons up to October 2000, when they were harvested. The continuous maize plots were cropped with maize during all the 4 seasons (1998-2002). In November 2000, half of each of the plots was tilled using an ox-drawn plough. All the plots were then cropped with maize for two subsequent seasons, with basal P fertilizer application of 18 kg P ha^{-1}. Half of all sub-plots were fertilized with 40 kg N ha^{-1}. In this paper we report data on measurements taken in the sub-plots that received no mineral N fertilizers.

Mineral N dynamics

Season 1

Soil was sampled from all the treatments on the 28th of October 2000 (preseason sampling year 1, PSS1), before the onset of rains. On this date, sampling was also done from an unmanaged miombo woodland (dominated by *Brachystegia spiciformis* and *Jurbernardia globiflora*) adjacent to the experiment for comparison with the managed woody legume system. Detailed monitoring of mineral N dynamics under maize during the following two cropping seasons was done in four contrasting treatments [maize monoculture, *Acacia, Sesbania* with and without tillage (*Sesbania*-no-till)]. *Sesbania* was included to represent high quality litter whereas *Acacia* represented slower decomposing organic materials (Mafongoya et al., 1997). An unfertilized continuous maize treatment was included as a control while the

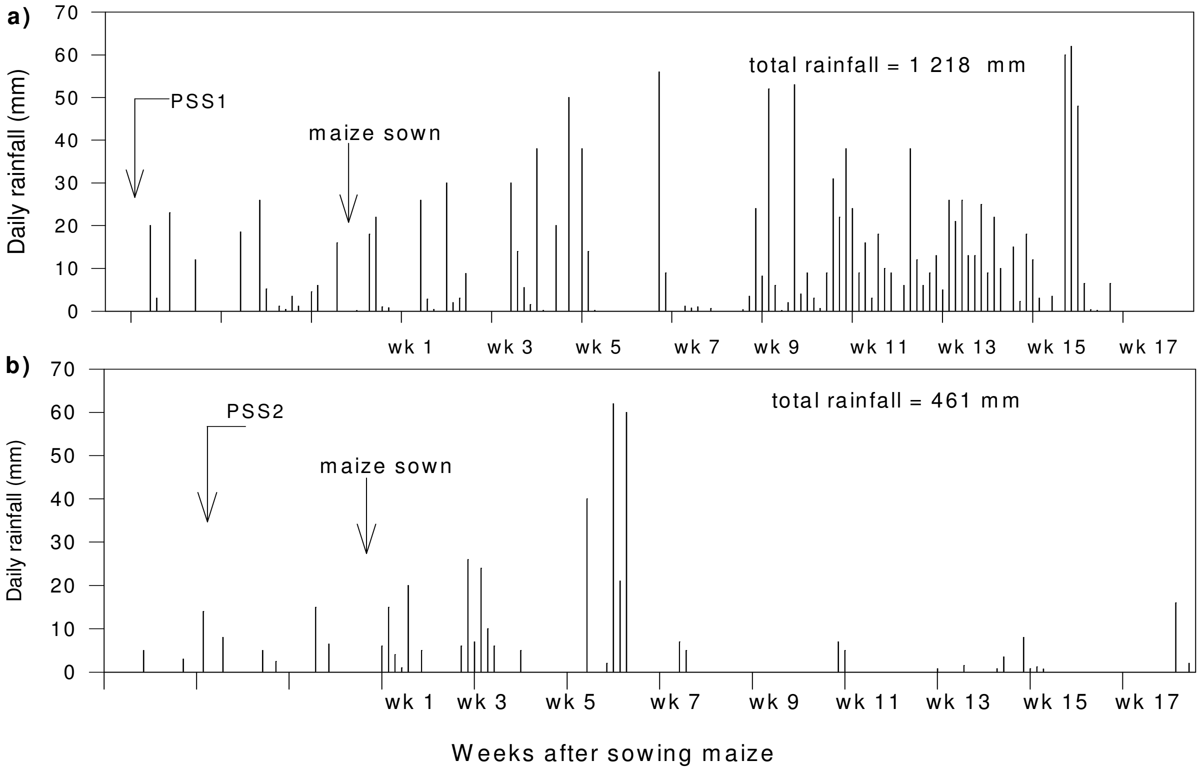

Figure 1. Rainfall distribution during the study period (a) October 2000 to April 2001 and (b) November 2001 to April 2002, at Domboshawa, Zimbabwe.

Sesbania non-till treatment was included to investigate the effect of tillage management on mineral N dynamics and nitrous oxide emissions. Soils were sampled using augers in sections of 0-20, 20-40, 40-60, 60-90, and 90-120 cm. In each plot, soil was collected and bulked from two locations for each depth. Sub-samples were taken to the laboratory in polyethylene bags and stored at 4°C prior to extraction usually within 2 days of collection. Maize was planted on the 30th November 2000 and soils for monitoring mineral N dynamics were sampled one week after planting maize (5th December, week 1). Thereafter, soils were sampled at two-week intervals during maize growth period to result in six sampling dates (1, 3, 5, 7, 9 and 11 weeks after planting maize). The last sampling was at maize physiological maturity on the 5th of April 2001 (week 18), twelve days after the last rains of the season (Figure 1).

Season 2

Soils were sampled following season 1 protocol. Pre-planting samples were taken on the 13th of November 2001 at the beginning of the second rainy season (PSS2). Maize was planted on the 5th of December 2001 and soils for monitoring mineral N dynamics were sampled one week after planting maize (12th December). Thereafter, soils were sampled at two-week intervals during maize growth period to result in five sampling times (PSS2, 1, 3, 5, and 8 weeks after planting maize). The final samples were taken at 22 weeks after maize planting, to determine residual soil mineral N after 2 maize crops following the termination of fallows.

Nitrate and ammonium analysis

Ten grams of field moist soil were extracted in 50 ml 0.5 M KCl. The soils were shaken on a rotary shaker for one hour and then filtered through No. 1 filter paper into polythene containers. Another sub sample of the soil was dried at 105 ^{o}C for 24 hours to determine the moisture content of the extracted soil. The NH_4-N phenate method was used for NH_4-N determination while the NO_2-N cadmium reduction method (Keeney and Nelson, 1982) was used for nitrate determination. The N concentration was determined colourimetrically with the absorbance read at 640 nm and 543 nm for ammonium and nitrate, respectively.

Coring rings with an internal diameter of 7.2 cm and 5.5 cm height were used to sample soils for bulk density. Soils were sampled from four pits that had been opened for root studies in satellite plot adjacent to the main experiment during the 2000/01 season. Four soil cores were taken per pit for each separate 20 cm section down to 120 cm. Soils were dried at 105^{o}C for 24 hours and bulk density was determined as: bulk density (g cm^{-3}) = mass of oven dry soil (g) / volume of soil cored (cm^{3}). The respective average bulk densities of the different soil layers were used to convert NH_4-N and NO_3-N concentrations from mg kg^{-1} to kg N ha^{-1}. We disregarded the loosening effect of tillage on bulk density changes in topsoil as changes are known to be temporary in nature on coarse textured soils (Twomlow and Breneau, 2000)

Nitrous oxide determination

Nitrous oxide fluxes were measured during the first maize cropping following termination of fallows from early December 2000 to early February 2001. The closed soil cover chamber technique (Mathias et al., 1980; Kaiser et al., 1996) was used to quantify N_2O-N losses in unfertilized subplots following *Sesbania* with or without tillage, *Acacia*, and continuous maize. We avoided measurements in fertilized subplots because we wanted to investigate the legume effects and avoid masking with N fertilizer. Measurements were taken at weekly intervals, for the first eight weeks after establishing the maize crop. PVC rings of 25 cm diameter were driven some 7 cm into the soil a day before the actual gas sampling was done. On the following day around 11 00 hrs, cylindrical chamber lids of 20 cm height were placed on the rings and sealed. These lids were equipped with rubber stoppers and self-sealing gas sampling septa. Four replicate chambers were used per plot and each treatment was replicated three times. Each chamber covered an area of 491 cm^{2} and had a headspace volume of 9.8 dm^{3}. Accumulated headspace was then sampled using a syringe at 30 and 60 minutes after enclosing the chambers. A 12 ml gas sample was withdrawn and the gas was injected in evacuated Labco Exetainer gas testing vials that do not allow gaseous diffusion and exchange with the atmosphere. The first gas sample was collected directly before closing the chamber lid, to obtain the background N_2O atmospheric concentration. Samples for soil moisture and NO_3-N determination were also collected in the top 20 cm layer on each date that nitrous oxide fluxes were determined. A thermometer was buried in the 0-10 cm topsoil to determine soil temperature.

The vials with gas samples were sent to USDA/ARS laboratory in Fort Collins, USA, and N_2O was analyzed by electron capture gas chromatography. Gas samples were analyzed for N_2O concentration by attaching each Exetainer to an evacuated inlet system. The inlet was connected to a 2-ml gas-sampling loop used to introduce a gas sample into the gas chromatograph (Mosier and Mack, 1980). An electronic manometer monitored the sample pressure for each sample and inlet sample pressure was recorded and used to calculate N_2O concentration as compared to gas standards handled in the same way. Gas concentrations were corrected for standard temperature and pressure according to atmospheric pressure and mean temperature of the gas sampling chamber over the flux measurement period. This sampling procedure and analytical system has been used in studies conducted at a remote site in the Amazon (Palm et al., 2002) and in the USA (e.g. Delgado et al., 1996; Mosier et al., 1993).

The flux rates were calculated using the slope of the temporal change of the concentration within the closed chamber, as described by Matson and Harriss (1995): N_2O flux = slope x 7027. Soil moisture was determined gravimetrically after drying the samples at 105 ^oC for 24 h. The water-filled pore space (WFPS) was determined as follows: WFPS (%) = [(% gravimetric water x soil bulk density) / total soil porosity], where soil porosity = (1-soil bulk density/soil particle density). The soil particle density was taken as 2.65 g cm^{-3}. Soil bulk density was determined using undisturbed soil cores, and was found to average 1.39 g cm^{-3} for the 0-20 cm depth. Soil NO_3-N was analyzed as described earlier.

Data analysis

A two-way analysis of variance was performed on nitrate, ammonium and total mineral N data using the Genstat statistical package (GENSTAT, 1997). Means for mineral N for miombo woodland treatment were determined separately. Leaching losses were estimated by analyzing changes in mineral N amounts in different soil layers with time, early in the season when N uptake by maize was minimal. We integrated the weekly N_2O flux measurements to obtain estimates of total losses within the 8-week measurement period, and used correlation analysis to investigate the relationship between soil factors (soil nitrate, WFPS) and N_2O flux rates.

Results

The daily rainfall for the 2000-2001 (October 2000 to April 2001) and 2001-2002 (November 2001 to April 2002) seasons is shown in Figure 1. This is the period during which the measurements were taken. The arrows indicate the sampling times for monitoring mineral N dynamics. Total rainfall for the 2001-2002 season was only 461 mm, 80 % of which was received between December and January.

Pre-season mineral N

NH_4-N was concentrated in the 0-20 cm layer for the *Acacia, Sesbania, Cajanus* and the unmanaged miombo ecosystem (Figure 2 a). It was greatest under the miombo woodland (20 kg N ha^{-1}), followed by the *Sesbania* and *Acacia* treatments which had about 16 kg N ha^{-1}, and least for the grass fallow which had 6.6 kg N ha^{-1}. There were no significant treatment differences in the amount of NH_4-N from depths greater than 40 cm ($P>0.05$). NO_3-N for the soils sampled before the rains on 28 October 2000 differed significantly between the various treatments ($P<0.01$) (Figure 2 b). NO_3-N concentrations in the 0-20 cm layer were greatest following cowpea-maize rotation and *Acacia* treatments, which amounted to 6.8 kg N ha^{-1}. The adjacent unmanaged miombo woodland, which had 2.6 kg N ha^{-1} in the 0-20 cm, had the least NO_3-N concentration in almost all layers. A distinct bulge in soil nitrate was present starting at the 60 to 80 cm layer for the continuous maize treatment, and at the 80 to 90 cm depth for the cowpea-maize sequence treatment. The continuous maize treatment had the largest accumulation of nitrate of 12 kg N ha^{-1} at the 100-120 depth compared with 2.1 kg N ha^{-1} for *Sesbania* and 2.6 kg N ha^{-1} for *Acacia* treatments at the same depth.

Total mineral N was greatest for the *Acacia* and miombo woodland treatments (about 22 kg N ha^{-1}) in the topsoil (0 to 20 cm) and was predominantly in the NH_4-N form (88%) (Table 2; Figure 2 b). There was, however, a rapid decline in mineral N with depth for these treatments as both NH_4-N and NO_3-N decreased. There was mineral N accumulation for the maize continuous and cowpea-maize sequence treatments at depths greater than 60 cm, which was primarily due to NO_3-N as the concentration of NH_4-N was fairly constant from the 40 cm depth (Figures 2 a & b). Total mineral N was less affected by treatments in the 20-60 cm zone. Total mineral N in the profiles to 120 cm deep was largest for the maize control (92 kg N ha^{-1}), followed by the cowpea-maize rotation, and least for grass fallow, with only 47 kg N ha^{-1} (Table 2). Total profile mineral N under the leguminous tree fallows and miombo woodland was comparable.

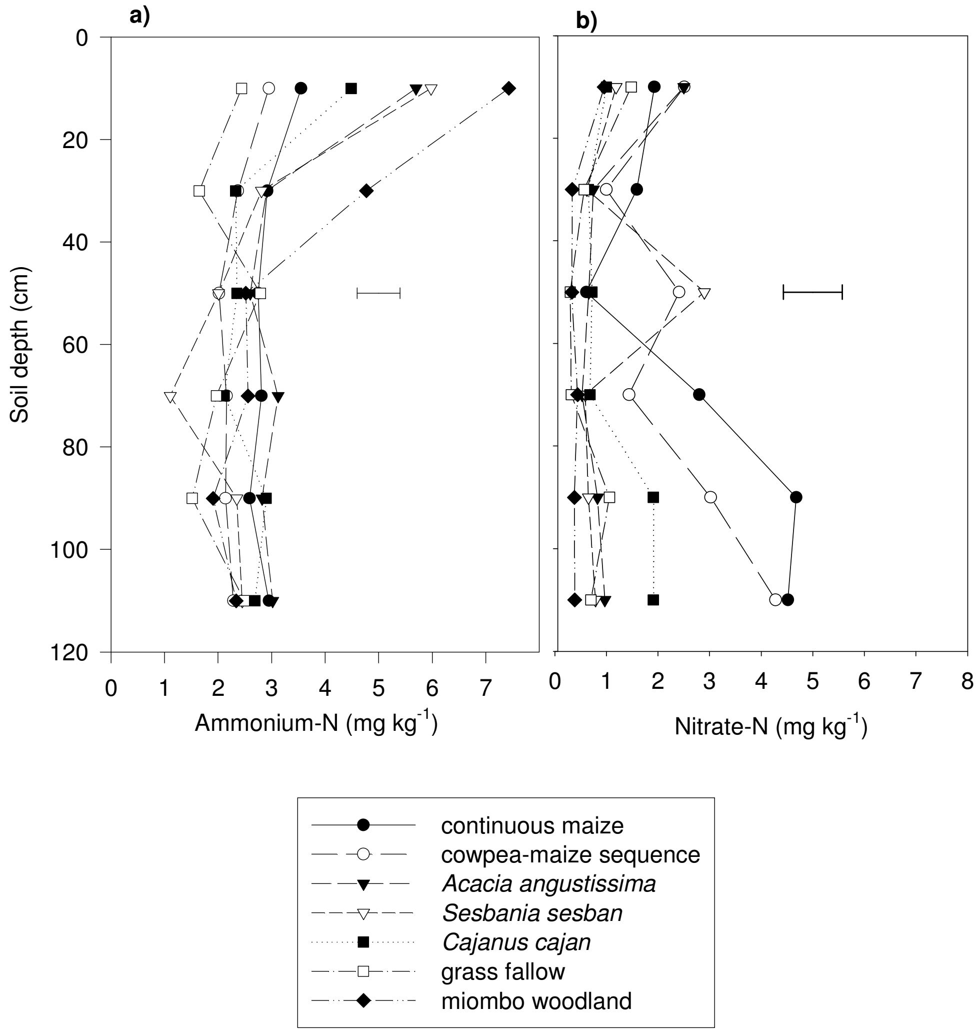

Figure 2. (a) Ammonium and (b) nitrate-N from plots that had continuous maize, cowpea-maize rotation, grass fallow, miombo woodland and following cutting of 2-year *Acacia angustissima*, *Sesbania sesban*, and *Cajanus cajan* improved fallows. Each error bar represents LSD ($P< 0.05$) for all depths.

Mineral N dynamics – first season

The relatively large amounts of NH_4-N and the significant treatment differences in NH_4-N in the profile noted near the end of the dry period in October 2000, decreased rapidly upon the onset of rains in mid November, and there were no significant differences between treatments by the third week after planting (Figure 3). Topsoil NH_4-N decreased from about 9 kg N ha^{-1}

Table 2. Mineral N per layer (kg N ha^{-1}) and total profile mineral N (kg ha^{-1}) as influenced by the different land use systems just before the start of the rains, October 2000 (PSS1).

	Treatment						
Depth	Maize cont.	Cowpea-maize	*Acacia*	*Sesbania*	*Cajanus*	Grass fallow	Miombo* woodland
0-20	14.8	14.7	22.1	19.4	14.8	10.5	22.6
20-40	13.0	9.7	10.5	9.9	8.6	6.4	14.8
40-60	9.1	11.9	8.8	13.2	8.3	8.3	7.6
60-80	15.1	9.7	9.8	5.4	7.5	6.1	8.1
80-100	19.6	13.9	9.8	8.1	12.9	7.0	6.2
100-120	20.1	17.8	10.7	8.7	12.4	8.5	7.3
	SED (treatments) = 1.87; SED (depth) = 1.23						
Total mineral N (kg ha^{-1})	92	78	72	65	64	47	67

* Not part of the randomized complete block design. Means given for comparative purposes only.

to less than 0.5 kg N ha^{-1} by the third week in the continuous maize treatment, and from 16 kg N ha^{-1} to about 2 kg N ha^{-1} for the *Acacia* and the *Sesbania* treatments. There were few significant treatment differences for most of the sampling dates, except for the fifth and ninth week when *Acacia* plots had significantly higher NH_4-N concentrations (Figure 3). There were no indications of NH_4-N accumulation in the subsoil at any point during the rainy period. After the termination of the rains on the end of March 2001, NH_4-N started to accumulate and had increased 3 fold by the 18th week after planting maize. At this point there was still no significant treatment separation, though the non-tilled *Sesbania* treatment had the largest amounts of NH_4-N in the topsoil (0-20 cm) and the tilled *Sesbania* had the greatest amount in the deepest layer.

There was a flush in NO_3-N in the *Sesbania* and *Acacia* plots at one week after planting (week 1) in the two top 20 cm layers (Figure 4). Topsoil NO_3-N increased from 3.2 to 34 kg N ha^{-1} in the *Sesbania* plots and from 6.7 to 29 kg N ha^{-1} in the *Acacia* plots during the period from 28 October to 4 December (PSS1 to week 1). At this time, the no-till *Sesbania* plots had comparatively small amounts of NO_3-N, which were of similar magnitude as that in the maize control treatment. There were no treatment differences in NO_3-N concentration at depth below 40 cm in the profile for the week 1 samples (Figure 4). The increase in NO_3-N amounts observed for the *Acacia* and *Sesbania* plots was not sustained as concentrations decreased rapidly. Topsoil NO_3-N had decreased to 8.6 kg N ha^{-1} and 11.2 kg N ha^{-1} for the *Sesbania* and *Acacia* plots, respectively, only three weeks after planting maize. The decrease in topsoil NO_3-N was accompanied by a relative increase in NO_3-N at depths

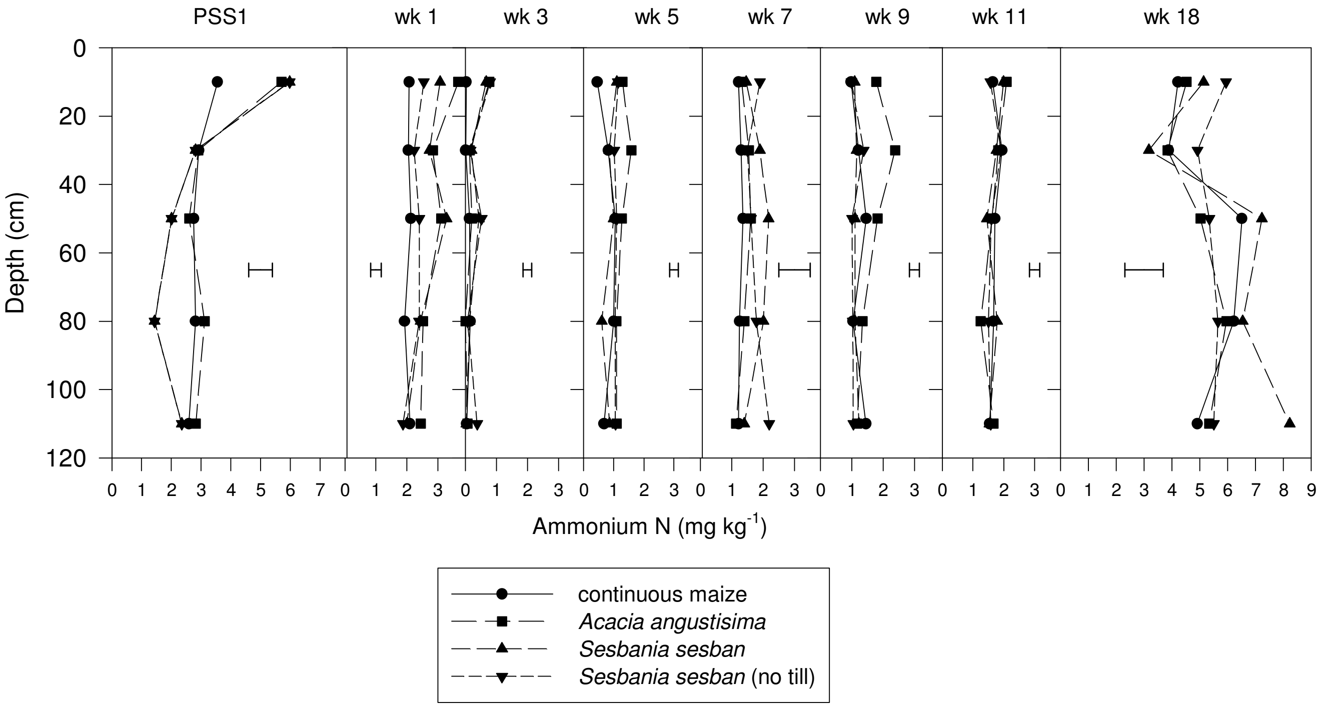

Figure 3. Ammonium-N at different soil depths during first season maize cropping, following plots that had continuous maize, and 2-year fallows of *Acacia angustissima* and *Sesbania sesban*. Note different scale than Figure 4. Each error bar represents LSD ($P < 0.05$) for all depths for the respective sampling dates.

below 40 cm. A noticeable bulge in NO_3-N had built up by the third week after incorporating the litter, with the control always lagging behind (Figure 4). There was evidence of NO_3-N movement down the profile as the bulge became more pronounced with depth and time. Beyond the 3rd week after planting, the two *Sesbania* plots had more NO_3-N in the profile compared with either the *Acacia* plots or the control. The exception was after 11 weeks when *Acacia* plots apparently had the highest amount of NO_3-N in the 40 to 100 cm depth zone. By this time the bulk of the NO_3-N for the *Sesbania* plots had moved to the 100 -120 cm layer or beyond (Table 3). Root length density for maize is known to be low at depths below 80 cm. The contribution of NH_4-N to total mineral N was insignificant for most of the season, and total mineral N dynamics largely followed NO_3-N concentrations. Following termination of the rains, NH_4-N slowly increased and became a significant component of the residual mineral N at maize maturity.

Between week 1 and week 3 apparent leaching losses were about 40, 29 and 9 kg ha^{-1} NO_3-N for *Sesbania*, *Acacia* and the unfertilized maize treatments, respectively, from the 0-40 cm depth to lower layers (Table 3). The rainfall received within this 2-week period was 104 mm, to an already fully recharged soil profile. Apparent leaching losses for the no-till

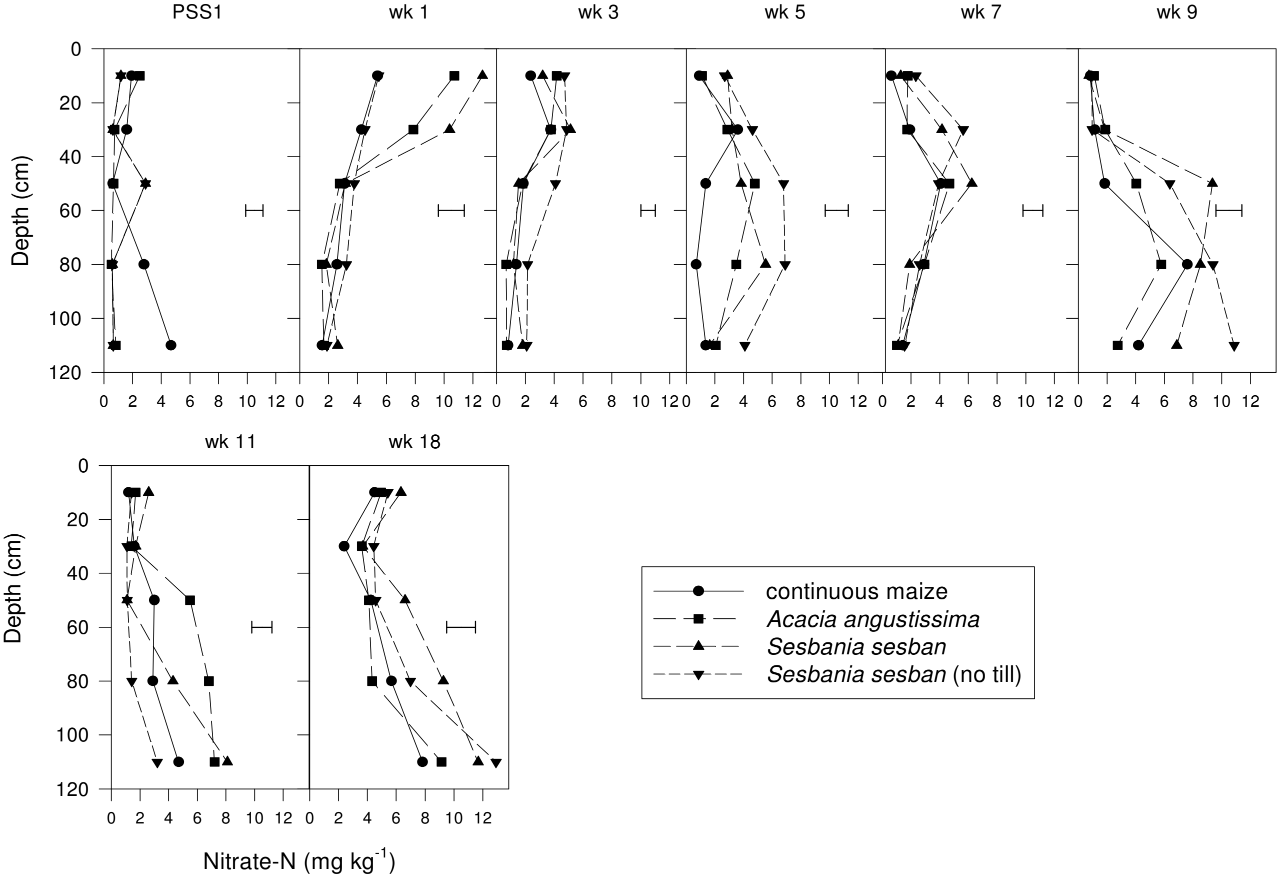

Figure 4. Nitrate-N at different soil depths during first season maize cropping, following plots that had continuous maize, and 2-year fallows of *Acacia angustissima* and *Sesbania sesban*. Each error bar represents LSD (P< 0.05) for all depths for the respective sampling dates.

Sesbania were small within this period, only 1.2 kg NO_3-N ha^{-1}, and were linked to the delayed mineralization in these plots.

Mineral N dynamics – second season

During the second season there were no differences in NH_4-N at the beginning of the season (Figure 5). There was a flush in NH_4-N at week 1, but this had decreased, as in the first season, by the third week after planting maize in the surface soil. NH_4-N concentration in *Acacia* plots was significantly larger than the other treatments at week 6, but only for the 0-40 depth (P <0.05). However, unlike the first season, there was a general increase in NH_4-N at all depths up to week 6. Samples taken at the end of the second cropping season, at 22 weeks, showed that there was very little residual NH_4-N at all profile depths (Figure 5).

NO_3-N in the *Sesbania* and *Acacia* plots increased significantly at one week after planting (week 1) in the two top 20 cm layers (Figure 6). Untilled *Sesbania* had a significantly greater NO_3-N concentration at 40-80 depth at week 1. In general, there were substantial amounts of NO_3-N in the profiles for all treatments, up to week 6. Measurements taken at 9 and 22 weeks showed little nitrate concentration for all the treatments throughout the profiles.

Table 3. Differences in soil NO_3-N contents between successive sampling dates at different soil depths for continuous maize and tree-fallow–maize sequences during the 2000/2001 rainy season at Domboshawa, Zimbabwe. Positive values indicate accumulation of NO_3-N while negative values indicate that NO_3-N had leached out of the layer.

	Treatments			
Soil depth (cm)	Continuous maize	*Acacia*	*Sesbania*	*Sesbania* no-till
	---------------------------NO_3-N (kg ha^{-1})----------------------------			
(a) Week 1 (4 December) –PSS1 (28 October)				
0-20	+9.7	+23.0	+32.1	+12.0
20-40	+7.5	+19.9	+27.3	+10.9
40-60	+7.0	+5.9	+0.7	+2.5
60-90	–0.9	+4.2	+5.2	+11.0
90-120	−14.7	+3.4	+8.3	+5.1
(b) Week 3 (20 December) – Week1 (4 December)				
0-20	–8.4	−18.3	–26.5	–2.1
20-40	−1.4	−11.4	−14.7	+0.9
40-60	–3.5	–2.7	–4.5	+0.9
60-90	–5.1	–3.6	–2.8	–4.5
90-120	–2.5	–4.0	–3.4	+0.9
(c) Week 9 (4 February) – Week 7 (18 January)				
0-20	+0.6	−1.8	−1.5	–3.9
20-40	–2.2	+0.4	–6.5	−13.1
40-60	–6.3	−1.7	+8.7	+6.9
60-90	+19.7	+11.9	+27.7	+28.5
90-120	+11.7	+7.2	+24.3	+36.9

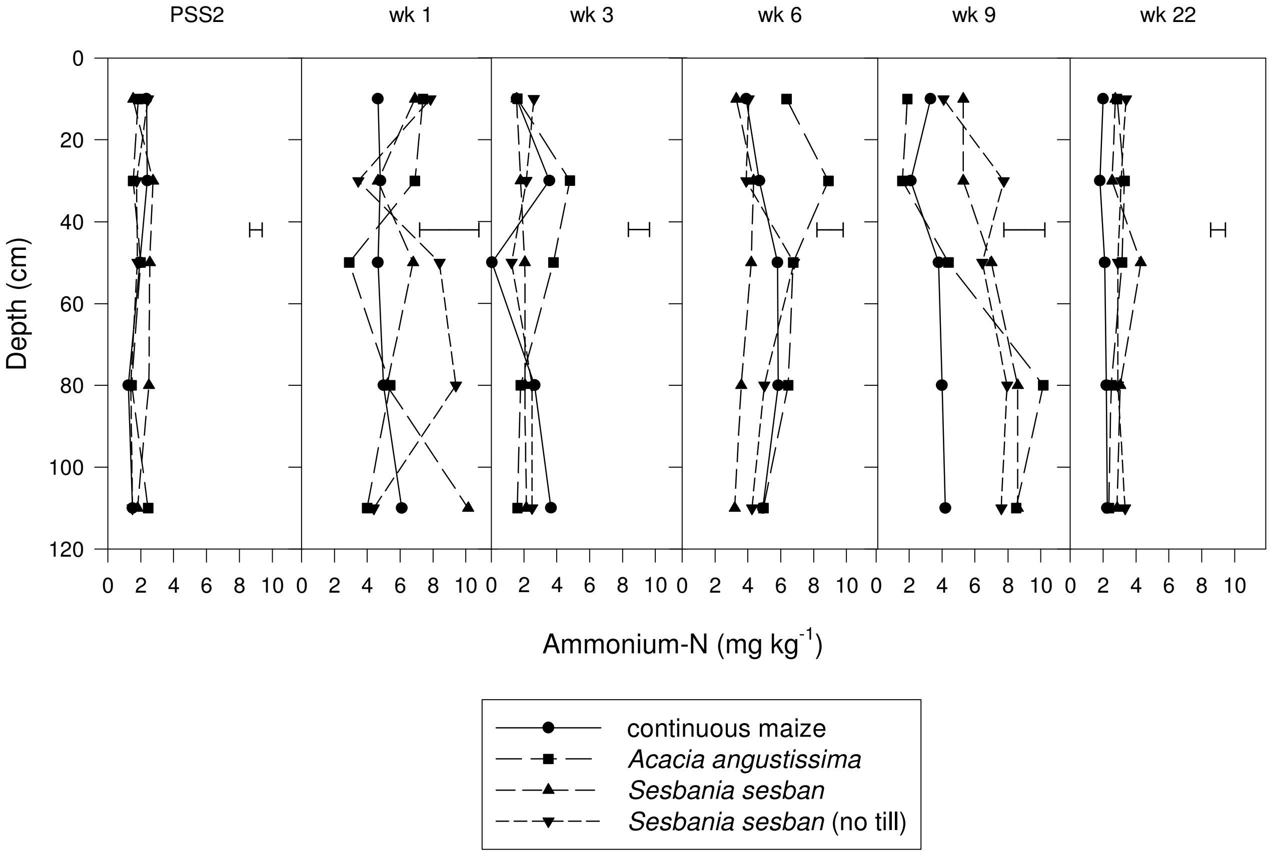

Figure 5. Ammonium-N at different soil depths during maize cropping, following plots that had continuous maize, and 2-year fallows of *Acacia angustissima* and *Sesbania sesban*, during the second season. Each error bar represents LSD ($P< 0.05$) for all depths for the respective sampling dates.

Nitrous oxide emissions

Nitrous oxide emissions were measured in unfertilized maize following *Sesbania* with or without tillage, *Acacia* and continuous maize treatments at weekly intervals for the first eight weeks of the first season. Emissions following improved fallows were significantly greater ($P<0.01$) than those from the unfertilized maize monoculture (Figure 7 a,b). N_2O fluxes were twice as high from the *Sesbania* tilled and *Sesbania* no-till treatments than from the *Acacia* plots and about 7 times as much as that from the continuous maize treatments, on measurements taken one week after planting maize (12.3 vs. 5.8 and 1.6 g N_2O-N ha^{-1} day^{-1} , respectively). Tilled *Sesbania* plots emitted the most N_2O during the first week and this decreased rapidly to less than half as much by the end of the second week (Figure 7 b). While emissions from *Sesbania* treatments had decreased by the second week, the *Acacia* treatment maintained a fairly constant flux rate of about 6 g ha^{-1} day^{-1} during the first three weeks. The

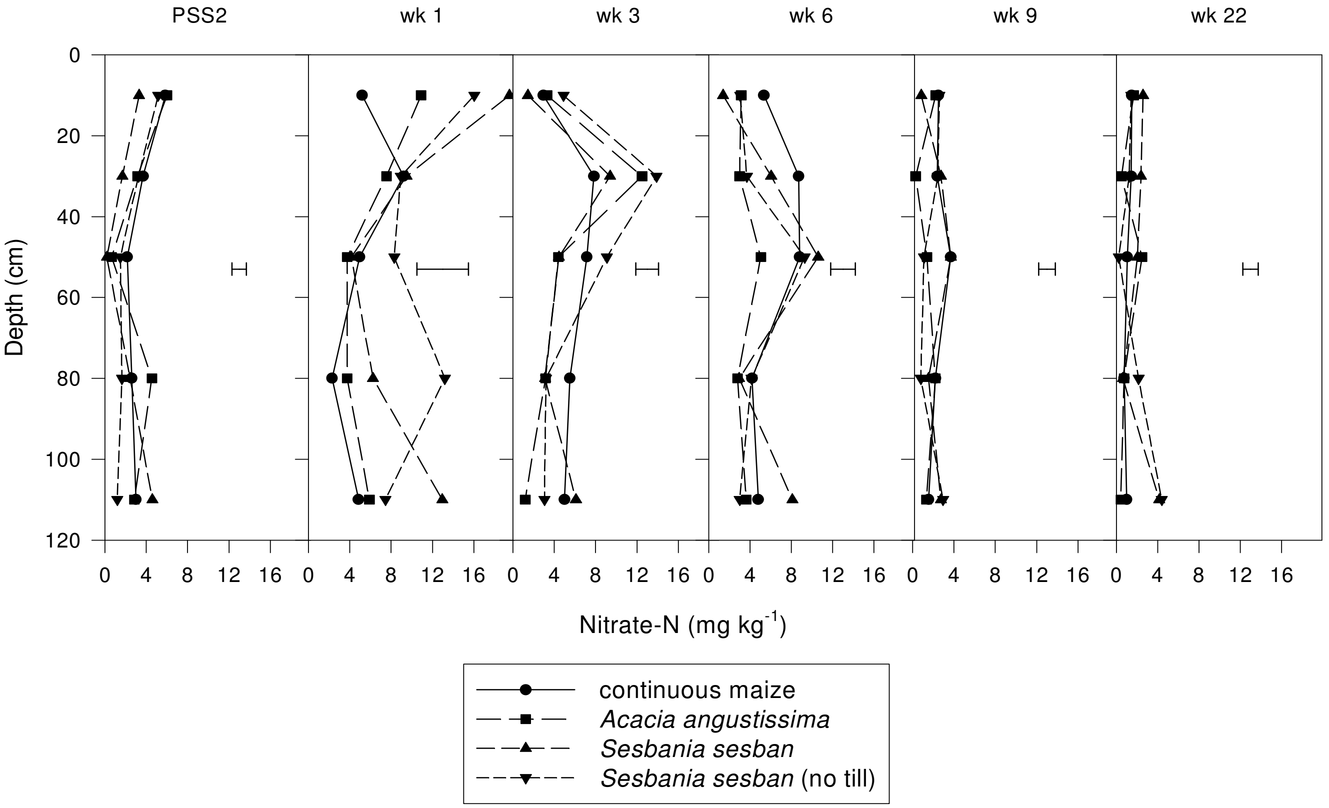

Figure 6. Nitrate-N at different soil depths during maize cropping, following plots that had continuous maize, and 2-year fallows of *Acacia angustissima* and *Sesbania sesban* during the second season. Each error bar represents LSD ($P < 0.05$) for all depths for the respective sampling dates.

unfertilized maize treatment showed consistently low N_2O emissions, which never exceeded 2 g N_2O-N ha^{-1} day^{-1} on any of the 8 sampling dates.

N_2O fluxes for all the treatments were low during the third week when the soil was relatively dry but peaked again for both *Sesbania* treatments (tilled and no-till) during the fourth week when soil moisture was at or above field capacity, with WFPS around 40 % (Figure 7 c). NO_3-N concentrations were fairly small (<4 mg kg^{-1}) in all plots by this time (Figure 7 d). Emissions after the fourth week continued to be small for all the treatments and were less sensitive to soil moisture fluctuations as observed early in the season. While by the seventh week the flux from the unfertilized maize was barely detectable, fluxes from the treatments where substantial legume residues had been added remained above 1 g N_2O-N ha^{-1} day^{-1}.

We assumed constant emission rates in between the weekly measurements and integrated to estimate total N_2O-N emissions for the 8-week period. Total N_2O-N emissions were lowest in the unfertilized maize plots with a cumulative total of only 60 g in the 56 days, and were greatest following tilled *Sesbania* plots with a total of 290 g for the same period (Figure 7a). No-till *Sesbania* lost a total of 240 g N_2O-N while emissions in *Acacia* plots were 180 g. For all the four treatments about 80 % of the total emissions were within the first four weeks.

Emissions were significantly correlated to topsoil NO_3-N concentration ($R^2 = 0.62$) (Figure 8), and not with either WFPS or soil temperature. Soil temperature ranged between 25-28 ^{o}C for the eight sampling dates. Soil NO_3-N increased immediately after cultivation in the topsoil and then declined rapidly within a three-week period, accumulating in deeper layers for all treatments (Figure 7 d). Despite heavy rainfall and higher soil moisture content coinciding with the 4th, 7th and 8th week sampling times, the emissions at these times were significantly less than those for the first week, even though the WFPS was comparatively greater.

Discussion

Pre-season mineral N

At the end of the fallow phase, NH_4-N concentration was relatively large in the top 0-20 cm layer, for *Acacia, Sesbania* and miombo woodland, which all had a pronounced litter layer (data not presented), while NO_3-N was found to have accumulated below the 80 cm depth for the continuous maize and cowpea-maize plots (Figure 2 a,b). The relatively larger NH_4-N concentration in the topsoil is probably due to ammonification that occurred at low rates during the long dry season in savanna environments, where nitrification is inhibited. Ammonification is known to progress at slow rates even under very dry soil conditions (Robinson, 1957). We suspect that the high NO_3-N concentration in the maize plots was leached to this depth during the previous rainy seasons. Under previous management the maize monoculture plots were fertilized with 40 kg N $ha^{-1}year^{-1}$ (Mafongoya and Dzowela, 1999).

NO_3-N concentrations were small in the subsoil under the trees at the end of the 2-year fallow period. Hartemink et al. (1996) reported that *Sesbania* and *Calliandra calothyrsus* reduced soil nitrate in the top 2 m by up to 200 kg N ha^{-1} one year after establishment. In Western Kenya, *Sesbania* roots penetrated to below 4 m, and were able to use deep moisture and capture N that was leached from below the rooting zone of maize (Mekonnen et al., 1997). Trees with deep roots intercept nitrate leaching down soil profiles and 'capture' nutrients accumulated in the subsoil below the rooting depth of maize (van Noordwijk et al., 1996). Nutrients taken up by trees from below the rooting zone of maize and other annual crops become an input to the soil-crop system when transferred to surface soil in the form of leaf litter, roots and prunings of tree leaves and branches (Schroth, 1995).

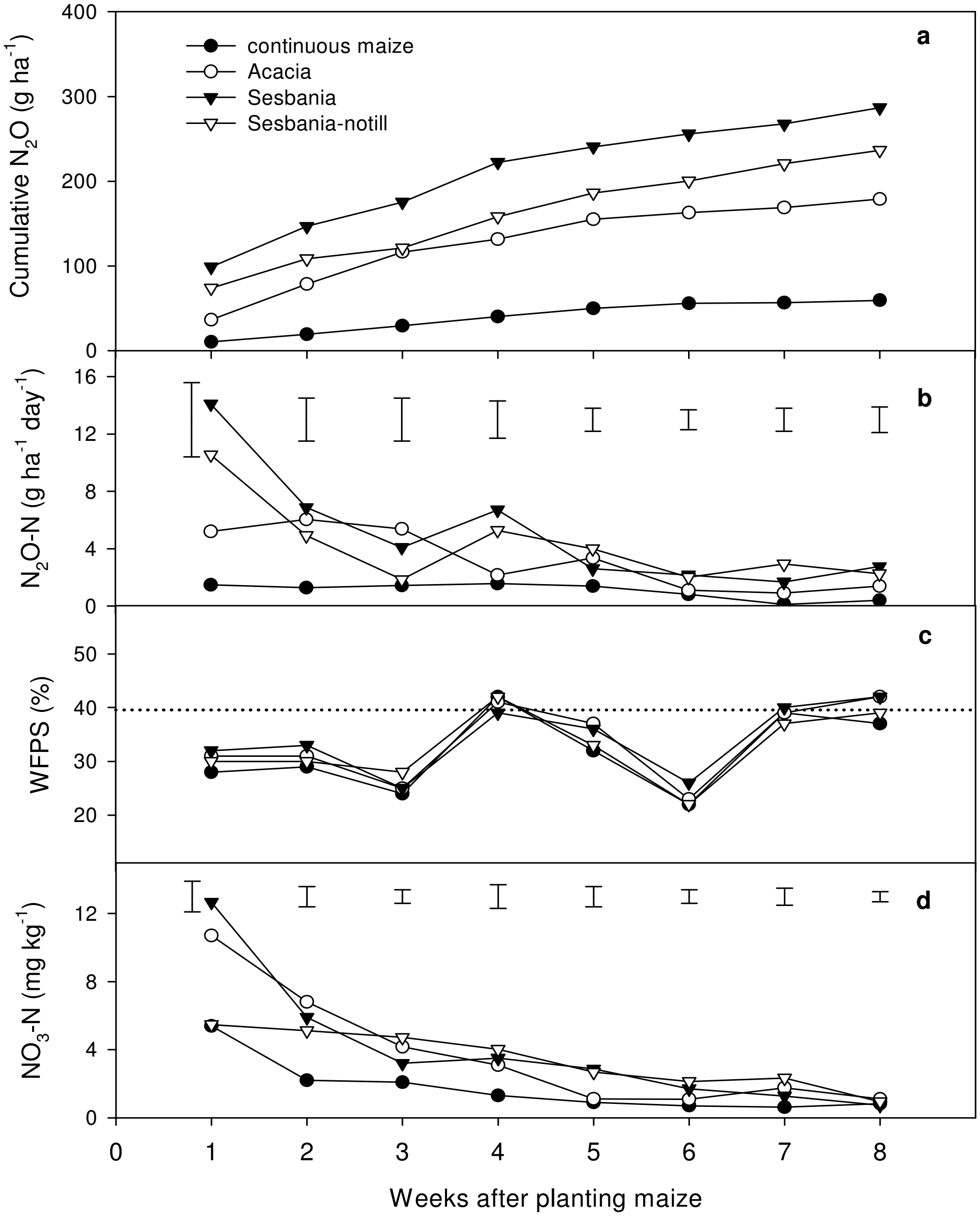

Figure 7. (a) Cumulative N_2O emissions measured over the first 56 days after planting maize (1 December 2000 to 26 January 2001) (b) daily N_2O flux rates (c) soil water filled pore space with dotted horizontal line representing % WFPS at field capacity, 0-20 cm layer and (d) Soil NO_3-N concentration (0-20 cm layer). Error bars represent LSD ($P<0.05$) for N_2O emissions and NO_3-N concentration for the respective sampling dates.

Mineral N dynamics

Warm, wet conditions in the soil during the last two weeks of November were ideal for the rapid decomposition of the litter that was in the soil. The re-wetting of the dry soil resulted in a flush of mineralization, the 'Birch effect' (Birch, 1964). This led to a pronounced flush of NO_3-N, evident in the top 40 cm of the soil in the week 1 sampling for the tilled plots of *Sesbania* and *Acacia* (Figure 4). Large amounts of nitrate in the tilled *Sesbania* plots in contrast to the low amounts in the non-tilled *Sesbania* plots at this stage in the season presumably resulted from rapid release of N stimulated by tillage (Table 3a). Unfortunately at this time in the season, this high concentration of mineral N is susceptible to leaching, as the maize roots are not yet sufficiently developed to absorb and intercept leaching nutrients. No-till enhances soil aggregation, which is associated with soil carbon sequestration, improved water infiltration and resistance to soil erosion (Beare et al., 1994; Elliot, 1986). The protection of high quality organic residues against microbial attack leads to delayed N release, a scenario that may reduce N loss when fast mineralization occurs before plant roots become established during the early crop phase.

The time lag in N mineralization noticed for *Sesbania* no-till treatment was only temporary as NO_3-N concentrations increased by the third week after planting maize. This delay in mineralization is too short and may not improve synchrony with crop uptake substantially, as the mineral N will become available when the maize root system is still insufficiently developed to effectively intercept the NO_3-N. In a recent review of management of organic matter in the tropics, Palm et al. (2001) also highlighted that high quality materials (high N, low lignin, low polyphenols) exhibit similar nitrogen availability patterns as mineral fertilizers, with a large proportion of the N available in advance of the main period of N-uptake by the growing crops.

As time following the termination of the fallows increased, there was evidence of accumulation of NO_3-N in deeper soil layers (Table 3 c). This is evidence of a ‘leaky’ system in the absence of deeper-rooted trees. Except for *Acacia* that coppices and continuously recycles nutrients through the prunings, other trees were no longer active. Therefore, the closed nutrient cycle that had been established during the fallow phase disintegrated within a few weeks of cropping, and the systems reverted to ‘leaky’ states (Nair, 1993). A high concentration of NO_3-N in *Sesbania* plots during the first season was also a result of poor uptake by maize due to pest attack (data not presented). The major form of mineral N between the first and eleventh weeks during the first season was NO_3-N, which is easily leachable compared with the NH_4-N form. NH_4-N did not accumulate in the soil as it was rapidly converted into NO_3-N. There was, however, accumulation of both NH_4-N and NO_3-N by the first week of April. At this time, the maize crop had reached maturity and nutrient uptake had ceased, and there were no longer any leaching losses as the rainy season had ended. During the second season mineral N also increased at the beginning of the rainy

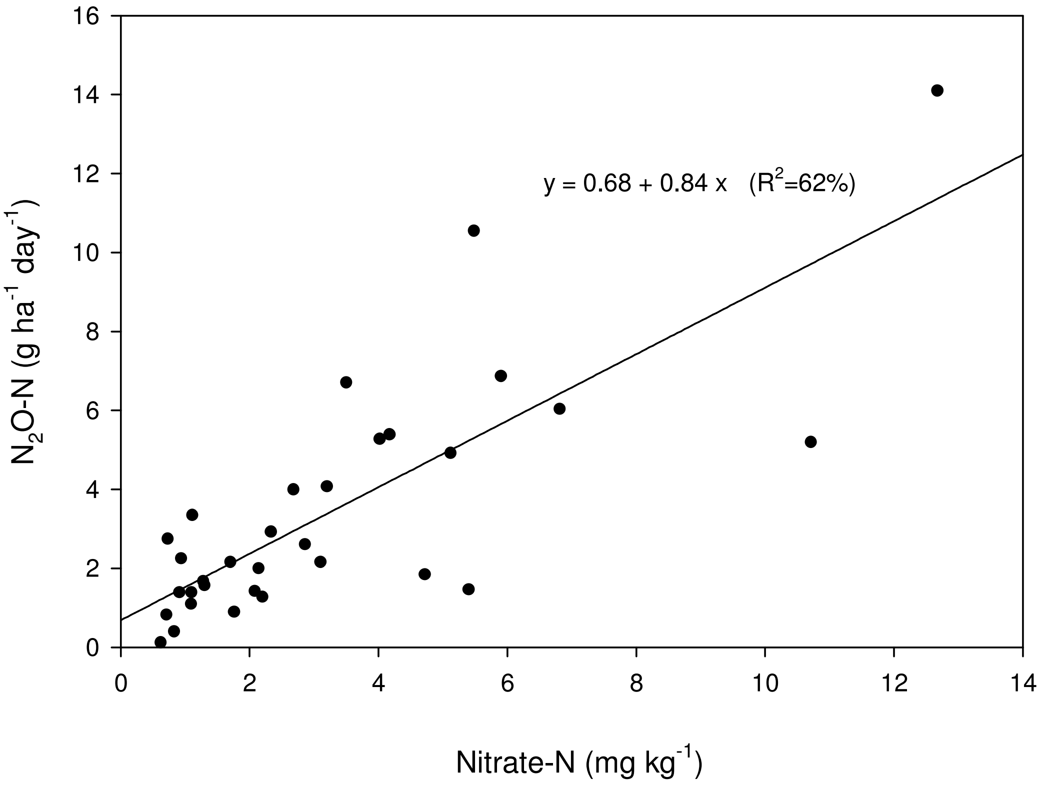

Figure 8. The relationship between N_2O emissions and topsoil NO_3-N concentration.

season. At week nine, NH_4-N was higher than NO_3-N due to dry soil (Figures 5 and 6). There was no evidence of leaching losses, as the rainfall was lower than the first season. Soil samples taken at the end of the second season had surprising smaller concentrations of both NH_4-N and NO_3-N, compared with concentrations at week nine.

This study has confirmed the rapid flush of mineral N in topsoil layer at the onset of rains after a pronounced dry season. However, this flush seems to be short-lived as the concentration of mineral N dropped within two weeks. This reduction is probably due to leaching, as plant N uptake can clearly be discounted on account of poor N uptake by maize early in the season. After four weeks of growth, N uptake by maize amounted to only 2.4, 2.1, 1.8 and 1.1 kg N ha^{-1} for *Sesbania, Sesbania* no-till, *Acacia* and continuous maize treatments, respectively (Chikowo et al., in press). In semi-arid tropical dryland agriculture, leaching losses depend on the coincidence of heavy rainfall with the application of N or organic matter mineralization. Kamukondiwa and Bergstrom (1994) working on a sandy soil in Zimbabwe reported N leaching losses of 17-39 kg ha^{-1} in a single season in a low input system.

Nitrous oxide emissions

Nitrous oxide emissions were significantly greater following improved fallows when compared with unfertilized maize monoculture (Figure 7a). The highest emission rates occurred in the *Sesbania* plots early in the cropping season, and were never high for the unfertilized maize during the entire eight weeks of measurements. The trends in N_2O emissions suggest that it is neither moisture nor tillage *per se* that leads to increased N_2O fluxes from cropping systems, but rather accelerated soil N cycling. Although the *Sesbania* and *Acacia* subplots where measurements were made received no N fertilizer on this site, high N input is maintained by N_2-fixation (Chikowo et al., in press). NO_3-N was highest in the tilled *Sesbania* plots for the top 20 cm layer during the first week, which then resulted in the comparatively higher N_2O flux. What the available data could not logically explain, though, were the higher emissions associated with untilled *Sesbania* compared with *Acacia*, despite *Acacia* having higher nitrate concentrations in the top soil on this sampling date.

During the fourth week when moisture was again at field capacity, N_2O fluxes for *Sesbani*a treatments increased, but only to as much as about 40% of the rates obtained during the first week. During the 8th week when soil moisture was at field capacity, there was no corresponding increase in N_2O emissions. This trend in N_2O fluxes could be explained by the NO_3-N dynamics as the season progressed. Early in the season, NO_3-N was concentrated in the top 20 cm layer (Figure 4). By the 8th week after planting maize, there was little NO_3-N in the top layers as it had either been taken up by the growing maize crop or leached to lower depths. Subsoil denitrification of the leached NO_3-N is unlikely because of poor availability of carbon as a substrate for the bacteria.

In a study of nitrous oxide emission from soils after incorporating crop residues in SE Scotland, Baggs et al. (2000) reported that most of the emission occurred during the first two weeks, returning to ‘background’ rates after 30-40 days. They found that the highest flux was from N-rich lettuce residues, 1100 g N_2O-N ha^{-1} being emitted over the first 14 days after incorporation by rotary tillage. Dobbie et al. (1999) measured emissions of nitrous oxide from intensively managed agricultural fields over three years and found exponential increases in flux with increasing soil water-filled pore space, temperature and soil mineral N. Fluxes were low when any of these variables was below a critical value. In a study of the effects of temperature, water content and N fertilization on emissions of nitrous oxide by soils, Smith et al. (1998) also confirmed that exponential relationships between N_2O flux and both water-filled pore space and temperature are only observed when soil mineral N was not limiting.

High amounts of readily decomposable organic matter could have enhanced the potential for denitrification through a general stimulation of microbial respiration, causing rapid O_2 consumption. Though a general relationship between total soil C and denitrification has been observed, rates of denitrification are highly correlated with "available" soil C as evaluated by readily mineralizable C or water soluble organic C (Reddy et al., 1982). Chang et al. (1998) showed that annual N_2O emissions increased with manuring rate and this is linked to the increase in easily mineralizable organic C that stimulates activity of the microbial biomass.

The revised IPCC (1997) guidelines estimate direct emissions of nitrous oxide from agricultural soils as a fixed percentage, 1.25 (0.25 - 2.25)%, of the additional N inputs, recognizing that in most agricultural soils biogenic formation of nitrous oxide is enhanced by an increase in available mineral N which, in turn, increases nitrification and denitrification rates.

Our results show that N_2O fluxes were small and that total N losses as N_2O gas were at most 0.2 % of the N applied as organic residues. We suspect that under the less reducing soil environment of the sandy loam soil at this site, NO gas may have constituted a large proportion of the overall gaseous N losses. In a study of the NO and N_2O emissions from savanna soils following the first simulated rains of the season, Scholes et al. (1997) reported that N_2O emissions averaged 8% of the total N emissions. Skiba and Ball (2002) also investigated the effect of soil texture and soil drainage on emissions of NO and N_2O and concluded that the maximum NO emissions were always from the most sandy, freely drained soils. Measurements were started only one week after ploughing meaning that the peak rates of N_2O emissions could have been missed. Even so it is likely that N_2O emissions were less than 1 kg N ha^{-1} $season^{-1}$, and total gaseous loss of N through nitrification/denitrification were less than 5 kg N ha^{-1} $season^{-1}$.

Conclusions

This work has shown an inherent problem in managing mineral N originating from mineralization of organic materials as it normally accumulates at the beginning of the season, well before peak demand by crops and before the maize root system has adequately developed. The delay in mineralization associated with minimum tillage was not long enough to significantly improve synchrony of mineral N availability and crop demand. The flush in mineral N in the topsoil layer seems to be of short duration as the concentration of mineral N dropped within two weeks. This reduction is probably due to leaching losses as plant N uptake can easily be discounted on account of poor N uptake by maize early in the season. This has strong implications on N management under smallholder systems for which N supplies are limited in quantity and often supplied from organic resources. With mineral fertilizers, synchronizing mineral N availability and demand is possible through split application of fertilizers. Nitrous oxide emissions following improved fallows were significantly greater than from the unfertilized maize. These emissions were however small, and are probably not the key N loss pathway. We did not quantify nitric oxide and N_2 gas emissions, but it is unlikely that these would make total gaseous N losses significant and contribute to poor N recovery that has been widely reported.

Acknowledgements

We gratefully acknowledge ICRAF-Zimbabwe for allowing us to use the long-term experiment at Domboshawa to make the measurements we reported in this paper. We thank A. Mosier for the N_2O analysis and most helpful advice. The work is an output of IMProved fALlows in Africa (IMPALA Project No. ICA4-CT2000-30011) funded by the European Union, and a grant from the Rockefeller Foundation for the first author's study at Wageningen University, The Netherlands.

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CHAPTER 5

Partitioning of simulated rainfall in a kaolinitic soil under improved fallow–maize rotation in Zimbabwe

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This chapter has been published as:

Nyamadzawo G, Nyamugafata P, Chikowo R and Giller K E 2003. Partitioning of simulated rainfall in a kaolinitic soil under improved fallow–maize rotation in Zimbabwe. Agroforestry Systems 59: 207-214.

Abstract

Research on improved fallows has concentrated on soil fertility benefits neglecting possible benefits to soil and water conservation. The effects of improved fallows on rainfall partitioning and associated soil loss were investigated using simulated rainfall on a kaolinitic soil in Zimbabwe. Simulated rainfall at an intensity of 35 mm h^{-1} was applied onto plots that were under planted fallows of *Acacia angustissima* and *Sesbania sesban,* natural fallow and maize (*Zea mays*) for two years. At the end of 2-years in October 2000, steady state infiltration rates could not be determined in *A. angustissima* and natural fallow plots, but they were 24 mm h^{-1} in *S. sesban* and 5 mm h^{-1} in continuous maize. The estimated runoff losses after 30 minutes of rainfall were 44% from continuous maize compared with 22% from *S. sesban* and none from *A. angustissima* and natural fallow plots. Infiltration rate decay coefficients were 36 mm and 10 mm for *S. sesban* and continuous maize, respectively. In October 2001 after one post-fallow crop, it was still not possible to determine the steady state infiltration rates in *A. angustissima* and natural fallows, but they were 8 and 5 mm h^{-1} for, *S. sesban* and continuous maize systems, respectively. The runoff loss, averaged across tilled and no-tilled plots, increased to 30% in the case of *S. sesban* fallowed plots and 57% for continuous maize; there was still no runoff loss from the other treatments. There were significant differences ($P<0.05$) in infiltration rate decay coefficients among treatments. The infiltration rate decay coefficient was 25 mm for *S. sesban* and it remained unchanged at 10 mm for continuous maize. It is concluded that planted tree fallows increase steady state infiltration rates and reduce runoff rates, but these effects markedly decrease after the first year of maize cropping in non-coppicing tree fallows.

Key words: Improved fallows, Infiltration, Infiltration decay coefficient, Runoff, Soil loss

Introduction

Many intensive agricultural systems have the potential to induce accelerated soil erosion and water loss. Water and soil losses are a widespread problem in Zimbabwe's smallholders' areas and southern Africa as a whole, where conventional tillage is practiced. Conventional tillage involves clean tillage using ox-drawn ploughs and has been estimated to result in soil losses of 10 to 34 t ha^{-1} y^{-1} (Vogel 1992 and Moyo 1997). Soil losses up to 50 t ha^{-1} y^{-1} through sheet erosion were estimated to occur using the Soil Loss Estimation Model from bare fallow plots in a sub-humid environment (Elwell 1983; Vogel 1992).

Improved fallow systems involving fast growing, N_2-fixing leguminous trees were found to increase soil organic matter, improve soil physical and chemical properties, and this will provide readily available nutrients for subsequent crop. Improved soil physical conditions under fallows include better soil aggregation (Mapa and Gunasena 1995), lower bulk density (Mapa and Gunasena 1995; Alegre and Rao 1996), lower resistance to penetration (Lal 1989), improved soil porosity and reduced surface sealing. Improved soil structure can result in preferential flow channels and increased hydraulic conductivity (Alegre and Rao 1996), infiltration rates (Lal 1989; Mapa and Gunasena 1995) and water holding capacity. Leaving the residues on the soil surface was shown to enhance infiltration and reduce soil erosion (Omoro and Nair 1993; Young 1990). However, most work done on improved fallows has concentrated on soil fertility (Buresh 1995; Hartemink et al. 1996) rather than on soil and water conservation. Sanchez (1999) identified the need to quantify the processes responsible for crop yield increases under improved fallows.

The objectives of this study were to (1) quantify infiltration rates, runoff, and soil and nutrient losses following improved fallows (2) quantify changes in infiltration as affected by changes in soil properties, and (3) quantify the effects of tillage practices on infiltration rates and runoff.

Materials and methods

The study was conducted at the Domboshawa Training Centre in Zimbabwe (approximately 19^o 35' S, 31^o 14' E and 1474 m altitude). The mean annual rainfall is 750 mm, usually received from November to April. The soils are classified as Alfisols (soil taxonomy) or lixisols (FAO). The soil texture is sandy clay loam, with 22% clay and 71% sand. Selected chemical properties of the soil in 0–30 cm layer were: pH (0.01M $CaCl_2$) = 4.8, organic carbon = 6 g kg^{-1}, total nitrogen = 0.04 g kg^{-1}, extractable phosphorus = 3.8 mg kg^{-1} and exchangeable K = 0.03 $mmol_c$ kg^{-1}. The study was conducted in a long-term experiment, initiated in the 1991-92 season, to compare planted fallows of different duration. The different duration fallows were established in a phased manner on 12 x 9 m plots. The 2-year fallows were first established in 1992-93 and were followed by four consecutive maize crops.

The 2-year fallows were re-established in the same plots at the start of the 1998-99 season. Rainfall simulations were conducted in October 2000 after cutting the fallows and before planting the first maize. Simulations were also conducted one year after fallow termination, before planting the second maize crop.

The treatments examined were planted fallows of *A. angustissima* and *S. sesban*, natural fallow (NF) and continuous maize (*Zea maize*). The plots were divided into sub-plots for imposing two tillage systems: conventional tillage (CT) and no-tillage (NT). Conventional tillage involved ploughing using an ox-drawn mouldboard plough to a depth of 15 to 20 cm. Details of biomass production of the fallow systems are not given in this paper, but litter additions through *A. angustissima* and *S. sesban* were 10 t and 5.7 t ha^{-1} at fallow termination, respectively. While *S. sesban* did not produce any re-growth, *A. angustissima* produced 1.5 t ha^{-1} of coppice growth during the cropping season. Biomass from NF was burnt in the plots at fallow termination. Maize stover was removed from the continuous maize plots and after the post-fallow maize crop in all plots.

Rainfall simulations

Rainfall simulations were conducted in the plots at a rainfall intensity of 35 mm h^{-1} on 1 m^2 experimental plots surrounded by a 50 cm buffer zone. A portable rainfall simulator based on single full cone nozzle principle and calibrated after Panini et al. (1993) was used. The plots, which had an average slope of 2%, were demarcated and hydrologically confined using aluminium sheets installed on all sides leaving about 7 cm of the sheets above the ground. A metal flume was anchored at the outlet, leading into a small trench to collect runoff. Borehole water with a pH of 6.8 and an electrical conductivity of 200 mS cm^{-1} ($SE = 3.5$) was used for simulations. In October 2000, rainfall simulations continued for 3 hours or until steady state runoff was attained. In October 2001, simulated rainfall was applied to dry (5% soil water) and wet (12% soil water) soil for a 30-minute duration. Dry runs were conducted on a dry soil and wet runs at the same spot used for dry runs the following day. In 2000, runoff intensity (mm h^{-1}) was periodically measured by sampling water flowing from each plot. The sediments in the collected runoff were dried and bulked for nutrient analysis. In October 2000, total runoff losses were estimated by plotting runoff against time and then obtaining an equation that described the data. The area under the runoff curves was calculated and expressed as a percentage of the total runoff area. In 2001, the same sampling procedure was followed as in October 2000, but in addition a container was anchored at the base of the outlet to collect all the runoff and sediments. Runoff was then estimated by summing up runoff collected from the container and that collected during periodic sampling. The sediment collected in the container was weighed before being mixed with the solids separated from runoff collected during the simulations. Solids were separated from water through centrifugation, dried at 60^0C for 12 hours to evaporate all the water, weighed and analysed for nitrogen, carbon and phosphorus. Organic carbon (OC) was determined using the modified Walkley–Black procedure (Nelson and Sommers 1982), total nitrogen (N) was determined using the modified Kjeldahl method (Bremner 1982) and (P) phosphorus using the Olsen method (Olsen and Sommers 1982).

Data analyses

For estimating infiltration rate, the empirical Horton type model was used. The balance of rain minus runoff estimated infiltration, Infiltration (I)= precipitation (P) – runoff (Q). A modified version of the Horton-type equation proposed by Morin and Benjamin (1977) was fitted to the infiltration data:

$$i = i_f + (i_o - i_f)\, e^{-R/K}$$

Where: i = estimated instantaneous infiltration rate, mm h^{-1}; i_f = final infiltration rate mm h^{-1}; i_o = initial infiltration rate, mm h^{-1}; R= cumulative rainfall, mm (intensity x time); K = the infiltration rate decay coefficient which expresses infiltration dynamics as affected by soil properties (mm). Data on time required to ponding and runoff, amount of runoff and quantity of soil lost, nutrient losses, K values, and steady state infiltration rates were subjected to analysis of variance using Genstat statistical analysis package.

Results

At the end of fallows in October 2000, ponding in continuous maize plots started 7 minutes after the onset of rainfall simulations (Figure 1a). In contrast, ponding in *S. sesban,* NF and *A. angustissima* plots started after 17, 40 and 109 minutes, respectively. In continuous maize plots, runoff started in less than 10 minutes from the onset of simulations (Figure 1b). The time required for runoff to occur in different treatments was in the order: continuous maize = *S. sesban* < NF < *A. angustissima.*

In 2001, treatments differed significantly in time required for ponding (Figure 2a). *Sesbania sesban* plots needed 11 minutes for ponding to occur, compared with 25 minutes for conventionally tilled NF plots. There was no ponding in *A. angustissima* plots during the 30 minutes of simulations. Tillage had no significant effect on time to ponding and runoff. Treatments differed significantly in time to runoff, with continuous maize and *S. sesban* taking the shortest time (Figure 2b). There was no runoff in *A. angustissima* and NF during dry runs (Figure 2b).

Infiltration curves

Steady state infiltration rates decreased over the 2 years of cropping after *S. sesban* fallows but they did not change in continuous maize (Figure 3a). In October 2000, steady state infiltration rates could not be determined in *A. angustissima* and NF plots because the rainfall intensity was less than the infiltration rates. However steady state infiltration rates were 24

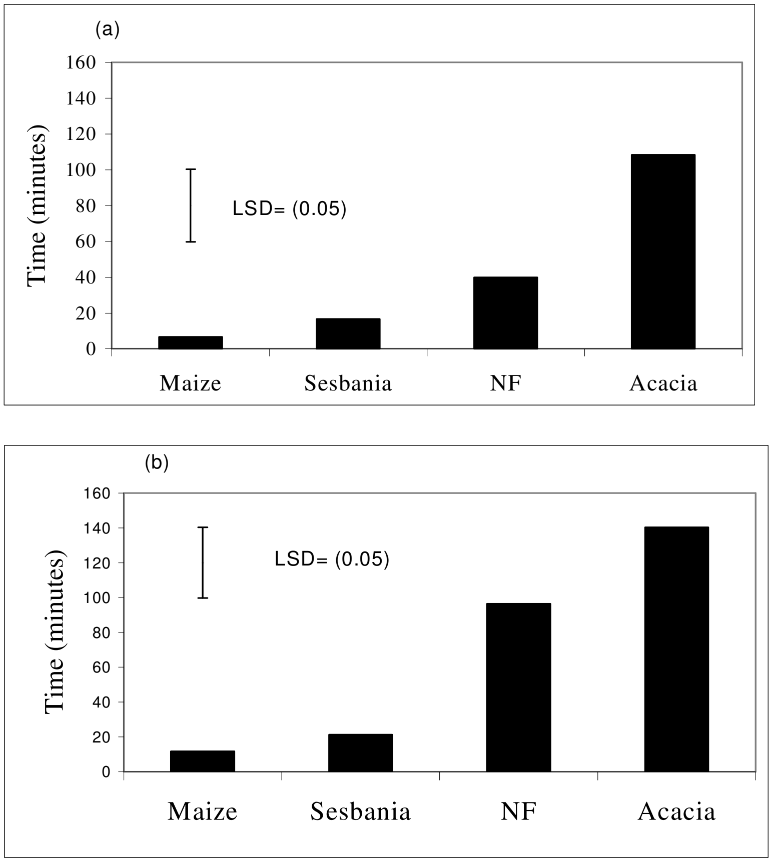

Figure 1. (a) Time to ponding and (b) time to runoff in *Acacia angustissima*, *Sesbania sesban*, natural fallow and continuous maize plots, October 2000 at Domboshawa, Zimbabwe.

mm h^{-1} in *S. sesban* and 5 mm h^{-1} in continuous maize plots. In October 2001, steady state infiltration rates could not be determined again in *A. angustissima* and NF plots, however it decreased to 8 mm h^{-1} in *S. sesban* plots and remained at 5 mm h^{-1} in the continuous maize plots (Figure 3a).

At the end of the fallow phase in October 2000, infiltration rate decay coefficients were 36 mm and 10 mm for *S. sesban* fallow and continuous maize, respectively (Figure 3a). A year later, in October 2001, infiltration rate decay coefficient was 25 mm for the *S. sesban* fallowed plots, but it remained at 10 mm for continuous maize plots. The infiltration rate decay coefficient could not be determined for *A. angustissima* and NF because steady state infiltration rates were determined for both 2000 and 2001. For the NF plots, steady state infiltration rates were only obtained during the wet runs (Figure 3b). The infiltration rate decay coefficients averaged over tilled and no-tilled plots for NF, *S. sesban* and continuous maize during wet runs were 30, 12 and 10 mm, respectively.

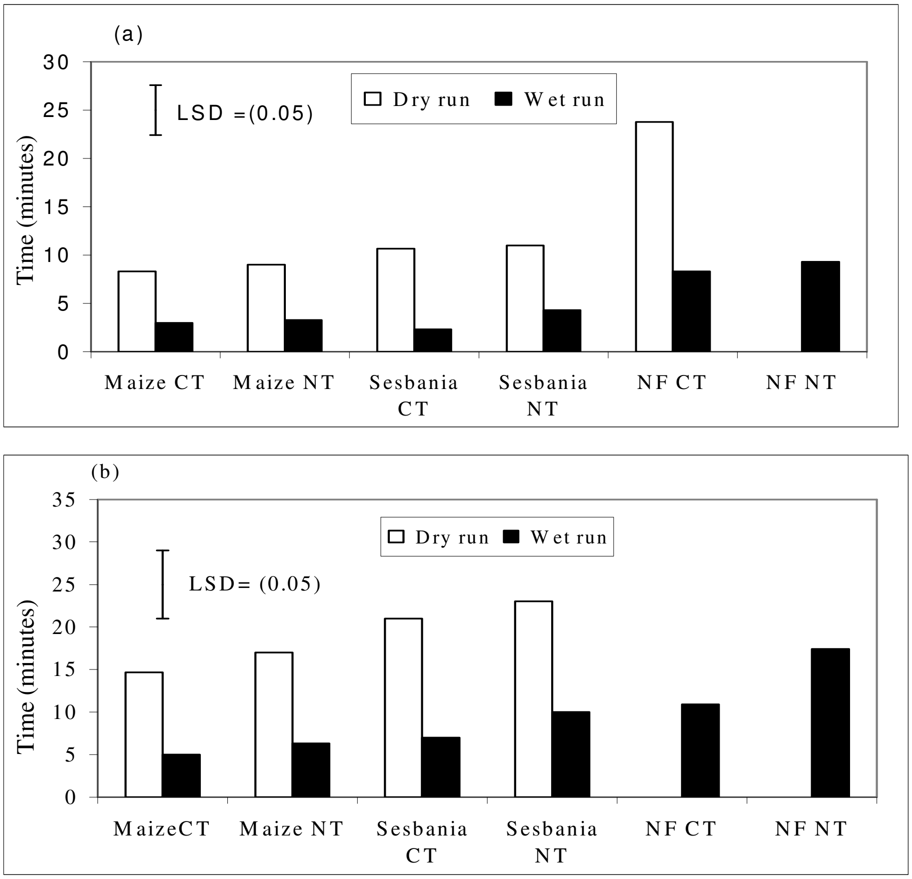

Figure 2. (a) Time to ponding and (b) time to runoff in *Sesbania sesban*, natural fallow and continuous maize, October 2001 at Domboshawa, Zimbabwe.

Runoff and sediment losses

In October 2000, the estimated runoff from continuous maize plots was 44% of the rainfall applied (Table 1), (R^2 =0.98 for the fitted curve). *Sesbania sesban* plots recorded the second highest runoff with 22% of water applied being lost (R^2 =0.99, for the fitted curve). Total soil loss was not measured in October 2000. In October 2001, the tilled and untilled continuous maize plots experienced 57% and 87% of the water applied as runoff (Table 1). The tilled and untilled *Sesbania sesban* plots experienced similar runoff at an average of 30%. There was no runoff in the case of *A. angustissima* and NF as all the water applied infiltrated into the soil. Soil loss was greatest under continuous maize plots. Tillage had no significant influence on soil losses.

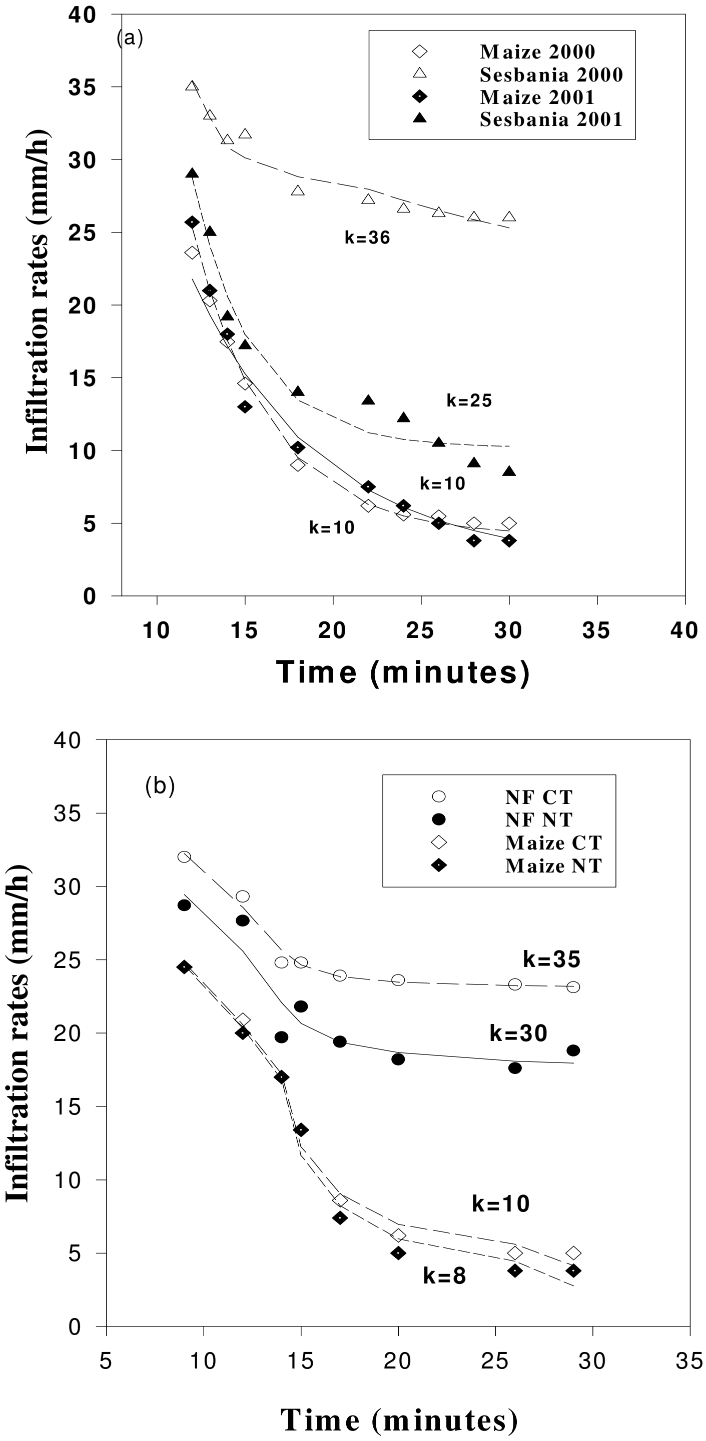

Figure 3. (a) Infiltration rates in the plots under *Sesbania sesban* planted fallow and continuous maize in October 2000 and 2001 and (b) infiltration rates in plots under natural fallow and continuous maize subjected to conventional tillage (CT) and no tillage (NT) during wet runs (12% water content) in October 2001 at Domboshawa, Zimbabwe.

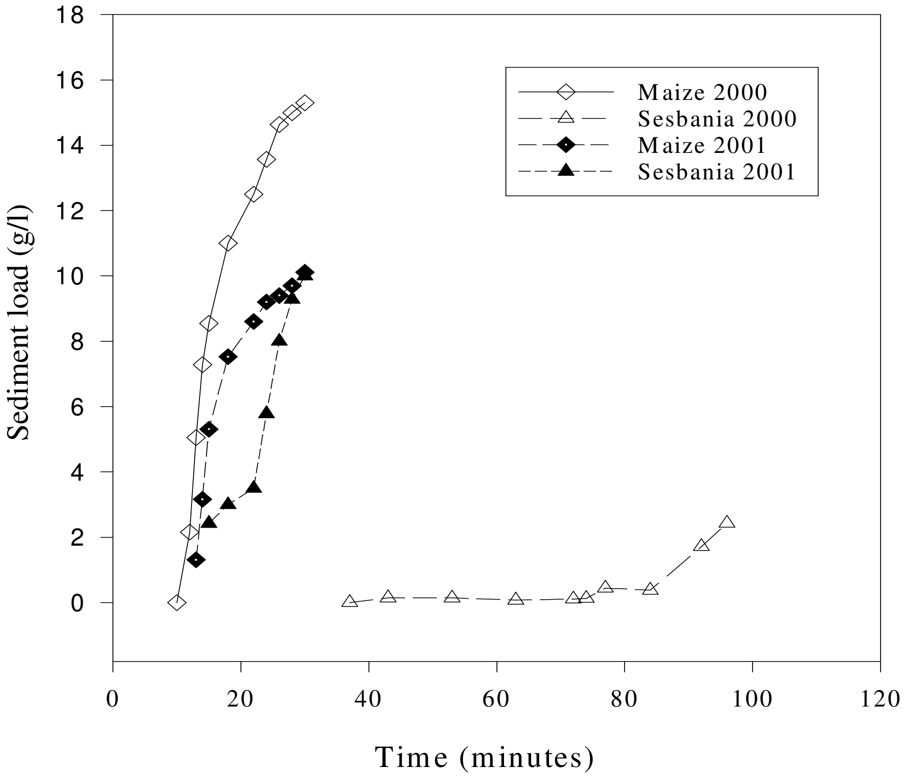

Figure 4. Sediment loads in continuous maize and *Sesbania sesban* treatments recorded during rainfall simulations in October 2000 and October 2001 at Domboshawa, Zimbabwe.

Soil loss was also expressed as sediment load in the runoff (g l^{-1}). The greatest amount of sediment load was in continuous maize plots. For both October 2000 and October 2001, mean sediment load was 16 g l^{-1} in continuous maize plots for the first 30 minutes. The sediment load rapidly increased during wet runs and went up to 70 g l^{-1} in continuous maize (data not presented). In October 2000, there was no sediment loss from *S. sesban* plots in the first 30 minutes but it increased to 11 g l^{-1} in 2001 in the same period (Figure 4).

In October 2000, there were no nutrient losses from NF and *A. angustissima* in the first 30 minutes of rainfall. Carbon and nitrogen concentrations of the sediment from *S. sesban* fallowed plot were 37 g kg^{-1} and 1.8 g kg^{-1} respectively (Table 2). Carbon and nitrogen concentrations in the sediment from the continuous maize plots were 10 g kg^{-1} and 0.5 g kg^{-1}, respectively. In October 2001, C and N concentrations of the sediment from continuous maize were similar to those in October 2000. In *S. sesban* plots, N concentration in sediment was 1.4 g kg^{-1} but C concentration remained the same as in the previous year. Carbon in sediments was also expressed as C enrichment ratios; this gives a ratio of the increase in

Table 1. Runoff and soil losses from plots under planted fallows, natural fallow and continuous maize during 30 minutes of simulated rainfall at Domboshawa, Zimbabwe in October 2000 and 2001.

Treatments	Runoff (% of water applied) October 2000	Runoff (% of water applied) October 2001†	Soil loss (t ha^{-1}) October 2001†
Maize CT	44	57	0.2
Maize NT	nd	83	0.2
Acacia angustissima CT	0	0	-
Acacia angustissima NT	nd	0	-
Sesbania sesban CT	20	31	0.1
Sesbania sesban NT	nd	29	0.1
Natural fallow CT	0	0	0.0
Natural fallow NT	0	0	0.0
SE	10.0	1.9	0.08

CT = conventional tillage, NT= no tillage
†Measurements are from the simulations conducted in dry soil conditions;
nd = not determined as tillage was not been applied at this time,
(-) = no runoff

carbon concentration in the sediment relative to the carbon concentration in the soil (Table 2). Carbon enrichment ratios were higher in *S. sesban* fallow relative to those in continuous maize. The different treatments over the years significantly differed ($P<0.05$) in the soil carbon (C) levels in 0–5 cm soil layer. At fallow termination (October 2000), soil C levels in continuous maize, NF, *S. sesban* and *A. angustissima* plots were 6.0, 8.8, 9.7 and 9.8 g kg^{-1}, respectively. There were no significant changes in carbon levels in the 0–5 cm depth after one cropping season. Treatment differences were not significant in total P concentration of the sediment in both years.

Discussion

Ponding and runoff occurred in continuous maize plots because of the direct impact of raindrop on the soil surface, as maize stover was removed from the plots (Figure 1). In October 2000, time to ponding and runoff was longer in fallow treatments partially because of the mulching effect. Tree fallows resulted in higher infiltration and low runoff rates (Table 1) because mulch formed with the biomass of trees protected the soil from direct raindrop impact. In October 2001, time to ponding and runoff remained low in continuous maize; but there was a decrease in the time to ponding and runoff in *S. sesban* and natural fallow plots. The decrease could be attributed to the absence of surface mulch in *S. sesban* and natural

Table 2. Nutrient concentrations and carbon enrichment ratios in the sediments collected from planted and natural fallows and continuous maize treatments in October 2000 and 2001 at Domboshawa, Zimbabwe.

Treatments	Carbon g kg^{-1}	Nitrogen g kg^{-1}	Total P g kg^{-1}	C enrichment ratio
October 2000				
Continuous maize	10	0.5	0.02	1.4
Sesbania sesban	37	1.8	0.03	4.3
Acacia angustissima	–	–	–	–
Natural fallow	–	–	–	–
October 2001				
Continuous maize NT	10	0.5	0.02	1.4
Continuous maize CT	10	0.5	0.03	1.4
Sesbania sesban NT	35	1.5	0.03	4.3
Sesbania sesban CT	37	1.4	0.03	4.1
Natural fallow (CT and NT)	–	–	–	–
Acacia angustissima (CT and NT)	–	–	–	–

CT = conventional tillage, NT = no tillage; (–) = no measurements in the absence of runoff

fallow plots after one year cropping. Surface litter had disappeared due to decomposition as a result of tillage, and weeding in NT plots. Mulch enhances infiltration rates (Alberts and Nibling 1994) and protects the soil from direct raindrop impact. Low infiltration rates in continuous maize could be due to surface sealing as a result of disintegration of soil structure and soil compaction caused by raindrop impact (Agassi et al. 1985).

Plots under *A. angustissima* maintained high infiltration rates of over 35 mm h^{-1}two years after fallow termination, because of the addition of biomass from the re-growth of cut stumps in the second cropping season and the presence of an active tree root system (Figures 1 and 2). Mulch in *A. angustissima* reduced the raindrop impact on the soil and hence reduced structural degradation. *Acacia angustissima* produced the greatest litter biomass and this gave a more stabilized soil physical environment and reduced soil loss. These results are supported by the findings of Mobbz and Cannell (1995).

In this study, the amount of C in the 0–5 cm soil layer (using pooled data for 2000 and 2001) explained 89% of variation in infiltration rate decay coefficient and 66% of variation in steady state infiltration rates, suggesting that soil C was an important factor in controlling these properties. Organic matter determines stability of soil aggregates, resulting from the chemical nature and its strong association with soil minerals. It is important for maintaining a good soil structure, which improves water infiltration.

The *S. sesban* fallow plots experienced rapid decline of infiltration rates and increased runoff and soil losses despite production of substantial amount of biomass, because of rapid decomposition of *S. sesban* foliage (Mafongoya et al. 1997), which resulted in lack of protection for the soil against the raindrop impact by the end of the first cropping season. The decline in filtration rates could also have been due to the decline in preferential flow channels after one season of cropping. This rapid decline in infiltration rates after the first crop seems to be accompanied by a decline in soil fertility as fertile topsoil gets eroded (Mafongoya and Dzowela 1999).

The different amounts of runoff despite similar infiltration rate dynamics in 2000 and 2001 were probably due to underestimation of total runoff using the curve method (Figure 3). Although considerable amount of soil was lost with runoff in continuous maize plots (Table 1), very little nutrients were lost because the soil was heavily depleted of nutrients (Table 2). This was also shown by low C enrichment ratios (Table 2). In 2000, high C and N concentrations in sediments from *S. sesban* were due to rapid decomposition of *S. sesban* residues and washout of nutrients through erosion. Although estimates of erosion made from small plots such as these cannot be readily extrapolated to the field or landscape scale (Stomph et al. 2002; van de Giesen et al. 2000), they are indicative of the differences between treatments and management. In the medium to long term, soil C following tree fallows will decrease due to erosion and accelerated soil loss (Unger 1997; Woomer and Swift 1994).

Conclusions

Planted tree fallow increase steady state infiltration rates and hence are effective in reducing runoff and soil losses. Cropping subsequent to non-coppicing tree fallows such as *S. sesban* results in a rapid decline in steady state infiltration rates and this leads to increased soil and water losses. Coppicing tree fallow using *A. angustissima* contributes biomass for surface mulching during the cropping phase, which protects the soil from direct raindrop impact and slows the decline of the steady state infiltration rates, resulting in reduced soil and water losses.

Acknowledgements

We thank ICRAF for facilitating this work at Domboshawa site. We are grateful to the European Union for funding the work through the ‘Improved Fallows for Africa’ (IMPALA) Project No. ICA4-CT 2000-30011.

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CHAPTER 6

Maize productivity and mineral N dynamics following different soil fertility management practices on a depleted sandy soil in Zimbabwe

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This chapter has been published as:

Chikowo R, Mapfumo P, Nyamugafata P and Giller K E 2004. Maize productivity and mineral N dynamics following different soil fertility management practices on a depleted sandy soil in Zimbabwe. Agriculture, Ecosystems and Environment 102: 119-131.

Abstract.

A field experiment was conducted to evaluate the performance of different soil fertility improvement practices on a degraded granitic sandy soil in Zimbabwe. Legumes capable of accumulating large amounts of nitrogen (N) through biological N_2 fixation and subsoil N capture were tested against soyabean/maize rotation, cattle manure fertilization and continuous maize (*Zea mays* L) with or without fertilizer. Soyabean (*Glycine max*) accumulated 82 kg ha^{-1} N (seed + stover), while mucuna (*Mucuna pruriens*) produced 87 kg ha^{-1} of N in its biomass. Soyabean fixed 76 % of its N, while mucuna fixed 96 % of the accumulated N as estimated by the ^{15}N natural abundance method. Although the following maize crop in the second season suffered from drought stress, maize N uptake was 14.8 kg ha^{-1} following soyabean and 16.4 kg ha^{-1} following mucuna, compared with 5.2 kg ha^{-1} for the unfertilized maize and 25.6 kg ha^{-1} for the maize fertilized with N at 90 kg ha^{-1}. *Cajanus cajan* and *Crotalaria paulina* added barely 10 kg ha^{-1} of N through their biomass and had no effect on N uptake by maize. Apparent recovery of the added N by maize was 47 % for the fertilized maize, 36 % for soyabean, 12 % for mucuna and 9 % for cattle manure. There was very little partitioning of N into grain and uptake was mostly before the onset of the drought. Despite the large differences in added residue N, differences in soil mineral N were only evident up to four weeks after the beginning of the rains, after which mineral N concentrations became very small in all treatments due to leaching, rather than crop uptake. By the 8th week after crop emergence, maize root length density had increased to about 0.1 cm cm^{-3} at the 60-80 cm depth, the rapid increase apparently stimulated by the drought. It was concluded that mineral N available to maize from the residues tested falls short of what is required to sustain high maize yields. In these environments where biomass accumulation in many legumes is restricted by soil biophysical factors (sandiness, poor nutrient concentrations, acidity), combinations of legume rotations and mineral N fertilization will remain the most viable option for sustainable agriculture.

Keywords: Legumes; Sandy soils; Soil fertility technologies; Root length density; Mineral N; Arenosol; Zimbabwe

1. Introduction

Maintenance or improvement of soil fertility has been a focus of many research projects in smallholder farming systems in southern Africa. Fertilizer use in many subsistence agricultural systems remains insufficient to meet the N demand of crops. Researchers, therefore, have explored a number of ways of incorporating N_2-fixing grain legumes into cropping systems (Mpepereki et al, 1996; 2000; Mapfumo, 2000, Sakala et al., 2003), organic resources such as cattle manure and agroforestry tree prunings (Mafongoya et al., 1997; Murwira, 1994), and "rainfall responsive" use of limited available mineral fertilizers (Piha, 1993), to increase availability of N to cereal crops. Harnessing N through biological N_2-fixation and appropriate residue management can be an effective method of sustaining soil fertility if conditions for N_2-fixation are optimized (McDonagh et al., 1993; Giller and Cadisch, 1995; Giller et al., 1997). There has also been a research focus on combining these organic resources with low rates of mineral N fertilizers, to improve synchrony and N use efficiency (Palm et al., 1997).

The practices described in these various papers have not been universally successful as adverse biophysical factors result in poor legume productivity or large N losses before crop uptake (Mapfumo et al., 1999; Giller, 2001). Where reasonable biomass has been achieved, long-term benefits are usually negated by rapid turnover rates of organic matter in the poorly aggregated soils. There has also been a problem in the direct evaluation and comparison of these practices, as experiments have been carried out at different locations with large variations in rainfall, soil types and management. While N balances under different maize management systems have been determined, few studies have incorporated aspects of root development and N capture. The extent to which the maize crop will explore the soil and capture the mineralized N from the above soil fertility management practices will depend on its root distribution in the profile and the root length density (van Noordwijk, 1989). Studies that investigate spatial root development of maize over time are important to explain the likelihood of successful nutrient capture. In low input systems where the N mineralized *in situ* can have a substantial influence on crop growth, there is a need for an improved understanding of N dynamics.

The objectives of this study were to (1) to evaluate the productivity of a range of 1-year N_2-fixing legumes on a sandy soil with little weatherable minerals; (2) to determine soil mineral N dynamics following 1-year legumes, cattle manure fertilization and in unfertilized maize plots; (3) to study the rooting pattern of maize roots during the first eight weeks after crop emergence and relate this to soil mineral N and (4) to determine N uptake and N recovery in the different systems.

2. Materials and methods

2.1. Study site and experimental description

The study was conducted on a smallholder farm in Chikwaka communal area, about 60 km northeast of Harare, Zimbabwe (17°35' S latitude, 31°14' E longitude) between November 2000 and May 2002. The mean annual rainfall is 750 mm and occurs during a unimodal rainy season extending from November to April. The 2000-01 season received above normal rainfall of 1120 mm, but rainfall in the 2001-02 season was below normal, with a total of only 412 mm, 80% of which was received between December 2001 and January 2002 (Fig. 1). Soil for site characterization was sampled from the 0-0.2 m layer, air-dried and analyzed for bases, C, total N and texture using methods described by Anderson and Ingram (1993). The soil was a highly leached coarse-grained sand derived from granite, with 4 % clay and 92 % sand contents to at least 1.2 m depth (Arenosol, FAO classification). The chemical properties were pH ($CaCl_2$)= 4.8; organic C = 0.35 %; total N = 0.03 %; Resin P = 5 mg kg^{-1}; and Ca, Mg, K = 0.83, 0.37 and 0.09 $cmol_c kg^{-1}$, respectively. The profile was deep, at least 2 m and well drained.

The experimental design enabled comparison of the best-bet soil fertility management practices that are already being adopted by farmers, and those that are still being refined. Prior to planting maize, the field was ploughed to 0.2 m depth using an ox-drawn plough. The treatments on plot sizes of 10 m x 12 m replicated four times in a randomized complete block design were: (i) unfertilized maize –control; (ii) fully fertilized maize (90 N, 18 P, 17 K kg ha^{-1}) - 24 kg N, 18 kg P and 17 kg K applied at planting in form of a compound fertilizer. The fertilizer was placed into the soil at the same time maize seed was sown. The remaining 66 kg of N was split applied at 4 and 8 weeks after crop emergence by placing the ammonium nitrate fertilizer on the soil surface close to the maize plants; (iii) basal fertilized maize (24 N, 18 P, 17 K kg ha^{-1}) applied in the form of a compound fertilizer as described above; (iv) maize fertilized with cattle manure only at 17 Mg ha^{-1}; (v) maize fertilized with cattle manure at 17 Mg ha^{-1} plus top dressing of N at 40 kg ha^{-1} as ammonium nitrate; (vi) soyabean; (vii) one year *Cajanus cajan* improved fallow; (viii) one year *Crotalaria paulina* improved fallow and (ix) *Mucuna pruriens* green manure. Weeds were controlled by hand hoeing three times during the maize growth period.

A second field experiment was also set up adjacent to the one described above, where the objective was to determine biological N_2 fixation as well as biomass yield of additional legumes not included in the best-bet soil fertility technologies experiment, over a two year fallow period. The extra legumes in this second field were *Sesbania sesban*, *Acacia angustissima* and *Macroptilium atropurpureum* (Siratro). *S. sesban* and *A. angustissima* were established by transplanting seedlings raised in a nursery and inoculated with peat soil that had compatible rhizobia. After one season it was clear that most of the legumes had failed to

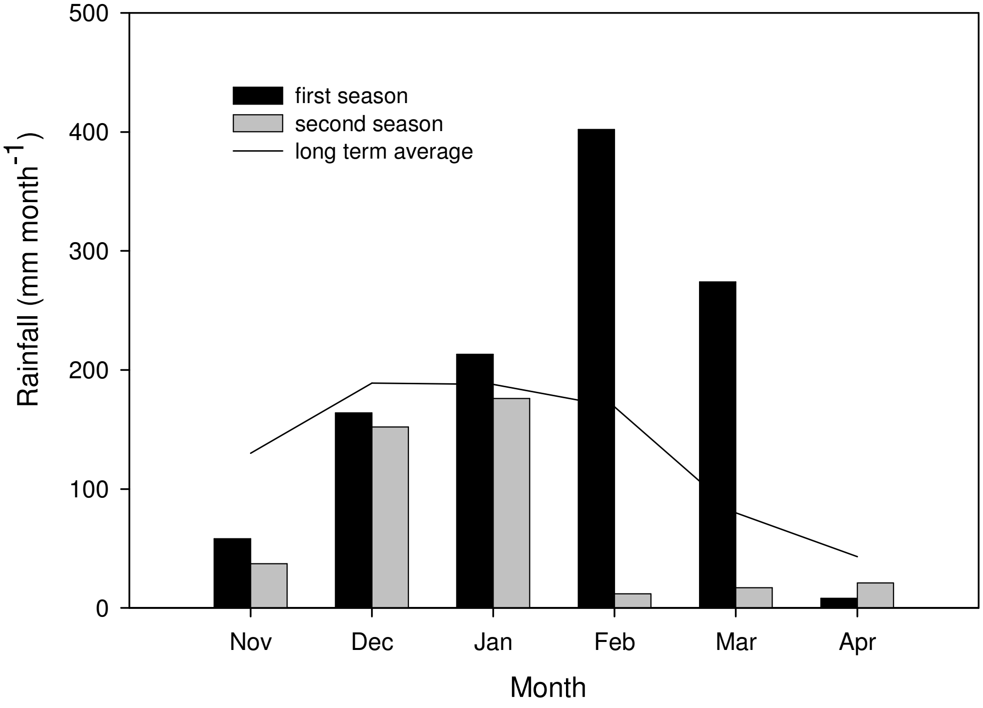

Fig. 1. Monthly rainfall distribution during the first and second seasons, and the long term average for the experimental site, Zimbabwe.

produce any significant biomass and at least 80 % of the plants had died during the long dry period between the rains (April to November 2001). The only data available from this experiment, being N_2-fixation rates from plant samples collected six months after planting these legumes is presented here.

Cattle manure was applied in the first season only, and its residual effects were assessed in the second season. Half of the cattle manured plots received a top dressing of N at 40 kg ha^{-1} as ammonium nitrate. The manure used was from a four-month old aerobically composted manure heap, which the farmer who hosted the trial, had prepared for use in his fields that season. The application rate used was determined by the host farmer based on his experience with cattle manure use on his farm. The manure had a sand content of 57 % and 0.78 % N.

Soyabean received a basal application of P at 18 kg ha^{-1} and N at 12 kg ha^{-1} and the seed was inoculated with an appropriate *Bradyrhizobium* strain just before planting. After harvesting soyabean seed, the stover and leaf litter were incorporated into the plots. Mucuna biomass was determined at flowering stage, and was incorporated into the soil by hand hoeing five months after sowing. *Cajanus cajan* and *Crotalaria paulina* had little biomass at the time, and were left in the plots to accumulate more biomass until November 2001, after which the litter, leaves and the stems were incorporated in the plots during land preparation for the subsequent maize crop.

During the second season all plots were cropped with maize and were fertilized with P at 18 kg ha^{-1} and K at 25 kg ha^{-1} basal fertilizer, in the form of single superphosphate and muriate of potash, respectively. Each of the plots was split into two subplots, with one receiving a top dressing of N at 40 kg ha^{-1} as ammonium nitrate and the other utilizing only the residual N from the previous season.

2.2. Mineral N dynamics

Mineral N dynamics were followed in plots that previously had unfertilized maize, mucuna green manure, soyabean and plots that had been fertilized with cattle manure. Soils were sampled at the beginning of the rainy season, on the 13th of November 2001 (Pre-season sampling, PSS). Soil sampling was done using augers at depth intervals of 0-20, 20-40, 40-60, 60-90, and 90-120 cm. Maize was planted on the 9th of December 2001 and soil samples for monitoring mineral N dynamics were taken one week after planting maize (WAP). Thereafter, soils were sampled at two-week intervals during the first eight weeks of maize growth. Field moist soils (10 g) were extracted in 50 ml 0.5 M KCl. The NH_4-N phenate method was used for NH_4-N determination while the NO_2-N cadmium reduction method (Keeney and Nelson, 1982) was used for nitrate determination. The N was determined colourimetrically with the absorbance read at 640 nm and 543 nm for ammonium and nitrate respectively. A sub sample of the soil was dried at 105 ^{o}C for 24 hours to determine the dry weight of the extracted soil. We refer to the sum of ammonium-N and nitrate-N as total mineral N. All results are expressed on an oven dry soil basis.

2.3. Spatial maize root distribution

A satellite maize plot was established adjacent to the main experiment and used for maize root development studies. Maize root development was determined by destructive sampling at 2-week intervals (2, 4, 6 and 8 weeks after emergence, WAE). Soils were excavated 0-15 cm from selected maize plants to a depth of 100 cm in 20 cm depth intervals. The distance from the plant to middle of the inter-row space was divided into 2 zones of 22.5 cm width (Zone 1, 0-22.5 cm; Zone 2, 22.5-45 cm). Four replicate monoliths from each of the zones were excavated. The excavated soils (15 x 20 x 22.5 = 6750 cm^3 volume) were soaked in water in large buckets, and later poured onto a 0.5 mm sieve to trap roots. Trapped roots were washed with excess water from a steady flow of water from a tap. Root length was determined using the line intercept method (Newman, 1966). Roots were spread out with random orientation in a thin film of water on a transparent acetate folio, and a glass plate with 1 cm grid size (D) was placed on top. The horizontal and vertical interceptions of the roots with grid lines were counted and added together (N). Root length and root length density were then calculated as follows (Tennant, 1975): Root length, L (cm) = ΠND / 4.

2.4. Nitrogen uptake and recovery

During the first season, above ground biomass of maize was determined by destructively sampling 4 plants per plot at 4, 6, 8, 12 and net plot harvest at 22 WAE. In the second season, when all the plots were now cropped with maize, dry matter accumulation was determined at 4 main growth stages, at 3, 6, 9 and 22 WAE. The plant samples were oven dried at 65 °C and dry matter yield determined. The samples were ground to pass through a 2 mm sieve and analyzed for N content using the semi-micro Kjeldahl method (Anderson and Ingram, 1993). Nitrogen recovery by the different treatments was estimated by the difference method (Jokela, 1992), with the assumption that soil N transformations were similar for the control and the fertilized treatments. This assumption is not always true, as priming effects of added fertilizers on N transformations have been reported (Jenkinson et al., 1985; Rao et al., 1991).

$$\%\ \text{N recovery} = \frac{\text{N uptake (treatment)} - \text{N uptake (control)}}{\text{Total N applied}} \times 100 \qquad (1)$$

2.4. N derived from N_2-fixation

The proportion of legume N derived from biological N_2-fixation was estimated using the N-difference and the ^{15}N natural abundance methods. The N difference method is based on legume N accumulation when the contribution of soil N to the total legume N is determined. The unfertilized maize crop was used as the non-N_2-fixing control crop and contribution of symbiotic fixation to the legume N was computed as:

$$\%\ \text{N from } N_2\text{-fixation} = \frac{\text{Total legume N - Total maize N uptake}}{\text{Total legume N}} \times 100 \qquad (2)$$

The ^{15}N natural abundance method, as outlined by Peoples et al. (1989), is based on N transformations in the soil that result in isotopic fractionation and a small increase in the ^{15}N abundance of soil mineral N compared with that of the atmosphere. With increasing N_2-fixation, the abundance of ^{15}N in the N_2-fixing plant decreases as N assimilated from the soil is diluted by atmospheric N_2 of lower ^{15}N abundance fixed in its root nodules. Using this method, the percentage of legume N fixed from the atmospheric N_2 was estimated as:

$$\%\ \text{N from } N_2\text{-fixation} = \frac{\delta^{15}\text{N (soil N)} - \delta^{15}\text{N (legume N)}}{\delta^{15}\text{N (soil N)} - \text{B}} \times 100 \qquad (3)$$

where $\delta^{15}N$ (soil N) was obtained from the unfertilized maize reference plant grown in the same soil as the legume, and B is $\delta^{15}N$ of the same nodulated N_2-fixing plant when grown with N_2 as the sole source of N. B values for the different legumes were obtained from literature (Boddey et al., 2000; Gathumbi et al., 2002; Peoples et al., 1989).

3. Results

3.1. Maize N uptake and yields: first season

Nitrogen uptake by maize was monitored for the various treatments. Uptake was very slow during the first six weeks after germination. As expected maize in fully fertilized plots had significantly greater N uptake by 6 WAE, while the unfertilized control had the lowest N uptake (Fig. 2). Nitrogen uptake in the basal fertilized treatment was good early in the season and was higher than the manure + N fertilizer treatment. But this was only so until the 10 WAE when there was more N uptake for the manure +N treatment. There was less N uptake in plots that that had been fertilized with only cattle manure compared with the basal fertilizer treatment.

At final harvest, the unfertilized maize had the lowest maize grain and stover yields while the fertilized maize had grain yields just above 2.1 Mg ha^{-1} (Fig. 3 a,b). Nitrogen uptake was highest for the fully fertilized maize with also the greatest apparent recovery efficiency of 47 % of the added N. Cattle manure without additional N fertilizer increased grain yields three-fold, but these yields were still less than 0.5 Mg ha^{-1}. Supplementing manure with 40 kg N resulted in better yield response, giving 0.7 Mg ha^{-1}. Basal fertilizer supplied insufficient N later in the season when N demand was high, and resulted in low yields, but the yields were greater than the cattle manure treatment. Nitrogen recovery efficiency was also lowest for the cattle manure treatment, with only 9 % of the added organic N recovered by the first maize crop (Fig. 3 c).

3.2. Legume productivity and biological N_2-fixation

The ^{15}N enrichment of all the legumes tested was significantly lower than that of maize, which was used as the non-fixing reference crop, indicating that all the legumes were biologically fixing N (Table 1). Using relationships (2) and (3) we estimated that mucuna derived at least 93 % of its total N from biological N_2-fixation; while soybean fixed 76 % of its N as determined by the ^{15}N natural abundance and 92 % when the N-difference method is used. The $\delta^{15}N$ signature for *Acacia angustissima* was 0.79 and that for *Sesbania sesban* was –1.19, and their N_2-fixation rates ranged between 76 – 84%. Although N_2-fixation rates were high for these woody legume species, total N fixed was small as these legumes grew poorly and produced little biomass. Siratro and *Crotalaria. paulina* also grew poorly under the low soil fertility environment, and estimates of their N_2-fixation rates were 43 and 46 %, respectively (Table 1).

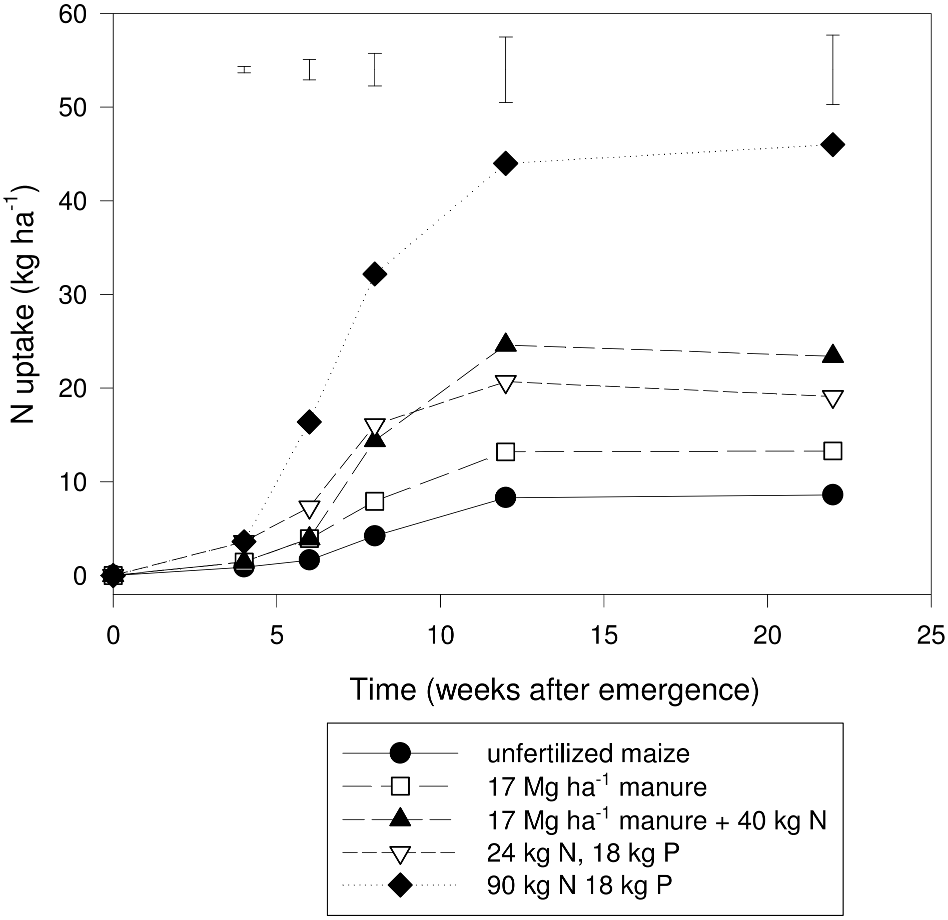

Fig. 2. Nitrogen uptake by maize as influenced by five management practices that are normally used by smallholder farmers on a depleted sandy soil in Zimbabwe. Bars represent LSD, $P < 0.05$.

Soyabean grain yield was just over 1 Mg ha^{-1}, while combined soyabean stover and litter biomass was 1.7 Mg ha^{-1}. This was equivalent to total N accumulation of 82 kg ha^{-1}, with 54 kg of the N harvested in the seed (Table 1). Total above ground N input to the soil by soyabean through leaf litter and stover was only 28 kg and net N input was even lower due to soil N exported through harvested seed. Mucuna had the greatest N biomass yield and net N input into the system (Table 1). Though total soyabean N was comparable to mucuna, most of the N was harvested in the seed, and would not contribute to the N economy of the soil. Using the natural abundance method, net N input from soyabean was only 8 kg ha^{-1}, which was comparable to the N input from the other legumes that had failed to produce any useful biomass like *Cajanus cajan* (Table 1). The calculation however, excluded possible inputs through roots and nodules.

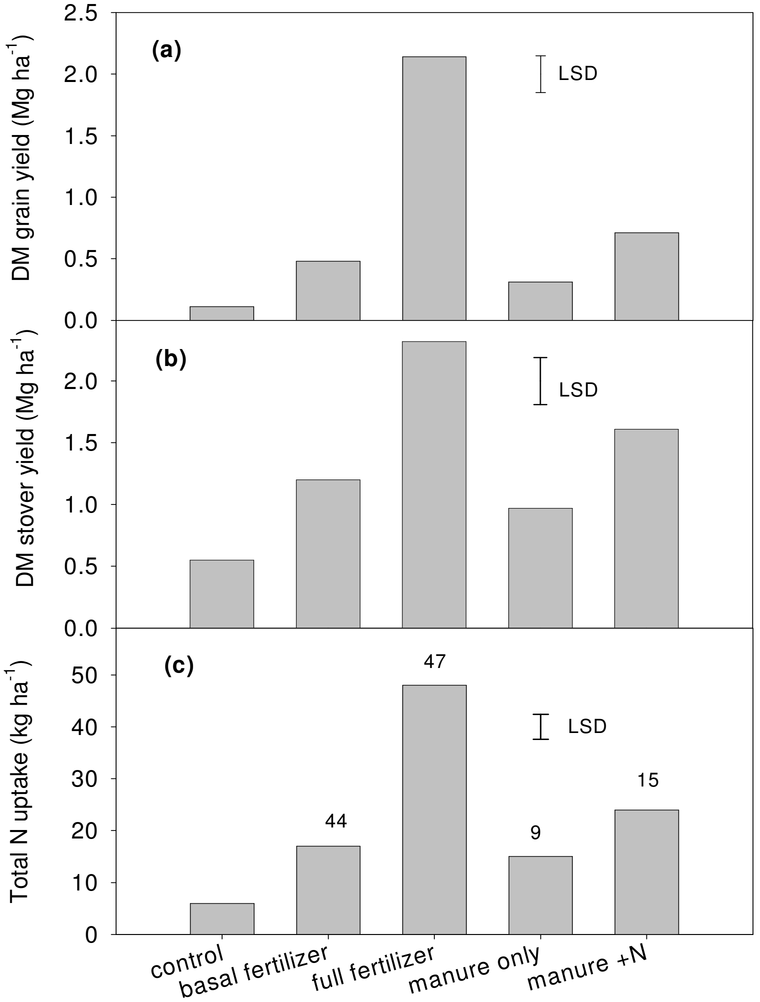

Fig. 3. (a) Grain yield (b) stover yield and (c) total N uptake by maize as influenced by different soil fertility management practices on a sandy soil. Apparent N recovery rates are indicated by numbers inserted in (c). Vertical error bars represent LSD, $P<0.05$.

3.3. Nitrogen uptake and recovery by maize: second season

There was very little N uptake by maize in the unfertilized treatment, and significant differences in N uptake were already evident by the third WAE (Fig. 4). From 9 WAE soil moisture became the most limiting factor to growth, and as expected N uptake was reduced. The N applied at 8 WAE for the fully fertilized plots was largely not utilized as there was little extra N uptake after this time (Fig. 4). Consequently total N uptake was smaller than the first season, and was comparable to treatments that received top dressing of N at 40 kg ha^{-1}. Maize grain and stover yields in all treatments were lower than in the first year (Fig. 5a). For most of the treatments, there was more N in the stover than in the grain due to poor

Table 1. Biomass production, biological N_2-fixation, and N input through litter and stover into the soil from selected legumes grown on a sandy soil in Zimbabwe

Legume	Biomass (t ha^{-1})	Total plant N (kg ha-^{1})	B value	$\delta^{15}N$	% N from N_2-fixation (Ndiff & NA)	Net N input (kg ha^{-1}) (Ndiff & NA)
Soyabean	1.75	82	-1.40[a]	-0.59	92 (76)	21 (8)
C. cajan	0.33	7	-0.90[b]	0.14	13 (65)	7 (4)
C. paulina	0.16	4	-0.13[c]	1.02	0 (46)	4 (2)
Mucuna	3.95	87	-0.38[d]	-0.28	93 (96)	(84)
A. angustissima	nd	nd	-1.50	-0.79	nd (79)	nd
S. sesban	nd	nd	-1.76[c]	-1.19	nd (84)	nd
Siratro	nd	nd	-1.16[a]	0.64	nd (43)	nd
Reference				2.01		

$\delta^{15}N$ = see Materials and methods for explanation
B = is the $\delta^{15}N$ of the same nodulated N_2-fixing plant when grown with N_2 as the sole source of N, a measure of isotopic fractionation during N_2-fixation
Ndiff = N difference method
NA = ^{15}N natural abundance method (figures in brackets based on NA method)
nd = not determined;
[a]Boddey et al., 2000; [b]Peoples et al., 1989;
[c]Gathumbi at al., 2002; [d]Ramos et al., 2001.

translocation of N from stover to grain because of the drought (Fig. 5b). There were marginal residual effects of cattle manure in the second season after application. Maize after a soyabean crop had more N uptake compared with either manure only or *Cajanus cajan*. There was better N uptake response in plots where mucuna had been grown previously. The bulk of the N was taken up during the period up to 9 WAE. After this time, there was serious moisture stress that inhibited crop growth and plant N uptake, and resulted in depressed final total N uptake at the end of the season. Apparent N recovery by maize was highest (36 %) when maize was grown in sequence with soyabean (Fig. 5b).

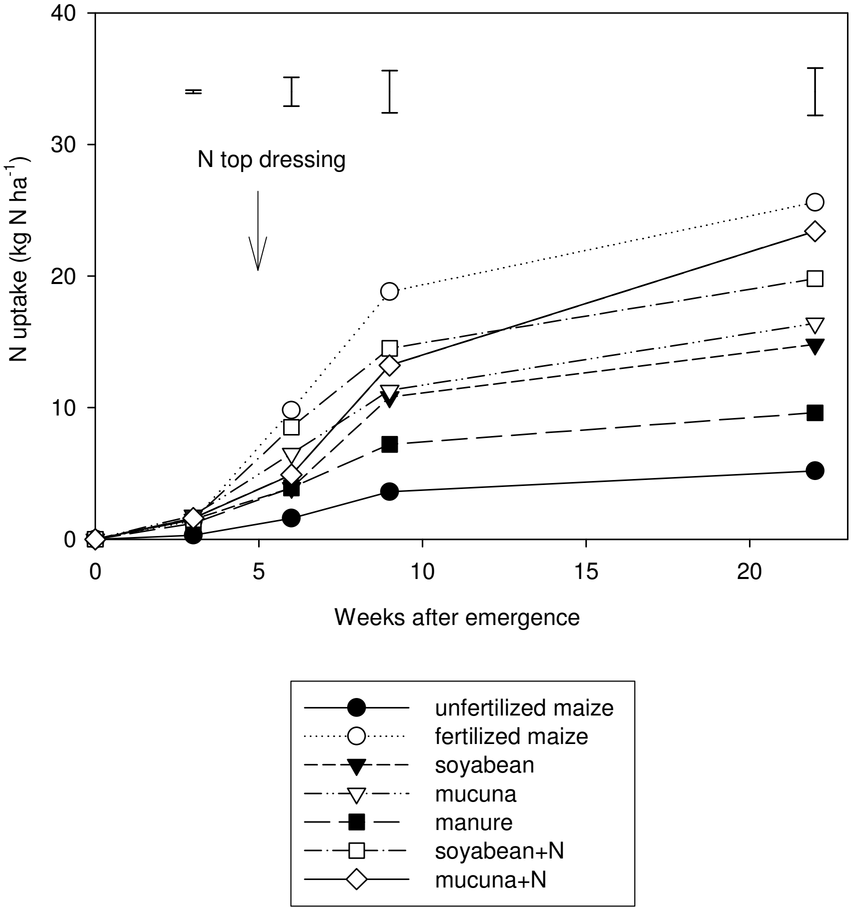

Fig. 4. Nitrogen uptake curves following legumes (with or without additional N), manure, fully fertilized or unfertilized maize during the second season. Error bars represent LSD, $P<0.05$, at the different sampling times during maize growth. Note the different scale from Fig.1.

3.4. Mineral N dynamics and maize root development

The highest concentration of mineral N was observed for the mucuna treatment early in the season followed by the soyabean treatment. The unfertilized maize had the least amount of mineral N in the profile. By the time we had our first sampling it appears there had already been a flush of mineral-N in the topsoil at the beginning of the rainy season (PSS, Fig. 6). Total mineral N was greater than 30 kg ha^{-1} for the 0-20 cm layer in plots that had mucuna , soyabean and cattle manure the previous season. As from the first week after planting maize (WAP 1), mineral N started to diminish from the profiles of all treatments, and this was at a time when more N in profile would be useful to the establishing maize crop.

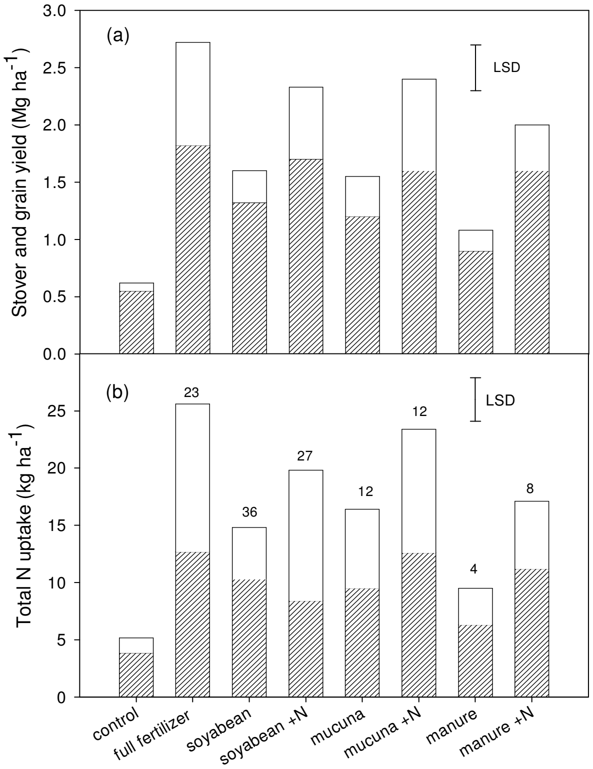

Fig. 5. (a) Maize stover (stripped section of bars) and grain yields (b) total N uptake partitioned into stover (stripped bars) and grain during the second season in plots that had been cropped with legumes or fertilized with animal manure and mineral N fertilizer. Nitrogen recovery rates are inserted as the numbers in (b).

By the 3rd week after planting maize (WAP 3), all the treatments had less than 10 kg ha^{-1} total mineral N in the top layer and there were no significant differences in mineral N amongst the treatments for both the topsoil and subsoil (Fig. 6). At this time soyabean plots had a pronounced bulge of NO_3-N at the 60-90 cm depth (data not shown). The bulge had disappeared by the 5th WAP sampling time, and there was very little NO_3-N in the profile for all the four treatments later on in the season. Mineral N concentration in the topsoil at 8 WAP was very small for all the treatments in the topsoil, and for the unfertilized maize and soyabean treatments for both the subsoil (Fig. 6).

Maize root development was investigated to get an idea of the distribution of maize roots during the season as the residues applied to the soil were also mineralizing with time. Maize root length density was small at 2 WAE, and confined to the 0-20 cm depth (Table 2). At 4 WAE, root length density had dramatically increased in the zone closest to the plant for

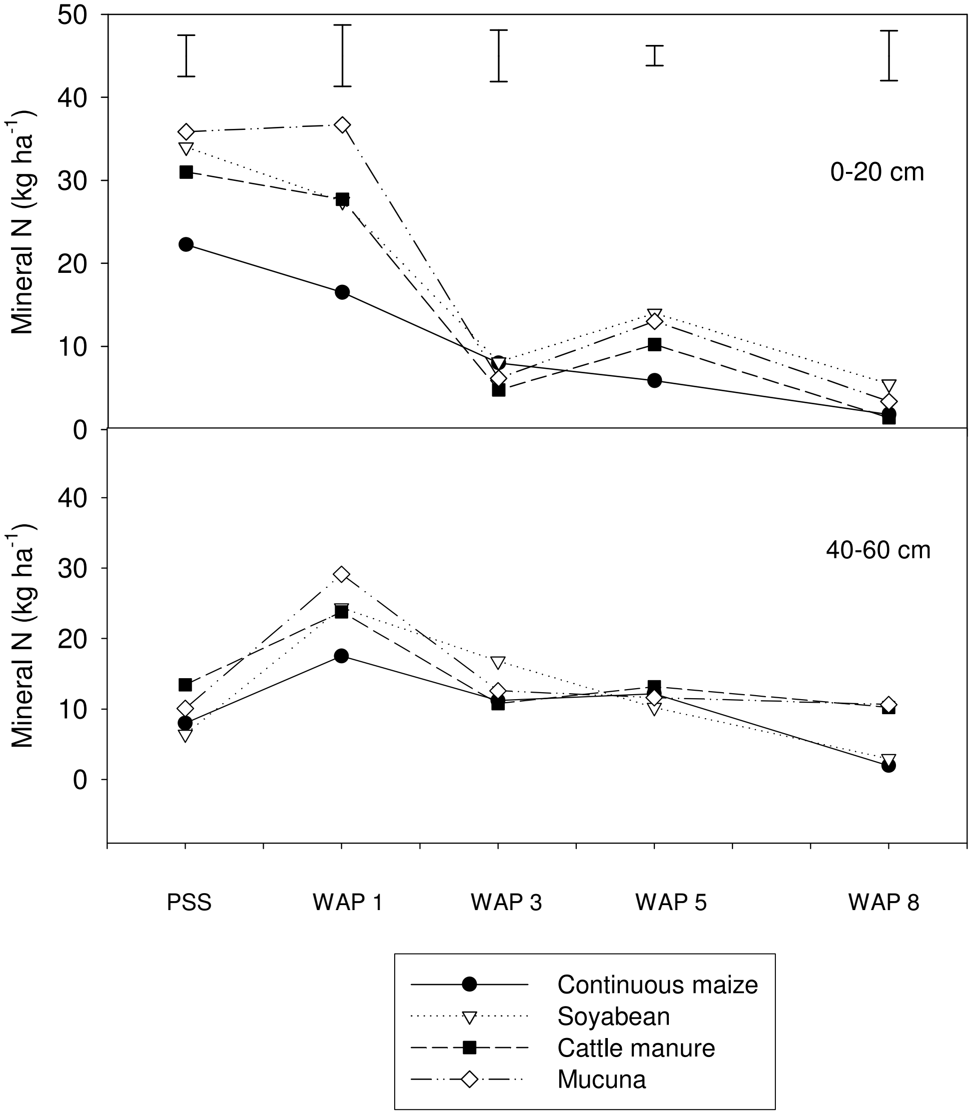

Fig. 6. Dynamics of total mineral N in topsoil and subsoil in maize plots that had unfertilized maize, cattle manure and previously cropped with soyabean and mucuna green manure. Bars represent LSD, *P* <0.05, for both depths.

the 0-20 cm depth, but there were very few maize roots in the 20-40 cm depth at this time. At 6 WAE, the root length density for the 0-40 cm depth for both zones had increased to >0.1 cm cm^{3}. By the 8th WAE, the entire 1 m profile had maize roots, though the root length densities at the 80-100 depth for zone 1 and the 60-100 depth for zone 2 were still less than 0.1 cm cm^{-3} (Table 2).

Table 2. Root length density (cm cm^{-3}) of maize with time (weeks after emergence of maize plants, WAE), depth and distance from maize plant recovered using a 0.5 mm mesh size sieve in a sandy soil in Zimbabwe

Sampling time	Depth (cm)	Zone 1	Zone 2
2 WAE	0-20	0.032 (0.01)	0.004 (0.001)
	20-40	0.000	0.000
4 WAE	0-20	0.338 (0.18)	0.041 (0.011)
	20-40	0.030 (0.02)	0.009 (0.006)
	40-60	0.000	0.000
6 WAE	0-20	1.040 (0.35)	0.269 (0.09)
	20-40	0.266 (0.08)	0.131 (0.07)
	40-60	0.078 (0.03)	0.019 (0.004)
	60-80	0.004 (0.002)	0.000
8 WAE	0-20	1.514 (0.66)	0.722 (0.31)
	20-40	0.882 (0.34)	0.443 (0.24)
	40-60	0.476 (0.26)	0.322 (0.19)
	60-80	0.126 (0.08)	0.090 (0.05)
	80-100	0.085 (0.02)	0.005 (0.003)

WAE = weeks after emergence of maize plants
Zone 1: 0-22.5 cm from the maize plant; Zone 2: 22.5-45 cm from the maize plant
Standard Deviation values given in parenthesis

4. Discussion

4.1. Legume productivity and N_2-fixation

Mucuna and soyabean produced fairly large amounts of biomass, and had high rates of N_2 fixation, while *Cajanus cajan* and *Crotalaria paulina* failed to produce useful amounts of biomass (Table 1). The highest net input of N into the soil was through mucuna green manure. Mucuna is a herbaceous legume adapted to a wide range of soils in the tropics, and high N_2-fixation rates by mucuna have often been reported (Giller, 2001). In West Africa, mucuna accumulated high N consistently across sites and significantly increased the yields of rice (Becker and Johnson, 1998). It is one of the legumes that have featured prominently in farming systems research in the tropics. Though soyabean derived the bulk of its N requirements from biological N_2-fixation (76 %), only 34 % of its accumulated N was returned to soil in the stover and litter. Its net N input was as low as 8 kg ha^{-1}, an amount that was similar to that contributed by relatively poor performers such as *Cajanus cajan*. Generally most soyabean varieties are bred to efficiently translocate N to the seed, hence they are usually net exporters of N. For grain legumes to contribute N to the cropping system, the

% N fixed should be greater than the % N removed in the grain, and the stover should be returned to the soil (Giller, 2001). The poor biomass productivity by *Cajanus cajan* reported in this study only confirms earlier findings by Mapfumo et al. (1999), who reported N fixed on several farms on very sandy soils to be largely less than 20 kg ha^{-1}.

Other than soyabean and mucuna, the rest of the legumes failed to produce adequate biomass to build soil N or supply enough mineral N to the following maize crop. The woody legumes (*Sesbania* and *Acacia*), that have been shown to grow well in Zimbabwe on an experimental site with 22 % clay, failed to grow through the dry season with less than 10 % survival by the next rainy season. The water holding capacity of the studied soil was very poor, and this coupled with the very low soil P resulted in poor root growth of the legumes. The growth and biomass production of these legumes might be improved if P fertilizer was applied. However, under current farmer circumstances in most smallholder farms in Zimbabwe, this option is not feasible. Currently soil fertility management practices that require farmer's investment through use of mineral fertilizer to boost productivity of a non-food legume crop for soil fertility restoration do not seem to appeal to most farmers. Generally farmers have tended to systematically grow even the grain legume crops on poor fields and concentrated on applying animal manure and the little mineral fertilizers available to maize, the staple grain (Chikowo et al., 1999). From our interaction with the farmer who hosted the experiment, it was most likely that soyabean would be a more permanent crop in his cropping system, than mucuna or any of the other tested legumes, even if seeds were to be made readily available. In Zimbabwe, mucuna has traditionally not been for human consumption. While our focus was on soil fertility build up for subsequent maize crops, the farmers' production objectives were clearly to meet immediate food security needs.

4.2. Nitrogen uptake and recovery by maize

Nitrogen recovery efficiency of 47% in the fully fertilized maize treatment for the first season was high, considering the sandy textured soils and the heavy rainfall that was received during the top dressing period (Fig. 3). Split application of mineral N fertilizer has been shown to increase N uptake and N recovery rates considerably in communal areas in Zimbabwe (Piha, 1993). Nitrogen recovery by maize in cattle manure treatments was generally poor, and can be attributed to the slow N mineralization from the manure, and possible immobilization because the manure had a very low N concentration. Mineral N concentration in the soil for manure treatment, and the other treatments, was inadequate to support a high yielding maize crop. The slow rate of N mineralization from aerobically composted manure has been observed elsewhere, and attributed to the high degree of C stabilization (Murwira and Kirchmann, 1993). Depressed N uptake after application of similar poor quality manure has been reported widely (Mugwira and Mukurumbira, 1984; Tanner and Mugwira, 1984). The residual effects of applying even large quantities of manure (37 Mg ha^{-1}) were found to be poor and this was also attributed to little mineralizable organic N remaining in the subsequent seasons (Nyamangara et al., 2003).

During the second season N uptake was affected by drought and N recovery for the plots fertilized with N at 90 kg ha^{-1} was as low as 23 %. The added N remained unutilized in the soil as the plants were wilting most of the season due to poor rainfall and poor water holding capacity of the sandy soil. We may have underestimated the N input to the system through the legumes, as we did not include root and nodule N. Although roots contain low concentrations of N, they continuously senesce during plant growth so that their N is released into the soil as the roots decompose. In a study of the contribution of N_2-fixation to tropical green manure crops and the residual benefit to subsequent maize crop using ^{15}N-isotopic techniques, Ramos et al. (2001) concluded that total below-ground N could constitute as much as 39 % of the total N accumulated by mucuna. The high apparent N recovery of 36 % following soyabean in our study may indicate that we underestimated the overall N input. In a study to assess the residual N benefits of soyabean to maize, Kasasa et al. (1999) also found increased maize yields following promiscuous soyabean varieties.

Root length densities for maize were less than 0.1 cm cm^{-3} in all layers except for the top 0.2 m during the first 4 WAE. This could have exposed the N applied in the basal fertilizer treatment and that mineralized from the organic materials, to leaching early in the season. At 6 WAE, the maize root length density had adequately increased in the 0-0.4 m layer, but was still low at layers below. van Noordwijk (1989) reported that root length densities of at least 0.1 cm cm^{-3} in the subsoil are required to sufficiently utilize available N. This is consistent with work by Piha (1993), who reported that there was just as good N recovery by maize when top dressing N fertilizer was applied in several split applications by broadcasting on the soil surface as from six weeks after crop establishment. This management practice offers an opportunity of saving labour and farmers could then devote more time to proper weed management, which could be just as important as fertilization in influencing the final maize yields.

5. Conclusions

The range of legume options available for use on depleted sandy soils in Zimbabwe is narrow. Soyabean seems to produce useful amounts of biomass and grain, but only after some basal mineral P fertilizer application and inoculation with compatible rhizobia. Mucuna is remarkably adapted to the harsh soil conditions and fixed the bulk of the N it accumulated without added P, but requires substantial labour and does not yield a directly usable product. Such factors strongly affect farmers' acceptance of green manuring as an option of replenishing soil fertility, in such farming system dominated by maize monoculture. The extent to which legume fallows can increase yields of crops in rotation varies according to the condition of the land and the quality of the rainy season. Planted legume fallows, legume/cereal rotations and applications of poor quality cattle manure are not enough in themselves to overcome major N nutrient deficiencies in soils that are already very degraded. While part of the early N requirements of growing maize plants can be met by these technologies, a large proportion of the N needed later in the season will have to be met from mineral sources. Where both soil organic matter and P contents are very poor, as is often the case in many communal area soils, legumes may not accumulate significant amounts of biomass and will fix N poorly. Areas for future research for smallholder farms in Zimbabwe, therefore, include technologies that will improve legume establishment and growth on degraded soils, as well as efficient recovery of applied mineral fertilizers.

Acknowledgements

We thank the European Union for financial support through the IMProved fAllows in Africa (IMPALA) Project in Zimbabwe, and the Rockefeller Foundation for funding the first author's study at Wageningen University, The Netherlands. George Nyamadzawo is thanked for assistance with field work.

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CHAPTER 7

Senesced legume litter decomposition and N mineralization under leaching conditions in a sandy soil

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To be submitted for publication in a modified format as:
Chikowo R, Leffelaar P A and Giller K E. Senesced legume litter decomposition and N mineralization under leaching conditions in a sandy soil

Abstract

The release of mineral-N in soil from plant residues is regulated by their ‘quality’ or composition. Legume materials used by farmers in agroforestry systems in southern Africa are often in the form of litter with N concentration <2 %, and wide C:N ratios, following a long dry season between the rainfall seasons. 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 leaching tubes in the laboratory. We could adequately describe the mass loss of the litter using a modified exponential decay model: $Y = (Y_0\text{-}Q)e^{-kt} + Q$. 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 of the *Acacia* prunings and *Acacia* litter, the total mineralized N was similar, as mineralization from fresh prunings was depressed by the high protein binding capacity of its polyphenols. Except for *Sesbania* litter, the rest of the senesced legume materials showed N immobilization up to 60 days. While N supply may be poor, these slow decomposing materials are potentially useful for maintaining soil organic matter in smallholder farms in Africa.

Key words: *Acacia angustissima*, leaching, residue quality, polyphenols, smallholder farms, immobilization

1. 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. 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., 1998a), whereas poor quality materials have characteristics that inhibit decomposition.

Determination of N release from plant residues is often included in decomposition studies. Most studies have determined N concentrations, C:N ratios, lignin and polyphenol concentrations and computed ratios for the various combinations as possible predictors for N mineralization or immobilization (Mafongoya et al. 1998a; Handayanto et al., 1997). There are, however, varied reports in the literature on the relative importance of each of these residue quality parameters. In an attempt to increase the predictive understanding of N release by organic materials, several researchers have used multi-variable equations that indicate a hierarchical set of N, lignin and polyphenol content for predicting N release (Mafongoya et al., 1997; Constantinides and Fownes, 1994; Palm and Sanchez, 1991). A decision tree, which uses critical values of the different resource quality parameters to quantitatively define high and low quality organic materials as they relate to N release patterns, was developed by Palm et. al. (1997).

In Zimbabwe at the time of terminating legume tree fallows, the bulk of the standing biomass is woody, as most leaves senesce and fall to the ground during the long dry period between the rainfall seasons (Chikowo et al., in press). Due to retranslocation of nutrients, the senesced leaves or litter have lower N and higher C:N ratio, are more lignified and may show different mineralization rates compared with the fresh material. Fresh tree prunings (leaves and twigs) are most widely studied for decomposition patterns (e.g. Mafongoya et al., 1998a), and apparently little attention has been paid to N mineralization by the litter component. We investigated *Acacia angustissima* and *Sesbania sesban* litter decomposition in a litterbag experiment, and also investigated N mineralization of both fresh prunings and litter under leaching conditions in a leaching tube incubation experiment. In tropical environments both leaching and non-leaching conditions occur during the cropping season following incorporation of tree litter and prunings.

2. Materials and methods

2.1 Experiment 1: Litter decomposition in litterbags

The experiment was conducted 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) between December 2000 and April 2001. The soil is a sandy clay loam with 22 % clay content, and classified as a Lixisol (World Reference Base for soil Resources). Total rainfall received during the experiment was 1200 mm, and on average day air temperatures are known to range between 25 and 30 °C during this period.

Mass loss rates of incorporated *Sesbania* and *Acacia* litter were assessed by placing 30 g dry weight litter into 25 cm x 25 cm litterbags with 2 mm mesh size. A total of 21 litterbags were used for each litter type. Approximately 25% of this litter were twigs of varying diameters ranging up to 5 mm. The litterbags were buried in the unfertilized maize plots at about 45° angle to a depth of 15 cm, at the time of establishing the maize crop. This is the tillage depth normally achieved by farmers using ox-drawn ploughs hence litter is incorporated to this maximum depth. Initial chemical properties of these litters are shown in Table 1. Three litterbags were retrieved 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 hours. 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 hours. Fresh litter used in the decomposition study was also ashed to determine initial ash content.

A modified exponential decay model was fitted to the mass loss data:

$$Y_t = (Y_o - Q)\, e^{-kt} + Q \qquad (1)$$

with 'Q' being the 'quantity' of litter that would remain undecomposed in the litterbags in the long run, and k, the relative decomposition rate constant.

2.2 Experiment 2: 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 in Zimbabwe with 4% clay content. All the residues were added at a rate equivalent to 100 mg N of residues kg^{-1} soil after they were analyzed for initial N, lignin, polyphenols and protein binding capacity of their polyphenols (Table 1).

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 hollow glass rod 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 (1mM $CaCl_2$; 1mM $MgSO_4$; 0.1mM KH_2PO_4 and 0.9 mM KCl) in 50 ml aliquots (Cassman and Munns, 1980). The initial leachate (day 0) was collected and analyzed for total dissolved N. Excess water was removed with a mild suction pump, and then the tubes were incubated in the dark at 24-25 ^oC. 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 NH_4^+ and NO_3^-. Net N-mineralization was calculated by subtracting N released from the unamended soil control from N released from 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.

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

3. Results

3.1 Composition of legume materials

The chemical composition of the materials used in the study varied widely (Table 1). *Acacia* had the highest concentration of N and polyphenols, and consequently the narrowest C:N ratio. Also, *Acacia* polyphenols had the largest activity as indicated by large protein binding capacity. Except for *Acacia* litter, all the other materials had lignin concentrations <15 %. Total N was less than 2 % for all senesced litters, indicating large variations between the fresh and litter materials from the same species.

3.2 *Mass loss by legume litters*

The rate of mass loss for both *Sesbania* and *Acacia* litter was large 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 ($Y = Y_0e^{-kt}$). Data was then fitted to a

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	Polyphenol:N	(Polyphenols + Lignin) : N
Sesbania leaves	3.2	0.28	4.5	1.9	28	14	1.4	0.6	2.0
Sesbania litter	1.6	0.21	5.4	0.8	20	21	3.4	0.5	3.9
Acacia leaves	4.8	0.57	7.1	5.7	160	10	1.5	1.2	2.7
Acacia litter	1.5	0.17	24.4	1.3	29	24	16.2	0.9	17.1
Soyabean stover	1.7	0.20	12.9	0.6	18	25	7.6	0.8	7.9
Mucuna litter	1.8	0.31	11.5	3.4	52	24	6.4	1.9	8.3

%: (mg per mg dry weight) x 100

PBC: protein binding capacity, ug BSA mg^{-1} plant sample (BSA= bovine serum albumin)

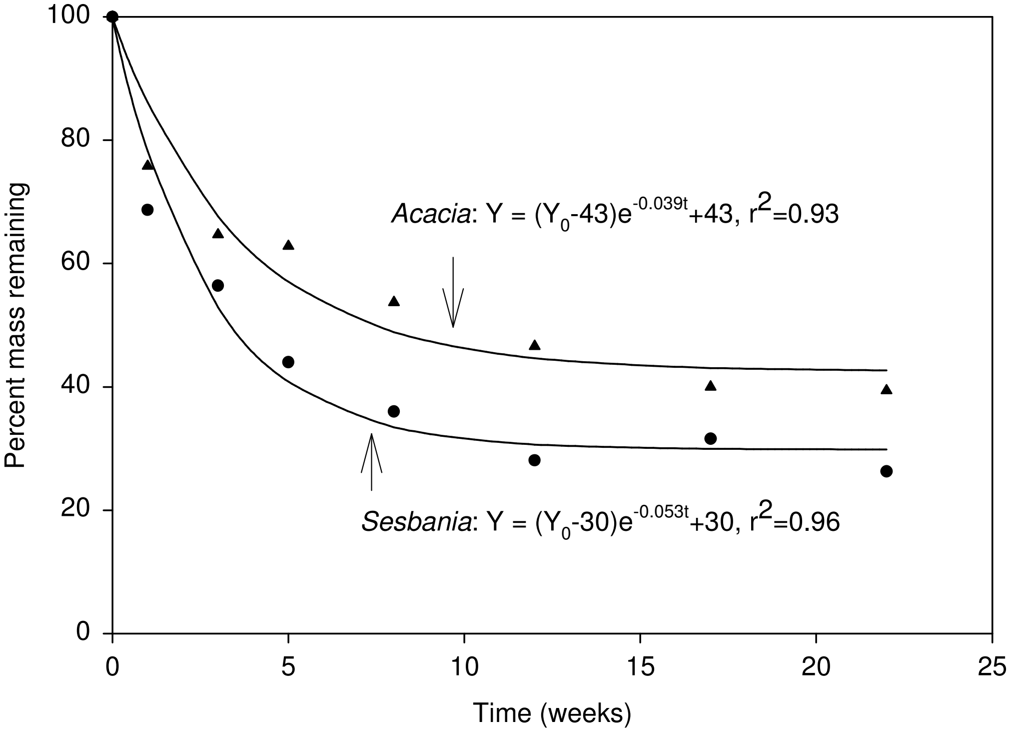

Figure 1. *Acacia* and *Sesbania* litter remaining in litterbags buried in soil on several retrieval times over a 22-week period under sub-humid conditions could be described by a modified exponential decay model.

modified single exponential decay model (Equation 1) which gave a linear relationship for the plot of $\ln\{(Y\text{-}Q)/(Y_0\text{-}Q)\}$ versus time. The proportions of recalcitrant material were found to 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 only as some mass loss maybe due to material movement through the mesh.

3.3 N mineralization patterns

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). Most of the senesced litter materials showed N immobilization between the 4th day to 60th day of incubation, and then net-mineralization. *Sesbania* litter immobilized N for a 2-week period

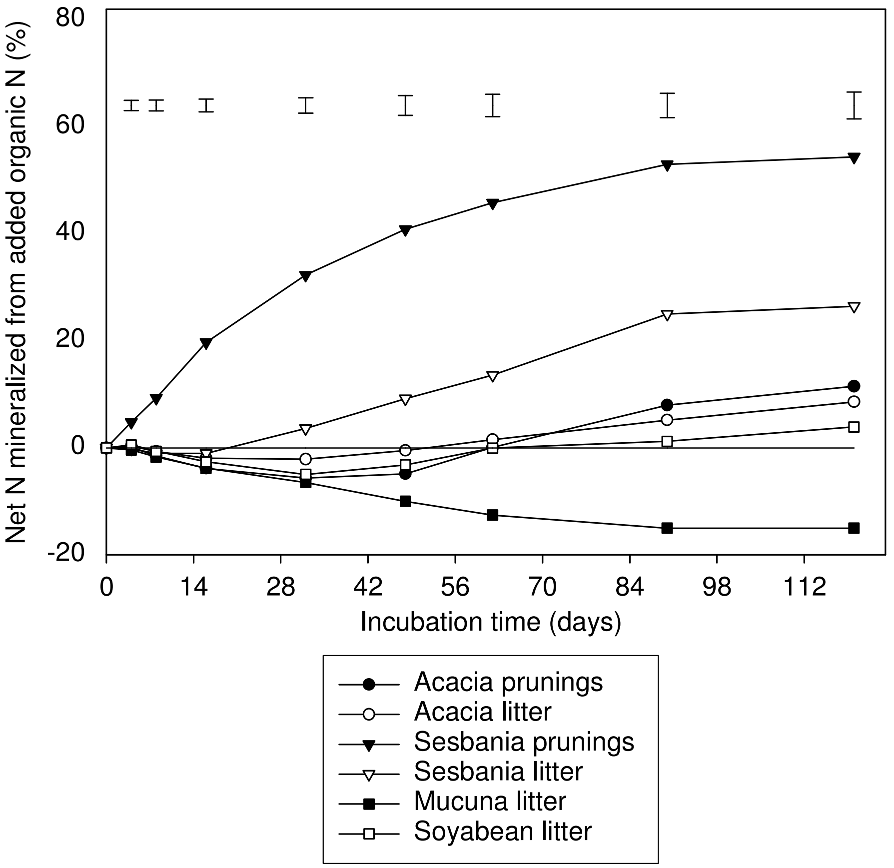

Figure 2. N release by various legume materials in a leaching tube incubation experiment. Bars represent least significant differences, P<0.05.

only and then mineralized N slowly over the next 90 days. Mucuna litter was an exception as it immobilized N for the entire incubation period (Figure 2). The proportion of added N mineralized after 120 days decreased with increasing polyphenol-to-N. There was no clear correlation between N mineralized and the lignin-to-N ratio as *Acacia* litter with the widest lignin-to-N ratio had net mineralization, while mucuna which had a considerably narrow ratio, had net immobilization (Figure 3).

4. Discussion

Acacia litter disappeared more slowly than *Sesbania* litter in the field litterbag experiment (Figure 1), and this was probably linked to the higher lignin content of *Acacia* litter than *Sesbania* litter (Table 1). Their relative decomposition constants were 0.039 and 0.053 d^{-1}, respectively. About 25 % of the litter we used was in form of small twigs of up to 5 mm

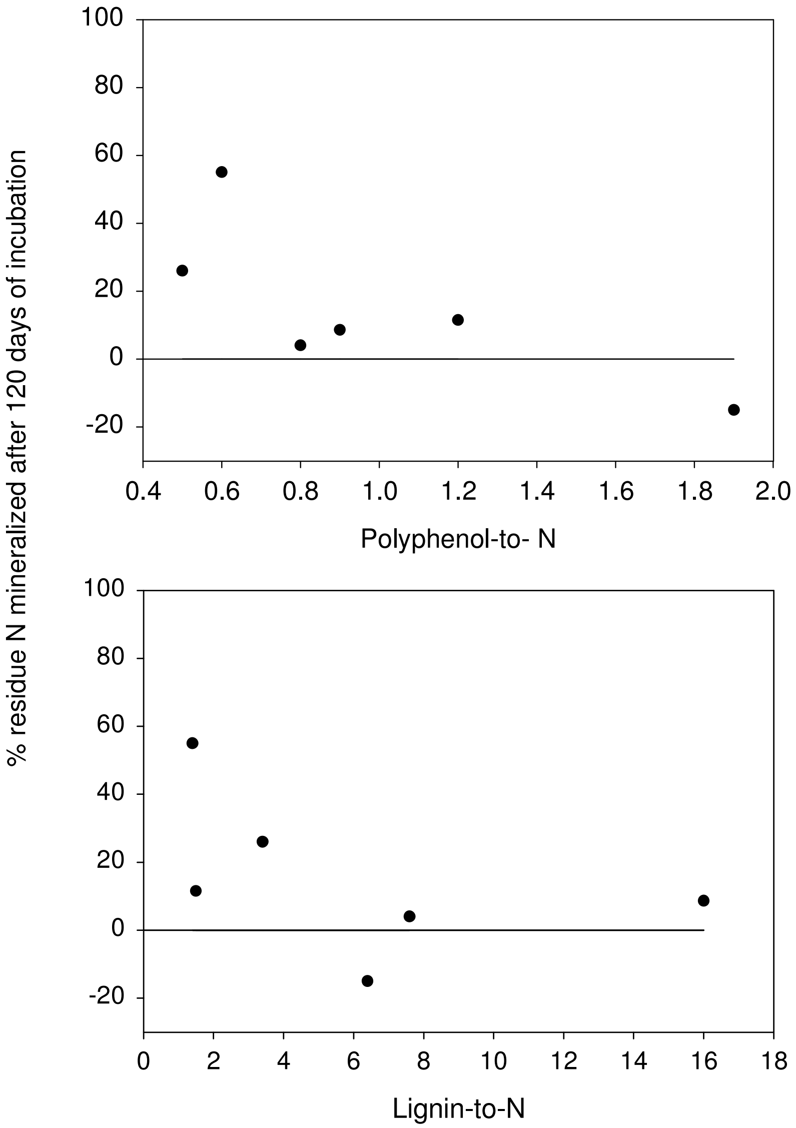

Figure 3. Relationship between the proportions of N releases after 120 days of laboratory leaching tube incubation and the residue polyphenol-to-N and lignin-to-N ratios.

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. At the end of the 22 weeks, the model we used predicted that 30 and 43 % of the litter would remain in the litterbags for *Sesbania* and *Acacia*, respectively. Lignin is a structurally complex plant constituent which is a major factor contributing to its recalcitrance to decomposition (Swift et al., 1979). In the leaching tube incubation experiment, N mineralization was greatly depressed for *Acacia* prunings when compared with *Sesbania* prunings. *Acacia* prunings had high concentration of polyphenols, which were very active in binding protein (Table 1). The presence of inhibitory compounds is an important component of litter quality. Polyphenols may also interfere with enzyme function or decomposer metabolism, resulting in reduction in decomposition of other litter constituents (Paustian et al., 1997). High activity of polyphenols as indicated by their high protein binding capacity has been shown to be highly correlated with reduced N mineralization rates (Handayanto et al., 1997). Earlier, Palm and Sanchez (1991) had also attributed the differences in N release by various tropical legumes to polyphenols in the legumes, and showed that polyphenol:N ratio was a good predictor of N mineralization. Our results showed that the proportion of added N mineralized after 120 days was not strongly related to the lignin-to-N ratio (Figure 3). The polyphenol-to-N ratio probably explained why mucuna litter immobilized N throughout the incubation period. Despite carrying out this experiment under leaching conditions, which should supposedly deplete the soluble active polyphenols that are able to bind plant protein (Handayanto et al., 1995), total mineralization for *Acacia* was still very poor. Thus, even under field conditions, it would be expected that N supply by materials with highly active polyphenols would be poor.

N mineralization from the fresh prunings was higher than that from litter from the same species. 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). The N concentrations were also significantly lower (Table 1). All these factors contribute to reduced N release. In a review of decomposition and N release patterns of tree prunings and litter, Mafongoya et al (1998b) showed that litter materials had lower nutrient concentrations compared with green foliage of the same legume species, and this was correlated with decomposition rates.

The differences in mass loss between *Sesbania* and *Acacia* litter were narrower compared to their respective N mineralization patterns (see Figures 1 and 2). Unlike the incubation experiment where all litter constituents for both *Acacia* and *Sesbania* litter were ground to pass through 2 mm mesh sieve, whole litter materials as found on the soil surface under the trees/shrubs were used in the litterbags. The different fractions of plant litter vary in their inherent decomposability due to differences in morphological and chemical constituents, and some decomposition models (e.g. Pastor and Post, 1986) incorporate particle size as a physical attribute of litter quality. *Acacia* litter had finer leaves and the soil-litter interface area was supposedly larger, thus resulting in comparatively faster mass loss than would be predicted from its chemical composition when compared with *Sesbania* litter. We suspect that an appreciable proportion of early mass loss in *Acacia* litter could have been due to loss of material through the mesh on sampling.

Poor N recovery following incorporation of high quality legume prunings such as *Sesbania* are probably a result of rapid N release and subsequent leaching before crop root systems sufficiently develop. Conversely, senesced materials release N too slowly, and this is inadequate to sustain a high N demanding crop. Materials with perfect synchrony of N release and plant N uptake demand are apparently not available. Mineral N availability 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 other N sources such as of microbial biomass turnover and labile organic matter. This study has shown that first order kinetic models used in a modified form, adequately describe mass loss of *Sesbania* and *Acacia* litter, and probably many other senesced legume materials. 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 legume materials we used means that crop fertilization with legume materials alone will not support high productivity. There remains the challenge to integrate results from litterbag and leaching tube incubation studies to the prediction of N availability in the field.

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CHAPTER 8

Integrating legumes to improve N cycling on smallholder farms in sub-humid Zimbabwe: Biophysical and environmental limitations.

To be submitted in a modified format as:

Chikowo R, Mapfumo P and Giller K E. Integrating legumes to improve N cycling on smallholder farms in sub-humid Zimbabwe: Biophysical and environmental limitations.

Abstract

The storage and release of nutrients by soil organic matter is a primary determinant of soil fertility in low-input agriculture. Traditional shifting cultivation systems utilized the soil organic matter built up during the fallow phase to supply nutrients. The present day circumstances dictate that food production be stabilized through fertilization, intercropping and short duration improved fallow–cereal cropping sequences. Here we synthesize results of research in sub-humid parts of Zimbabwe as regards options of N management on smallholder farms. We use data from field experiments with various legumes, literature concerning tropical soil N management to draw conclusions as to the partitioning of the initial N stocks for the different legume species. *Sesbania sesban, Acacia angustissima* and *Cajanus cajan* produced useful amounts of biomass on soils of at least loamy texture and improved N cycling significantly, (>150 kg N ha^{-1}) but adapted poorly to sandier soils. Under conditions of severe texture constraints, *Mucuna pruriens* showed robustness but has the disadvantage of having no direct food value. Gaseous N losses after incorporating legume materials were <0.5 kg N ha^{-1} and reducing nitrate leaching is the single largest challenge to increased N recovery in these highly porous soils. We use our present results and the knowledge available on legume N release characteristics to show the challenges that are inherent in N management on smallholder farms. We conclude that combinations of mineral N fertilization with available organic materials will be the way forward for continued production on some of the tropics' most marginal soils.

Introduction

Nitrogen stocks in many smallholder farms have declined as soil organic matter decreased due to both reduced organic matter inputs and decomposition under continuous cultivation. Crop residues poor in N, such as cereal stovers, are the major sources of organic materials, but these induce prolonged immobilization of N which deprives crops of available N during the early growing season (Giller et al., 1997). 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 kg farm^{-1} year^{-1} (Mapfumo et al., 2000; Giller, 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 barely 1 Mg ha^{-1} year^{-1}. With the exception of the crop roots, a substantial part of these crop residues are eaten by animals and may probably be returned to the same fields as manure. It is clear that 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, but we can be sure that additions are small and that 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, crop off-take and erosion. Given the crop residue management practices followed on most smallholder farms in Zimbabwe, there is invariably bound to be a deficit.

Legumes in the cropping system

Improved fallows, where tree legumes are grown in sequence with crops are an option to provide larger amounts of organic matter in a short time. *Sesbania sesban, Cajanus cajan, Acacia angustissima* are legume species that have produced high subsequent maize yields (Mafongoya and Dzowela, 1999). *Acacia* is hypothesized 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), but there has been some success in Benin (Becker and Johnson, 1998). The lack of a direct usable food product is the principal disincentive in farmers readily adopting green manuring. Also, unless farmers add some P fertilizer to the legume or to the cereal crop following a

Table 1. Biomass production, biological N_2-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., in press).

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	28	76	8 (+16)
C. paulina	0.2	4	46	2
Mucuna	3.9	87	96	84 (+26)
C. cajan	0.4	7	65	4
A. angustissima	nd[c]	nd	79	nd
S. sesban	nd	nd	84	nd
		Sandy clay loam		
Cowpea	2.5	48	58	17 (+13)
C. cajan	5.3	115	84	82 (+21)
S. sesban	5.7	152	55	38 (+29)
A. angustissima	9.9	218	56	69 (+60)

[a] Above-ground plant accumulated N (Soil N + N_2-fixed N) returned to the soil in form of litter and leaves.

[b] Amount of N_2-fixed and returned to soil through above ground non-woody components – soil derived N exported through woody parts and grain. Values in parenthesis are estimates of additional amounts of N_2-fixed in roots.

[c] nd= not determined. These legumes grew poorly on the sandy soil site.

green manure crop, there is no outright guarantee of massive crop responses to the legume N in the soils in which crop growth is often constrained by multiple nutrient deficiencies and unreliable rainfall (Grant, 1981). As green manures compete for land resources with other food crops, it will be important to ascertain from farmers how these will fit in the farmers cropping cycles. Soil fertility management, to a large extent, is a function of socio-economic processes associated with a household and its management.

Grain legumes have been grown by smallholder farmers in rotations with cereal crops and these can contribute N, but the contributions are very variable depending on legume type, N partitioning characteristics and rate of biological N_2-fixation. Estimates of net N inputs from N_2-fixation by various grain legumes in the tropics have been compiled and inputs range from large negative values of -47 to 137 kg N ha^{-1} (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 will invariably contribute very little N to the soil. The amounts of N returned below ground are difficult to quantify and therefore very poorly documented, but often they represent the only input of organic residues to the soil in the case where above ground residues are removed from the field.

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 different (Table 1). Mucuna derived at least 96 % of its total N from biological N_2-fixation, while soybean fixed 76 % of its N as determined by the ^{15}N natural abundance on a sandy soil. At the same site, *Acacia, Sesbania* and *Cajanus* fixed 79, 84 and 65% of their N, respectively. Although N_2-fixation rates were high for these woody legume species, total N fixed was small as these legumes grew poorly and produced little biomass. Total above ground N input to the soil by soyabean through leaf litter and stover was 28 kg ha^{-1}. After accounting for the soil N exported through seed harvest, soyabean net N input was only 8 kg ha^{-1}. This was improved when root N was estimated. As expected, mucuna had the greatest net N input into the system as no N was exported from the field through seed harvest. On the clay loam soil, *Sesbania* and *Acacia* had lower N_2-fixation rates, but overall N fixed and N cycling was significantly larger (Table 1).

The nutrient release dilemma of organic materials

Understanding the mechanisms by which the litter or prunings from the above-described practices affect crop growth requires the knowledge of factors regulating biodegradation. Characterization of organic materials has been the subject of many studies (Mafongoya et al. 1998; Cadisch and Giller, 1997; Handayanto et al., 1997). While nutrient quality explains and predict N release under controlled conditions, 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 in Zimbabwe showed nitrate in profiles moving well in advance of the crop demand

(Chapter 3, Figure 4). Specifically, the rapid mineral N accumulation in *Acacia angustissima* 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. A few weeks into the cropping season, mineral N originating from most organic materials used falls short of the amounts required to sustain high N demands by crops.

At the end of the 2-years of improved fallows, there is a mixture of plant materials that are at various stages of decomposition and the beginning of rains triggers mineralization. Managing N release in this scenario will remain difficult. 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. Certain tree prunings decompose too quickly and this decomposition is not synchronized with the demands of the cultivated crops. Materials with large active polyphenol amounts like *Acacia* prunings would decompose too slowly, again in asynchrony with plant uptake (Chapter 7, Figure 2). Though slow decomposing legume materials would not supply adequate N for immediate crop requirements, promoting their use could be an opportunity to build up and maintain reasonable soil organic matter contents on sandy soils.

Of the non-legume organic materials, cattle manure has been widely used. This leads to concentration of nutrients from the large pasture areas during grazing by animals into the manure which is collected overnight in cattle pens. There are a lot of losses of N in the process (e.g. 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 not favourable to support high crop yields (Mugwira and Mukurumbira, 1986).

N use efficiency: environmental and pest problems

Improved fallows have been associated with increased maize yields due to improved N cycling in southern Africa (Kwesiga and Coe, 1994). However, the more frequent droughts being experienced in southern Africa has adverse impact on the sustainability of the technology. In a long-term experiment where a number of maize crops were grown following improved fallows, Mafongoya and Dzowela (1999) reported maize yields significantly above the 1 t ha^{-1} Zimbabwe national yield average for the smallholder sector that practices maize monoculture with little or no external nutrient inputs. However, maize planted after the second fallow cycle in the same plots was poor due to pest infestation and excessive rainfall that reduced nutrient use efficiency during the first post fallow season, and drought during the second season (Table 2). The occurrence of pests and the highly variable rainfall reduces the usefulness of this technology considering that farmers have to trade-off two cropping seasons for soil fertility restoration.

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

Legume species	Phase 1[a]		Phase 2[b]	
	Season 1 (1995)	Season 2 (1996)	Season 1 (2001)	Season 2 (2002)
Sesbania sesban	4.9	3.7	0.67	1.30
Acacia angustissima	2.9	1.3	0.91	0.58
Cajanus cajan	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 Dzowela (1999)
[b] Chikowo et al. (in press)

N_2O emissions and C sequestration potential

The concentration of N_2O, CO_2 and other greenhouse gases has increased in the atmosphere, and there are increasing concerns of global climate change, manifested in higher temperature and increasing extremes of droughts and floods (Lal, 2003). Besides its critical role in sustaining agricultural production in many communities, promoting agroforestry is perceived as one of the options to enhance the C sinks in the biosphere, and thus mitigate global warming (Albrecht and Kandji, 2003; Dixon, 1995). The global warming potential of N_2O is 300 times higher than that of CO_2, and there are also concerns that increased N cycling could be associated with elevated N_2O emissions.

The trade-off between C sequestration and the emissions of N_2O will largely determine the usefulness of agroforestry in mitigating global warming. Reduced CO_2 emissions will only be significant if there is substantial C storage in the soil through increased soil aggregation. Carbon storage in the woody parts is only temporary as the wood in agroforestry systems is usually used as a source of fuel. In sandy soils where the C equilibrium level is low, and building soil organic matter with increased organic residue inputs is difficult due to poor physicochemical properties (Six et al., 2002; Ingram and Fernandes, 2001), C sequestration is invariably poor. Recent data from Kenya shows that 18 month-improved fallows with differenttree species increased soil C stocks by between 2.5-3.7 Mg ha^{-1} on a clay soil in all

Table 3. N_2O emissions in field experiments that involved improved fallows: (1) on a sandy loam soil in sub humid Zimbabwe, and (2) on a silty clay loam soil in humid tropics of western Kenya highlands.

Location, soil type and measurement duration	Treatment	Amount of N input (kg ha^{-1})	Total N_2O-N emission (g ha^{-1})
(1) Zimbabwe (sandy loam) (56 days)	Unfertilized maize	0	60
	Acacia angustissima	215	180
	Sesbania sesban	152	240
	[b]*Sesbania*-NT	152	290
(2) [a]Kenya (silty clay loam) (84 days)	Unfertilized maize	0	230
	Sesbania sesban	115	1 940
	Sesbania /Macroptilium	215	4 130
	Macroptilium	360	1 630
	Crotalaria grahamiana	288	1 860

[a]Data for Kenya adapted from Millar et al., unpublished results
[b]*Sesbania*-NT = *Sesbania sesban* plots that were not tilled

cases, and on a sandy soil some of the species did not induce any significant C changes (Albrecht and Kandji, 2003). In the absence of substantial aggregate protected C on sandy soils, the merits of agroforestry on these soils will be realized through other benefits like reduced erosion-induced C losses due to increased water infiltration. No-tillage management is useful in the management of soil C as it may promote more sequestration due to better soil aggregation and reduced erosion (Potter et al., 1998). Coppicing legume tree species like *Acacia angustissima* are likely to offer the best opportunity for C sequestration. *Acacia* produces large biomass, and its litter decomposes slowly. Its large root volume results in substantial C storage below-ground (Chapter 2). However, in dry environments competition for water maybe the overriding factor restricting its successful integration in the cropping system.

Our results of N_2O emissions following two-year improved fallows on a sandy loam soil in southern Africa indicated that legumes increased N_2O emissions compared to unfertilized maize monoculture, but losses were < 0.5 kg ha^{-1} for a measurement period of 56 days (Chapter 4). In that work we suggested that under the less-reducing conditions of the open textured soils, a large proportion of the gaseous N could have been a lost in the form of nitric oxide (NO). In the humid tropics of western Kenya, N_2O emissions on a heavier textured soil were substantially higher following improved fallows (Table 3). While the total emissions in both cases may be of little economic consequence to total N left available to the crop, these quantities of N_2O may be of significance to climate change in the long run, only if the improved fallow technology is adopted at a wide scale.

Nitrogen cycling: closing the loop

A lot is now 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., 2001). Despite the vast documentation of such knowledge, the challenge to increase crop productivity to levels adequate to sustain human populations in sub Saharan Africa is increasing as soil erosion and other forms of nutrient depletion are also gaining pace.

Figure 1a summarizes N cycling in an improved fallow system of *Sesbania sesban* 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, then 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. For the continuous maize cropping, crop production is supported through native soil organic matter decomposition. If the decomposition coefficient is assumed to be 2 %, 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 1b). With no substantial annual organic material additions (except from weeds), the capacity of soil to supply N gradually decreases, and so will the production intensity that can be supported. We established that gaseous N emissions are small under unfertilized conditions (Chapter 4), 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 (Chapter 5), the eroded soil has poor nutrient content and total N losses are thus small.

While N_2-fixation rate may not be that variable, it is clear that other components of the cycle are largely a function of the quality of the cropping seasons. It maybe 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

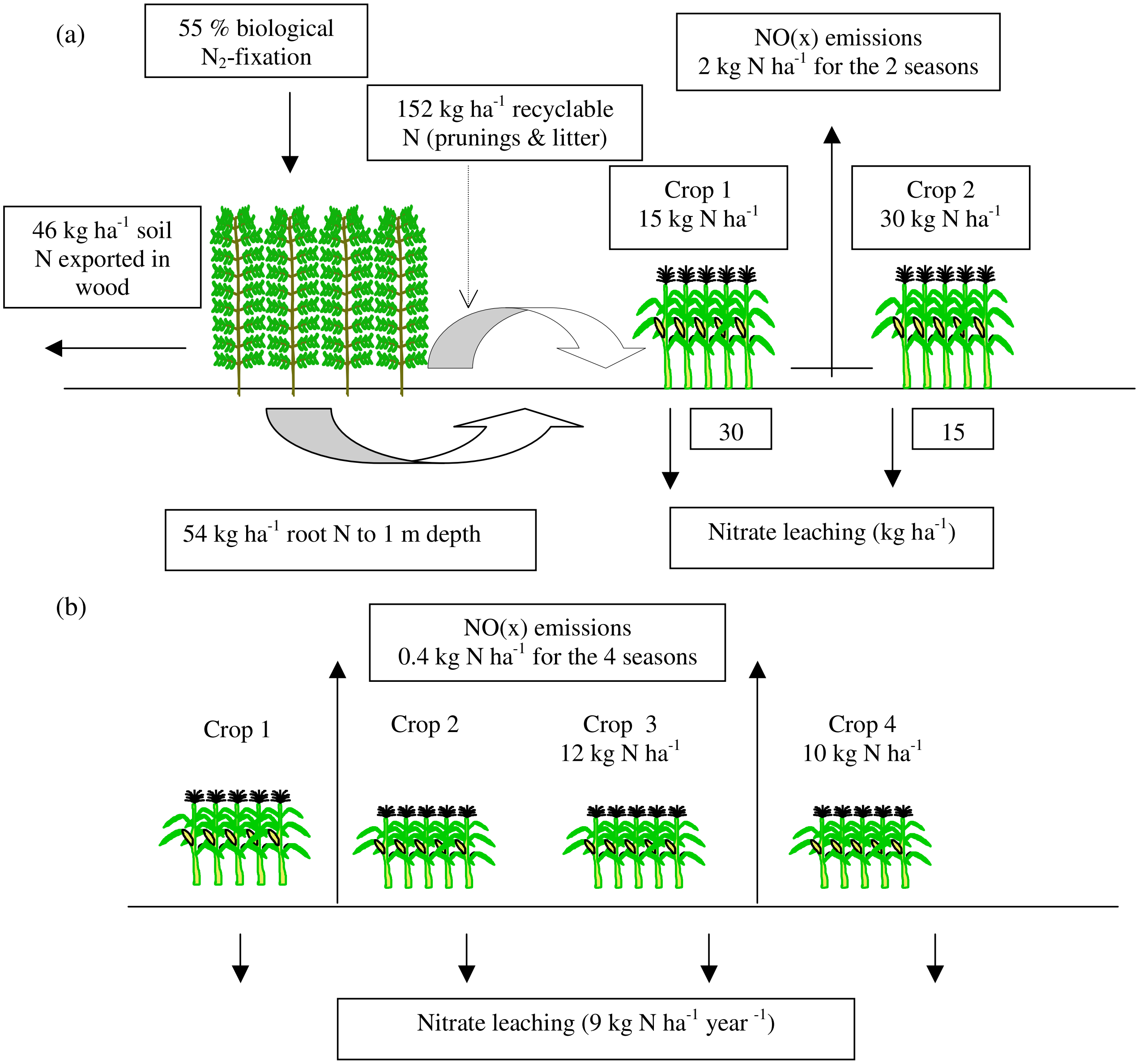

Figure 1. Nitrogen flows and use efficiency in (a) *Sesbania sesban*–maize-maize cropping sequence and (b) maize monoculture with no fertilizer application. It was assumed that the N mineralization from SOM was equal in both cases at 30 kg N ha^{-1} year^{-1} (2 % of native SOM).

large. However, such losses markedly increase in subsequent cropping seasons as the physical effects of improved fallows on water infiltration dynamics disintegrate

Generalizing N inputs and N loss pathways is rather difficult because both processes are controlled to a large extent by environmental and biophysical factors. However, we found that for many legumes large proportions of N came from N_2-fixation on the sandy soil, but these were large proportions of small amounts of N. Overall N cycling was therefore poor. On heavier soils agroforestry technologies will improve soil fertility, and given favourable environmental conditions, lead to increased subsequent crop yields. The gaseous N losses are likely to be low in porous soils where anaerobic conditions are less severe, and the combined N oxides will probably not exceed 2 kg ha^{-1}. The greatest threat to the N accumulated by the legumes is through leaching driven by the high intensity rainfall and the asynchronous nature in the release of N and its demand by crops.

Though no-tillage results in better soil physical structure and reduced soil erosion compared to conventional tillage, maize yields under no-tillage were generally lower due to poor N availability. There is need for fertilizer N in addition to organic N, and the strategy has to be the use of all available resources as fallow systems alone may not be attractive to farmers. On sandy soils the focus should be on management of available organic N sources and mineral N fertilizers in relation to crop demand without major emphasis on increasing soil organic matter.

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Summary

Traditional shifting cultivation systems utilized the soil organic matter built up during the fallow phase to supply nutrients in low-input agriculture in Zimbabwe. The present day circumstances dictate that food production be stabilized through fertilization, inter-cropping and short duration improved fallow-cereal sequences.

Two-year legume ‘improved fallows’ of *Sesbania sesban, Acacia angustissima* and *Cajanus cajan* were evaluated for their residual nitrogen (N) effects on two subsequent maize crops under minimum and conventional tillage management (Chapter 2). Maize monoculture and cowpea (*Vigna unguiculata*)-maize-maize sequence treatments were included as controls. N_2-fixation was estimated using the ^{15}N natural abundance method to allow the N accumulated by the fallows to be partitioned into N_2-fixation and soil N capture. The proportion of N_2-fixed in litter was 56, 55, 84 and 58 % for *Acacia, Sesbania*, *Cajanus,* and cowpea, respectively, resulting in inputs of biologically fixed N of 122, 84, 97 and 28 kg N ha^{-1}. Maize growth following the legumes for two subsequent seasons was in most cases not directly related to the N inputs. This was caused by cutworm (*Agrotis* sp.) infestation on maize during the first year in the *Sesbania* and *Acacia* plots, while the second season maize was affected by drought particularly in the *Acacia* plots where there was high moisture demand by the re-growing trees. During the second season, N uptake by maize following *Sesbania* was significantly higher than in the rest of the treatments. Conventional tillage resulted in better yields than minimum tillage across all treatments and in both seasons.

Soil samples for mineral N determination in profiles were taken at fallow termination and during maize cropping using an auger in 0.20 m sections to 1.2 m depth, every two weeks (Chapters 3 and 4). Using the closed chamber technique, N_2O fluxes were also determined in the same plots at the same time as mineral-N determinations. Pre-season NH_4^+-N amounts were > 12 kg N ha^{-1} in the 0-0.2 m layer for treatments that had a large litter layer. NO_3^--N amounts below 0.6m depth were <3 kg N ha^{-1} $layer^{-1}$ for *Sesbania, Acacia, Cajanus* and natural woodland compared with > 10 kg N ha^{-1} $layer^{-1}$ in the control plots where maize had been cultivated each year. There was a flush of NO_3^--N in the *Sesbania* and *Acacia* plots with the first rains. Topsoil NO_3^--N had increased to >29 kg N ha^{-1} by the time of planting the maize crop. This increase in NO_3^--N in the topsoil was not sustained as concentrations decreased rapidly within three weeks of maize planting, to amounts of 8.6 kg N ha^{-1} and 11.2 kg N ha^{-1} for the *Sesbania* and *Acacia* plots, respectively. Total NO_3^--N leaching losses from the 0-0.4 m layer ranged from 29-40 kg ha^{-1} for *Sesbania* and *Acacia* plots within two weeks when 104 mm rainfall was received to a profile that was already at field capacity. Nitrate then increased below the 0.4 m depth during the early season when the maize had not yet developed a sufficient root length density to effectively capture nutrients.

One week after planting maize, N_2O fluxes of 12.3 g N_2O-N ha^{-1} day^{-1} from *Sesbania* plots were about twice as high as those from *Acacia*, and about seven times the 1.6 g N_2O-N

ha^{-1} day^{-1} from maize monoculture. This coincided with the mineral N peak in the topsoil. The unfertilized maize showed consistently low N_2O emissions, which never exceeded 2 g N_2O-N ha^{-1} day^{-1} for all the eight sampling dates. The decrease of mineral N concentration in the topsoil resulted in reduced N_2O fluxes, despite very high soil moisture conditions. N_2O-N emissions were greatest for *Sesbania* plots with 0.3 kg ha^{-1} lost in 56 days. It is concluded that, under high rainfall conditions, there is an inherent problem in managing mineral N originating from mineralization of organic materials as it accumulates at the onset of rains, and is susceptible to leaching before the crop root system develops.

Research on improved fallows has mainly concentrated on soil fertility benefits neglecting possible benefits to soil and water conservation. The effects of improved fallows on rainfall partitioning and associated soil loss were investigated using simulated rainfall (Chapter 5). Rainfall was applied at an intensity of 35 mm h^{-1}. Immediately after fallow clearance, infiltration rates were greater than the water application rate for the *Acacia* and natural fallow treatments, but steady state infiltration rates were 24 mm h^{-1} in *Sesbania* and 5 mm h^{-1} in continuous maize. The estimated runoff losses after 30 minutes of rainfall were 44% in case of continuous maize compared with 22% from *Sesbania* and none from *Acacia* and natural fallow plots. Infiltration rate decay coefficients were 36 mm and 10 mm for *Sesbania* and continuous maize, respectively. After one post-fallow crop, water infiltration was still greater than 35 mm h^{-1} in the *Acacia* plots. Steady state infiltration rates were 8 and 5 mm h^{-1} for *Sesbania* and continuous maize systems, respectively. The runoff loss after 30 minutes, averaged across minimum and conventional tilled plots, increased to 30% in the case of *Sesbania* plots and 57% for continuous maize. It is concluded that planted tree fallows increase steady state infiltration rates and reduce runoff rates, but also that these effects markedly decrease after the first year of maize cropping after non-coppicing tree fallows.

A field experiment was also conducted for two seasons to evaluate the performance of various soil fertility management practices in increasing maize yields on a poor course-textured sandy soil (Chapter 6). The treatments included (1) mucuna (*Mucuna pruriens*) green manure followed by maize, (2) one year *Cajanus* followed by maize, (3) first season *Crotalaria paulina* followed by maize in the second season, (4) soyabean (*Glycine max*) followed by maize, (5) maize for both seasons but fertilized with animal manure in first season only, and (6) maize for both seasons with or without mineral fertilizer during the two seasons. Soyabean accumulated a total of 82 kg ha^{-1} N, with 54 kg in seed that was harvested, while mucuna produced 87 kg ha^{-1} of N in its biomass that was all incorporated into the soil. Soyabean fixed 76 % of its N, while mucuna fixed 96 % of the accumulated N as estimated by the ^{15}N natural abundance method. *Cajanus* and *Crotalaria* accumulated barely 10 kg ha^{-1} N in their biomass and had no effect on N uptake by maize in the following season. Estimated recovery of the added N by maize was 47 % for the mineral fertilized maize, 36 % for soyabean, 12 % for mucuna and 9 % for cattle manure. Despite the large differences in added residue N via mucuna and soyabean, differences in soil mineral N were only evident up to four weeks after the beginning of the rains, after which mineral N concentrations became very small in all treatments due to leaching, rather than crop uptake. It was concluded that mineral N available to maize from the residues investigated falls short of what is required to sustain high maize yields due to slow mineralization or immobilization. In these environments where biomass accumulation in many legumes is restricted by soil biophysical factors, combinations of legume rotations and mineral N fertilization will remain the most viable option for sustainable agriculture.

Legume materials used by farmers in agroforestry systems in southern Africa are often in the form of litter with low N, and high C:N ratios, following a long dry season between the rainfall seasons. The decomposition of *Sesbania* and *Acacia* litter was investigated in the field using litterbags, and N mineralization of a range of legume materials using leaching tubes in the laboratory (Chapter 7). For the field litterbag decomposition experiment, the course of the decomposition could be adequately described by the function: $Y = (Y_0\text{-}Q)e^{-kt} + Q$, where Q was the proportion of the recalcitrant material. Using this function, the relative decomposition constants for *Sesbania* and *Acacia* litters were determined to be 0.053 and 0.039 d^{-1}, respectively. Under laboratory incubation conditions, N mineralized from fresh *Sesbania* prunings was 55% after 120 days compared with only 27% for the *Sesbania* litter. 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 of the *Acacia* prunings (4.8 %) and litter (1.5 %), the total mineralized N was similar, as mineralization from fresh prunings was depressed by the high protein binding capacity of its polyphenols. Except for *Sesbania* litter, the rest of the senesced legume materials showed N immobilization up to 60 days.

The study showed that *Sesbania, Acacia* and *Cajanus* produced useful amounts of biomass on soils of at least loamy texture and that they improved N cycling significantly, but growth was poor in lighter soils. In light sandy soils mucuna grew well but has the disadvantage of having no direct food value. Gaseous N losses after incorporating legume materials were small, and the reduction of nitrate leaching is the single largest challenge to increased N recovery in the highly porous soils.

Samenvatting

Stikstofstromen in agroforestry systemen in het sub-humide Zimbabwe: een poging tot een integrale studie

Regis Chikowo

Traditionele zwerflandbouwsystemen in Zimbabwe gebruiken de gedurende de braakperiode opgebouwde organische stof om nutriënten te leveren aan toekomstige gewassen waarbij overigens weinig hulpbronnen worden gebruikt. De huidige omstandigheden vereisen dat voedselproduktie gestabiliseerd wordt door middel van bemesting, tussenteelt en kortdurende verbeterde braak-graan rotaties.

Twee jaar durende 'verbeterde braakperiodes' met de leguminosen *Sesbania sesban, Acacia angustissima* en *Cajanus cajan* werden onderzocht met betrekking tot de nalevering van stikstof (N) aan twee erop volgende maisgewassen na minimum- (handgemaakte plantgaten) en gangbare- (ploegen) grondbewerking (Hoofdstuk 2). Een mais monocultuur en een koeieboon-mais-mais opeenvolging vormden de controlebehandelingen. De vastlegging van moleculaire stikstof (N_2) door de leguminosen werd bepaald door gebruik te maken van de ^{15}N methode. Daardoor kon de stikstofaccumulatie tijdens de braakperiodes opgedeeld worden in biologische N_2-vastlegging en in stikstof die in minerale vorm opgenomen werd uit de bodem. Het aandeel van gefixeerde N_2 in gewasmateriaal bedroeg respectievelijk 56, 55, 84 en 58 % voor *Acacia, Sesbania*, *Cajanus,* en koeieboon, hetgeen overeenkomt met een bijdrage van biologisch gefixeerde stikstof van 122, 84, 97 en 28 kg ha^{-1}. Maisgroei in de twee seizoenen na de leguminosen was meestal niet direct gerelateerd aan deze stikstofhoeveelheden. Dit werd in het eerste jaar veroorzaakt door een sterke infectie met Aardrups (*Agrotis* sp.) in de voormalige *Sesbania* en *Acacia* velden, terwijl de mais in het tweede seizoen beïnvloed werd door droogte. Dit was vooral het geval in de *Acacia* velden waar veel bodemvocht werd onttrokken vanwege de hergroei van bomen. Gedurende het tweede seizoen was de N opname door mais na *Sesbania* significant hoger dan in de overige behandelingen. Gangbare grondbewerking leidde voor alle behandelingen en voor beide seizoenen tot betere opbrengsten dan minimum grondbewerking.

Anorganische bodemstikstofprofielen werden aan het einde van de braakperiode en gedurende de teelt van mais om de twee weken bepaald in bodemmonsters van lagen van 0,2 m dikte tot een diepte van 1,2 m. De monsters werden door middel van een grondboor genomen (Hoofdstuk 3 en 4). Lachgasfluxen (N_2O) werden in dezelfde velden en op de dezelfde momenten bepaald met behulp van gesloten fluxkamers. Bij aanvang van het seizoen bedroeg de hoeveelheid ammoniumstikstof (NH_4^+-N) meer dan 12 kg N ha^{-1} in de 0-0,2 m laag voor de behandelingen die een dikke strooisellaag hadden. Nitraatstikstofhoeveelheden (NO_3^--N) op dieptes van meer dan 0,6 m bedroegen minder dan 3 kg N ha^{-1} $laag^{-1}$ voor *Sesbania, Acacia, Cajanus* en natuurlijk bos, terwijl in de controlevelden, waar elk jaar mais geteeld was, de stikstofhoeveelheid meer dan 10 kg N ha^{-1} laag $^{-1}$ bedroeg. In de *Sesbania* en *Acacia* velden werd een plotselinge toename van NO_3^--N geconstateerd bij de eerste regenbuien, en in de bovenste bodemlaag was deze hoeveelheid toegenomen tot meer dan 29 kg N ha^{-1} toen het maisgewas werd geplant. De toegenomen hoeveelheid NO_3^--N in de bovengrond nam echter binnen drie weken na het planten van mais weer af tot 8,6 kg N ha^{-1} en 11,2 kg N ha^{-1} voor respectievelijk de *Sesbania* en de *Acacia* velden. De totale NO_3^--N uitspoelingsverliezen uit de bovenste 0,4 m dikke bodemlaag bedroegen 29 tot 40 kg ha^{-1} voor de *Sesbania* en *Acacia* velden nadat er in twee weken tijd 104 mm regen viel op de bodem die al op veldcapaciteit was. Onder deze 0,4 m dikke laag nam de hoeveelheid nitraat toe gedurende het vroege seizoen waarin de mais nog niet voldoende wortellengte had ontwikkeld om effectief nutriënten op te nemen.

Eén week na het planten van mais waren de N_2O fluxen uit de *Sesbania* velden (12,3 g N_2O-N ha^{-1} dag^{-1}) ongeveer twee keer zo hoog als die uit de *Acacia* velden, en ongeveer zeven keer zo hoog als die uit de mais monocultuur velden (1,6 g N_2O-N ha^{-1} dag^{-1}). Dit viel samen met de piek van de anorganische stikstof in de bovengrond. De niet bemeste mais had altijd lage N_2O emissies, namelijk minder dan 2 g N_2O-N ha^{-1} dag^{-1}, voor alle acht de bemonsteringsdata. De afname van de anorganische stikstofconcentratie in de bovengrond had kleinere N_2O fluxen tot gevolg, ondanks de zeer hoge bodemvochtgehaltes. De grootste N_2O-N emissies werden gemeten in de *Sesbania* velden met waardes van 0,3 kg ha^{-1} over 56 dagen. Het blijkt dat in het geval van hoge regenval het onvermijdelijke probleem optreedt dat anorganische stikstof, afkomstig van mineralisatie van organisch materiaal, bij het begin van de regenbuien accumuleert en gevoelig is voor uitspoeling voordat het wortelsysteem van het gewas zich ontwikkelt.

Onderzoek aan verbeterde braak heeft zich voornamelijk gericht op de voordelen voor de bodemvruchtbaarheid, terwijl de mogelijke voordelen voor bodem- en waterconservering werden verwaarloosd. De effecten van verbeterde braak op de verdeling van regenwater over de bodem en de hiermee samenhangende grondverliezen werden daarom onderzocht met behulp van een regenvalsimulator (Hoofdstuk 5). De gebruikte regenintensiteit bedroeg 35 mm h^{-1}. Na het verwijderen van de begroeiïng van de verbeterde braak waren de infiltratiesnelheden groter dan de toegepaste regenintensiteit voor de *Acacia* en de natuurlijke braakbehandelingen. In de *Sesbania* en de mais monocultuurbehandelingen bedroegen de infiltratiesnelheden respectievelijk 24 en 5 mm h^{-1}. De geschatte afstromingsverliezen na 30 minuten regen bedroegen 44% bij de mais monocultuur en 22% bij de *Sesbania* velden. De afstroming was nihil bij de velden van *Acacia* en de natuurlijke braak. De afnamecoëfficiënten van de infiltratiesnelheden bedroegen 36 en 10 mm voor respectievelijk *Sesbania* en de mais monocultuur. Na één gewas ná de braakperiode bedroeg de waterinfiltratiesnelheid in het geval van de *Acacia* velden nog steeds meer dan 35 mm h^{-1}, terwijl voor de *Sesbania* en de mais monocultuur de infiltratiesnelheden respectievelijk 8 en 5 mm h^{-1} bedroegen. De afstromingsverliezen na 30 minuten, berekend als gemiddelde over de wel en niet (minimum grondbewerking) geploegde velden, namen toe tot 30% in het geval van de *Sesbania* velden en tot 57% in het geval van de mais monocultuurvelden. Geconcludeerd kan worden dat met bomen aangeplant braakland aanvankelijk de waterinfiltratiesnelheid doet toenemen en de afstroming doet afnemen, maar dat deze effecten sterk afnemen na het eerste jaar van maisteelt na het verwijderen van de bomen, die niet dan niet meer opnieuw uitlopen.

Teneinde verschillende bodemvruchtbaarheidverbeterende maatregelen te evalueren werd ook een veldexperiment gedaan gedurende twee seizoenen op een arme, groffe zandgrond (Hoofdstuk 6). Behandelingen omvatten (1) mucuna groenbemester (*Mucuna pruriens*) gevolgd door mais, (2) een jaar *Cajanus* gevolgd door mais, (3) een jaar *Crotalaria* *paulina* gevolgd door mais, (4) sojaboon (*Glycine max*) gevolgd door mais, (5) in beide seizoenen mais met alleen in het eerste seizoen dierlijke mest, en (6) in beide seizoenen mais met en zonder anorganische bemesting. Sojaboon nam 82 kg ha^{-1} N op, waarvan 54 kg in het geoogste zaad, terwijl mucuna 87 kg ha^{-1} N in de biomassa accumuleerde, hetgeen geheel in de bodem werd ondergewerkt. Sojaboon verkreeg zijn stikstof voor 76% via biologische vastlegging, terwijl mucuna 96% vastlegde via dit proces, zoals vastgesteld met behulp van de ^{15}N methodiek. *Cajanus* en *Crotalaria* namen daarentegen nauwelijks 10 kg ha^{-1} N op en hadden geen effect op de stikstofopname van mais in het volgende seizoen. De geschatte opname van de gegeven stikstof door mais was 47 % voor de anorganisch bemeste mais, 36 % voor sojaboon, 12 % voor mucuna en 9 % voor dierlijke mest. Ondanks de grote verschillen in de hoeveelheid aan de bodem toegevoegde stikstof via mucuna en sojaboon waren verschillen in anorganische bodemstikstof slechts merkbaar tot vier weken na het begin van de regens. Daarna werden anorganische stikstofconcentraties in alle behandelingen erg laag vooral vanwege stikstofuitspoeling en niet zozeer vanwege N-opname door het gewas. De conclusie is dat de voor mais beschikbare hoeveelheid anorganische stikstof afkomstig van de onderzochte gewasresten niet genoeg is om blijvend hoge maisopbrengsten te bewerkstelligen. Onder deze omstandigheden, waar biomassa-accumulatie voor veel leguminosen wordt beperkt door bodembiofysische factoren, zullen combinaties van leguminose-rotaties en anorganische stikstofbemesting de beste mogelijkheid bieden voor een duurzame landbouw.

Gewasmateriaal afkomstig van leguminosen zoals dat gebruikt wordt door boeren in agroforestry systemen in zuidelijk Afrika heeft, na een lang droog seizoen tussen de regenvalseizoenen, veelal lage N-gehaltes en hoge C:N verhoudingen. De afbraak van strooisel van *Sesbania* en *Acacia* werd in het veld onderzocht door gebruik te maken van strooiselzakjes (Hoofdstuk 7). Het verloop van de strooiselafbraak kon afdoende worden beschreven met de functie $Y = (Y_0 - Q)\, e^{-kt} + Q$, waarin Q het aandeel recalcitrant materiaal voorstelt. De met deze functie berekende relatieve afbraakconstantes (k) in de strooiselzakjes in het veld voor *Sesbania* en *Acacia* bedroegen respectievelijk 0,053 en 0,039 d^{-1}. Daarnaast werd stikstofmineralisatie onderzocht voor een serie leguminosematerialen door middel van uitspoelingskolommen in het laboratorium (Hoofdstuk 7). Het bleek dat stikstofmineralisatie van vers *Sesbania* snoeisel (blad en kleine takjes) 55% bedroeg na 120 dagen, terwijl dat van *Sesbania* strooisel (blad en kleine takjes van tenminste een jaar oud) slechts 27% was. Gedurende dezelfde periode mineraliseerde er slechts 12% van de door *Acacia* opgenomen N uit vers snoeisel en 9% uit *Acacia* strooisel. Ondanks de grote verschillen in stikstofconcentratie in het *Acacia* snoeisel en strooisel was de totale hoeveelheid gemineraliseerde N hetzelfde, omdat de mineralisatie van het verse snoeisel onderdrukt werd door de hoge eiwitbindingscapaciteit van de aanwezige polyfenolen. Stikstofimmobilisatie trad op tot zo'n 60 dagen bij alle leguminosestrooisels, behalve bij dat van *Sesbania*.

Deze studie laat zien dat *Sesbania, Acacia* en *Cajanus* bruikbare hoeveelheden biomassa opbouwden op bodems die tenminste een leemachtige textuur hadden, en dat deze gewassen de stikstofstromen behoorlijk stimuleerden, maar ook dat dit niet geldt voor lichtere gronden. Op lichte zandgronden groeide mucuna weliswaar goed, maar dat gewas heeft als nadeel dat het geen directe voedingswaarde heeft. Gasvormige stikstofverliezen na inwerken van leguminosemateriaal waren klein. Eigenlijk is het verminderen van nitraatuitspoeling de grootste uitdaging om de stikstofopname in deze zeer poreuze gronden te verhogen.

Curriculum vitae

Regis Chikowo was born in Rusape, Zimbabwe on 22nd December 1969. After high school, he was admitted to the University of Zimbabwe where he studied for a Bachelor of Science Honours degree in Agricultural Sciences with specialization in Soil Science, from 1991 to 1994. After his first degree, he worked as a high school Chemistry teacher for one year. In 1996 he was awarded a Rockefeller Foundation grant to study soil fertility management options for improved groundnut production in the smallholder farms in Zimbabwe. He worked with Prof. F. Tagwira, based at Africa University, in the eastern Zimbabwean town of Mutare. This research led to the completion of a Master of Philosophy (MPhil) degree in 1998. During the time he was studying for his masters degree, he was also involved in the Soil Fertility Network, a grouping of soil scientists and agronomists in southern Africa coordinated by CIMMYT, that focuses on soil fertility research in maize-based smallholder farming systems. The initial encounter with the man that was later to be his main mentor (Prof dr Ken Giller) was during this time. In 1999 he briefly worked as a Teaching assistant, and then as a Research assistant in the Soil Science Department of the University of Zimbabwe. In October 2000, he began working towards a PhD degree under the supervision of Prof K.E. Giller and Dr P. Mapfumo. He carried out field experiments in Zimbabwe and laboratory incubation experiments and the write-up of this thesis in Wageningen University.

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This research was part of the IMPALA project funded by the European Union (Project No. ICA4-CT 2000-30011), and a grant from the Rockefeller Foundation. The research was conducted at the University of Zimbabwe, and the Graduate School Production Ecology & Resource Conservation, Wageningen University