Abstract

Röing, K. 2005. Soil Nitrogen Fluxes in Swedish and Nigerian Agricultural Systems. Doctoral thesis. ISSN 1652-6880, ISBN 91-576-6956-2.

The aim of this thesis was to study selected processes of N fluxes in Swedish and Nigerian agricultural systems and relate them to the use of mineral and organic amendments and other agricultural management practices.

Long-term effects of crop rotation, crop residue treatment and mineral fertiliser application levels on topsoil carbon (C), plant N uptake, net N mineralisation and soil organic matter fractions in temperate soils were investigated using soils from Swedish long-term agricultural field experiments (16-40 years). Topsoil carbon (C) was measured and plant N uptake was estimated in a pot experiment using soils (0-30 cm) from six locations in Sweden: Fjärdingslöv, Lönnstorp, Lanna, Bjertorp, Högåsa and Röbäcksdalen. Topsoil C content was significantly affected by crop rotation (ley > cereals), although crop residue return had no significant effect. Plant N uptake was up to 50% higher in soils from crop rotations with long-term leys than cereals. Net N mineralisation and microbial respiration was measured in an incubation study using soils from four locations: Lönnstorp, Lanna, Bjertorp, Röbäcksdalen. Net N mineralisation was greater in soils from ley crop rotations. Crop residue return had no effect on net N mineralisation. Soils from two locations (Lönnstorp and Lanna) were size-density fractionated. Preliminary results indicate that an unexpectedly high fraction of soil C and N in the low-input soils was found in fine fractions not associated with minerals.

Abundance and mobilisation of non-exchangeable ammonium (NEA) in soils (0-30 cm) from five locations of the long-term experiments in Sweden was estimated. NEA contents in these Swedish soils ranged from 20-200 ppm and increased with clay content. NEA content decreased over 168 days by up to 60% during a pot experiment where ryegrass was grown, suggesting that NEA partly can become plant-available during the cropping season.

The potential for *in situ* produced legume organic matter (OM) was tested in a dry season legume fallow rotation in a field experiment in Ibadan, Nigeria. Five legumes (*Pueraria phaseoloides, Vigna unguiculata, Glycine max, Mucuna pruriens and Cajanus cajan*) were evaluated in terms of dry season biomass production, effect on following maize crop and fertiliser yield increase. Biomass production ranged from 1000-8300 kg ha^{-1}, which was generally greater than that of the natural fallow. Maize yields, which ranged between 1000-2600 kg ha^{-1}, increased with 10-35% after addition of the *in situ* produced legume OM. Depending on legume placement (early incorporation, surface application and late incorporation) maize grain yield increased with up to 25 kg for every kg of fertiliser added.

N_2O fluxes were measured *in situ* in a legume-maize crop rotation in a field trial in Ibadan, Nigeria, where OM was incorporated prior to maize planting. Fluxes were measured during two rainy seasons and one dry season. Fluxes up to 138 μg m^{-2} h^{-1} were observed. Annual N_2O-related N losses were estimated to be up to 8 kg N ha^{-1}.

The results presented here indicate that farmer management decisions, be it in Sweden or Nigeria, can significantly affect N fluxes, which will in turn affect long-term agricultural and environmental sustainability.

Key words: long-term field experiments, N mineralisation, non-exchangeable ammonium, tropical cropping systems, Africa, N_2O

Author's address: Kristina Röing, Department of Soil Sciences, SLU, Box 7014, SE-750 07 Uppsala, Sweden. E-mail: Kristina.Roing@mv.slu.se

“Doubt is not a pleasant condition, but certainty is absurd”

Voltaire (François Marie Arouet) 1694-1778

Contents

The papers in this thesis are based on data collected by Kristina Röing, at several occasions, in several locations. Jan Persson, Gyula Simàn, Lennart Mattsson, Jakob Magid and Bernard Vanlauwe were the driving forces in planning this investigation and for defining its general aim. Kristina Röing was responsible for carrying out this investigation, with support from Olof Andrén, Jakob Magid, Bernard Vanlauwe and Lennart Mattsson.

In Papers I and II, Kristina Röing was responsible for detailed planning, sampling and experimental work in Sweden. Kristina Röing was responsible for the statistical analysis, with the assistance of Ulf Olsson. The writing was performed by Kristina Röing, supported by Olof Andrén.

In Papers III and IV, Kristina Röing was responsible for detailed planning, sampling and experimental work in Nigeria. Kristina Röing was responsible for the statistical analysis, with the assistance of Ulf Olsson. The writing was performed by Kristina Röing, supported by Olof Andrén.

Preface

Papers I-IV

The thesis is based on the following papers, which are referred to by their Roman numerals:

I. Röing, K. Andrén, O. Mattsson, L. 2005. Long-term management effects on plant N uptake and top soil carbon levels in Swedish long-term field experiments – cereals and ley, crop residue treatment and fertiliser N application. *Acta Agriculturae Scandinavica*, 55(1), 16-22

II. Röing, K. Andrén, O. Mattsson, L. ”Non-exchangeable” ammonium in soils from Swedish long-term agricultural experiments – mobilisation and effects of fertiliser application. (Accepted in *Acta Agriculturae Scandinavica)*

III. Röing, K. Andrén, O, Diels, J. Abaidoo, R. Improved fallows in West African cropping systems – fertiliser yield increase in dry season legume-maize rotations. (Manuscript)

IV. Röing, K. Andrén, O. Boeckx, P. Diels, J. Abaidoo, R. N_2O fluxes in maize-legume cropping systems in Nigeria – effect of legume residue incorporation and fertiliser application. (Manuscript)

Paper I is reproduced here by permission of Taylor & Francis Group Ltd. UK.

Related paper

Röing, K. Goossens, A. Diels, J. Sanginga, N. Andrén, O. Vanlauwe, B. 2004. Initial nitrous oxide fluxes from a soil cropped with a maize-legume system in the derived savannah zone of Nigeria – effect of fertiliser and application of organic matter. West African Journal of Applied Ecology, 6, 47-54.

Introduction

About 40% of the world's population are involved in agricultural production (http://www.fao.org/waicent/portal/statistics_en.asp; 28 January 2005). In the developed world, cash-crop systems with high inputs are predominant, whereas subsistence farming, with little or no external inputs, dominates in the developing world. This thesis deals with aspects of agricultural systems in two very different countries, Sweden and Nigeria. Some contrasting facts about agriculture in these countries are presented in Table 1.

Table 1. *Some facts about agriculture in Sweden and in Nigeria in 2003* (http://www.fao.org/waicent/portal/statistics_en.asp)

Country	Sweden	Nigeria
Total area (10^6 ha)	44.9	92.4
Cultivated land (10^6 ha)	3.1	22.6
Population (10^6)	9	127
GNI per capita (US$)[1]	29 000	320
Life expectancy (yrs), men/women	78/83	51/52
Pop. involved in agr. prod.	1.3 %[2]	66 %
Main crops	Wheat, barley oats, ley	Maize, millet, yam, cassava
Yields (kg) per ha (cereals)	4500[2]	1000
Mineral fertiliser consumption (10^6 kg)[3]	880	166
Fertiliser use per ha (kg ha^{-1})[4]	284	7

[1] http://news.bbc.co.uk/1/hi/country_profiles/default.stm
[2] Jordbruksverket, 2004
[3] Total consumption of compound fertilisers
[4] Mineral fertilisers

Nitrogen (N) is critical for agriculture in general, where increased crop production demands a soil N delivery synchronised with plant demand. However, the focus differs significantly between Sweden and Nigeria. Whereas the developed world is facing environmental problems due to N surpluses (leaching, eutrophication, volatilisation), the developing world is facing problems of declining soil fertility. Both worlds, however, contribute to the greenhouse gas (GHG) problem (N_2O, CO_2, CH_4).

The amount of N that a soil can mineralise, i.e. transform organically bound N to mineral N, is one limiting factor in agricultural production. The actual N mineralisation rate, as well as its synchrony with plant demands, is also crucial for the reduction of N losses to the environment. The combined use of mineral resources, including mineral fertilisers, and organic amendments, such as crop residues and farmyard manure (FYM), has long been known to affect topsoil C contents, soil N mineralisation and agricultural production.

There are many factors that affect N transformation in soil, some of which have been little studied. For example, the long-term effects of various cropping systems on soil C and N mineralisation in Sweden are far from completely understood. Improving our knowledge based on these long-term aspects is necessary for predicting future resource needs as well as for sustainable land use.

It is generally recognised that soil fertility in West Africa is declining. As annual nutrient losses can be as high as 60 kg NPK ha^{-1} year^{-1} (FAO, 2001), mainly due to erosion, the focus is on improving soil fertility in these cropping systems.

For a farmer, the ability to estimate and manipulate the N pools and N fluxes in a given soil allows more efficient use of the available resources. Consequently, knowledge about soil N fluxes is necessary for long-term agricultural and environmental sustainability, both in Sweden and Nigeria.

Objectives

The overall aim of my thesis was to study N fluxes in temperate and tropical climates and relate them to agricultural productivity. The thesis has three major themes. Each of these themes could warrant a thesis on its own. To describe and compare them in full detail would be to go beyond the scope of this thesis. The themes are:

Theme 1: Nitrogen (N) mineralisation and soil organic matter (SOM) in Swedish agricultural systems.
The main focus of this theme was the long-term effects of different management practises (crop rotations, mineral fertiliser N application and crop residue treatment) on topsoil carbon (C) concentration, N mineralisation capacity and the distribution of different fractions of SOM. The null hypothesis was that crop rotations with high organic matter input (leys, FYM etc) induce greater N mineralisation capacity and measurably different SOM fractions, which can be related to N mineralisation capacity.

Theme 2: Non-exchangeable ammonium in Swedish agricultural systems.
For the non-exchangeable ammonium (NEA) theme, the main objective was to study NEA in Swedish cropping systems. It has been suggested that NEA, a N fraction previously believed to be unavailable to plants, can actually be mobilised and taken up by plants during the cropping season (Mengel & Scherer, 1981; Scherer, 1993). As Swedish soils have long been known to have a high capacity to “fix” ammonium-N (Jansson, 1958), I investigated the extent to which selected Swedish soils contain NEA, and if that NEA could be mobilised.

Theme 3: N in maize legume crop rotations in Nigerian agricultural systems.
Most African tropical soils have low C and N contents (C% < 1%, N% < 0.1%), which are declining due to shortened fallow periods and the need to feed a growing population. The International Institute of Tropical Agriculture (IITA) has

developed a technology using N-fixing legumes together with cereal crops (maize, sorghum, millet) in rotation, which seems to restore soil fertility while providing farmers with legume grains and increased maize yields (Sanginga *et al.*, 2001). For my field experiment, the main objective was to test the effects of different OM management systems on N retention of dry season legume fallow crops. In addition, as greenhouse gas emissions are believed to increase as a result of increased agricultural productivity, particularly in tropical regions (Erickson & Keller, 1997), nitrous oxide (N_2O) emissions were measured in a field experiment in Nigeria. These emissions could also represent a substantial loss of N.

The specific objectives were to:

- estimate long-term effects of different Swedish cropping systems, crop residue management systems and mineral fertiliser application levels on N mineralisation capacity and topsoil C contents;
- measure C and N contents of different size-density fractions of soil organic matter (SOM) and correlate these with net N mineralisation in Swedish soils (only preliminary analysis of results available);
- measure soil contents of NEA in Swedish cropping systems;
- estimate mobilisation of NEA in Swedish cropping systems;
- study the effects of five dry-season fallow legumes and three organic matter (OM) management systems on the efficiency of added mineral fertiliser N in legume-maize crop rotations in Nigeria; and
- measure N_2O fluxes from soil under a maize crop in Nigeria where dry season legume OM had been incorporated at maize planting

Background

N transformation processes

The universal N cycle, which links the different N transformation processes, consists of three interdependent sub-cycles – the elemental cycle (E), the autotrophic cycle (A) and the heterotrophic cycle (H) (Figure 1).

The elemental cycle connects organically derived N with N in the atmosphere through the processes of denitrification and biological N_2-fixation. Denitrification, ($NO_3^- \rightarrow NO_2^- \rightarrow NO \rightarrow N_2O \rightarrow N_2$), where soil nitrate is transformed to N_2 by denitrifying bacteria, such as *Pseudomonas, Alcaligenes, Flavobacterium* and *Bacillus* spp., occurs under anaerobic conditions. In addition, *Rhizobium* spp. bacteria, which live in symbiosis with leguminous plants, also have the ability to denitrify NO_3^- to N_2O (Sahrawat & Keeney, 1986).

Biological N_2-fixation ($N_2 + 3\ H_2 \rightarrow 2\ NH_3$) is the result of symbiotic, non-symbiotic and associative symbiotic microbial activity. For example, symbiotic microorganisms, in central Sweden, can fix several hundred kilos of N per ha compared with 5-10 kg fixed by the non-symbiotic microbes (Andrén *et al.*, 1989).

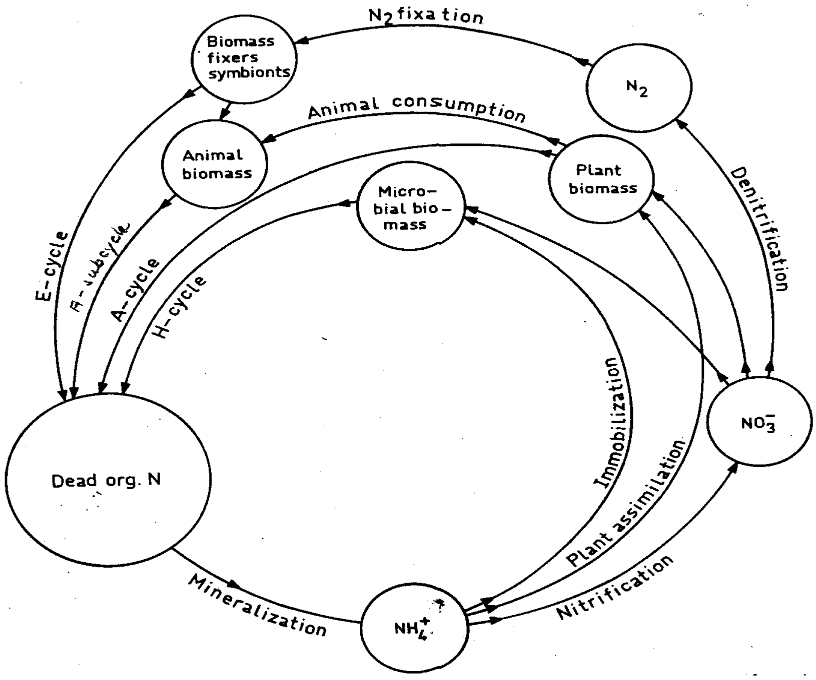

Figure 1. The universal N cycle (Jansson & Persson, 1982). E= the elemental cycle, A= the autotrophic cycle, H= the heterotrophic cycle.

The autotrophic sub-cycle converts organically bound N to NH_3 or NH_4^+ through the process of mineralisation, or ammonification. The converted N can be immobilised (converted back to organic forms through assimilation into microbial biomass) or further converted to nitrate, in a two-step process: first oxidation to nitrite, NO_2^- by bacterial species belonging to the genera *Nitrosomonas, Nitrosospira, Nitrosolubus*, after which *Nitrobacter* bacteria complete the oxidation to NO_3^- in a process that is described as nitrification. These bacteria are autotrophic, i.e. CO_2-C is their energy source, and they are limited by the supply of oxygen. Ammonia oxidation can also result in production of nitrous oxide, N_2O, through reduction of nitrite under certain conditions.

The heterotrophic sub-cycle is governed by the activities of microorganisms that obtain their energy and carbon from the breakdown of organic soil material. The main effect is again the conversion of organically bound N to NH_3 or NH_4^+ through mineralisation. Mineralisation in this form is influenced by pH, temperature and soil moisture. The mineralised NH_4^+ can be immobilised by soil microbial biomass, and used for further build-up of the microbial biomass, or further nitrified to NO_3^-. NH_4^+ is normally preferentially immobilised over NO_3^-, although the reverse can occur when NH_4^+ concentrations are low (Jansson, 1958; Recous *et al.*, 1990). The continuous transfer of mineralised N between the competing processes of mineralisation and immobilisation, has been referred to as MIT – the mineralisation-immobilization turnover (Jansson & Persson, 1982). The net effect (mineralisation or immobilisation) is the difference between the gross effects.

For agricultural production purposes, the more N a soil can provide for plant uptake, the better. However, soil N can become unavailable to plants due to several different processes. Denitrification, as previously mentioned, occurs under slightly anaerobic conditions, and involves the production of N_2 in several steps. Nitrous oxide, N_2O, a precursor to N_2 during denitrification, can also be produced, either through a process called chemodenitrification (where NO_2^- interacts with SOM) or after nitrification, when NH_4^+ is oxidised to NO_3^- under aerobic conditions in several steps (Smith *et al.*, 1990). One of these steps is nitrite, NO_2^-, and certain strains of nitrifying bacteria have the capacity to enzymatically reduce nitrite to N_2O (Bremner, 1997). Other gaseous losses include volatilisation of ammonia, which can occur when there is free NH_3 near the soil surface, which is often linked to the application of ammonia-containing inorganic and organic (FYM) fertilisers (Nelson, 1982). Soil N (mainly NO_3^-) can also be lost through leaching (Stevenson, 1982). In addition, ammonium can undergo substitution reactions with other cations and become fixed by clay minerals (Stevenson, 1982). This NH_4^+ pool is often referred to as fixed ammonium, or non-exchangeable ammonium (NEA).

In conclusion, N can be lost from soil through gaseous emissions (NH_3, N_2O, NO_x), leached as NO_3 and NH_4, immobilised for longer or shorter periods through plant and microbial growth or 'fixed' as NEA. The underlying concept behind N management is simply to minimise losses and synchronise mineral N delivery rates with crop demands, which holds true for Swedish as well as Nigerian agriculture.

Soil organic matter

Soil organic matter (SOM) contains approximately 5% N, which is mainly found in organic forms. Only about 1% of soil N is directly plant-available (NH_4^+ and NO_3^-). As N is paramount to agricultural production, soil N research during the last century has involved great efforts in finding methods that reliably predict N mineralisation. For reviews of this topic please refer to Powlson (1997) and Jarvis *et al.* (1996).

Soil C-to-N ratio has long been used as an approximate index for predicting N mineralisation. In search for better methods, several aspects of SOM have been considered. SOM, which is the substrate for N mineralisation, was early on divided into an 'active' and a 'passive' pool (Jansson, 1958). The concepts of 'active' and 'passive' SOM pools were later modified to include more or less well defined pools, such as 'metabolic', 'inert, 'microbial biomass', 'protected' etc. These pools have been assigned different turnover rates and C-to-N ratios (see e.g. Bosatta & Ågren, 1985; Cambardella & Elliot, 1992; Kätterer & Andrén, 2001).

In the quest for finding biologically meaningful pools, several methods for separating and quantifying SOM fractions have been attempted. Fractions have been separated by density (Hassink, 1994, Meijboom *et al.*, 1995, Golchin *et al.*,

1998) and by size and density in combination (Magid *et al*, 1996, Magid *et al.*, 1997, Hassink *et al.*, 1997). Differences between fractions have been linked to N mineralisation and management-related effects (Hassink, 1994). In general, the so-called light fraction is believed to be associated with relatively fresh plant residues, whereas the heavier fractions are older, and more resistant, organo-mineral complexes of SOM (Hassink, 1994).

Recently, measurable physiochemical aspects of SOM have been considered in a conceptual model presented by Six *et al.* (2002), where soil C is believed to occur as unprotected (light fraction and particulate organic matter), physically protected (micro-aggregates or associated with silt/clay), or biochemically protected. However, much work remains before the conceptual fractions (e.g. "protected") and the methods for separation (e.g. size-and-density) match perfectly. Until then, the understanding will be limited by the gap between concept and method.

Non-exchangeable ammonium

Although the presence of NEA has been known, or suspected, for several decades (Jansson, 1958), it is only more recently that research has focused on the potential availability of this fraction of soil N for plant uptake.

NEA refers to the fraction of soil N that is bound within clay minerals. It is now generally accepted that NEA is always found in clay minerals of the 2:1 type (Nömmik & Vathras, 1982; Young & Aldag, 1982; Scherer, 1993), where an octahedral Al-O-OH sheet lies in between two Si-O sheets. The negative charge of this lattice, which occurs due to isomorphous substitution of Al^{3+} and Si^{4+} by lower valence cations, has to be balanced by other cations, such as K^+, and NH_4^+. When the clay minerals are charge saturated with K^+ and NH_4^+, the crystal lattice collapses and "fixes", or traps, the ions in the inter-layers in between two adjacent tetrahedral layers (Figure 2).

It is the size of the cation that determines whether or not it will be fixed (Nömmik & Vathras, 1982). Oxygen ions, arranged in a hexagonal manner, occupy the space between the 2:1 minerals. The "hole" within the hexagon has an approximate diameter of 0.28 nm and cations with similar diameter, such as K^+ (0.166 nm) and NH_4^+ (0.186 nm), will be able to fit in between. The capacity of a mineral to fix ammonium is greatest in vermiculite, followed by illite (Nömmik & Vathras, 1982; Scherer, 1993), and is related to differences in isomorphous substitution in the tetrahedral and octahedral layers and the extent of K^+ fixation (Nömmik & Vathras, 1982).

As K^+ ions are of a similar size as the ammonium ion they have the potential to compete for the same binding sites. However, the effects of K^+ on NEA can vary depending on when it is added. Ammonium fixation seems to be depressed if K^+ is added prior to the ammonium, not affected if added after and depressed or increased if added simultaneously (Scherer, 1993).

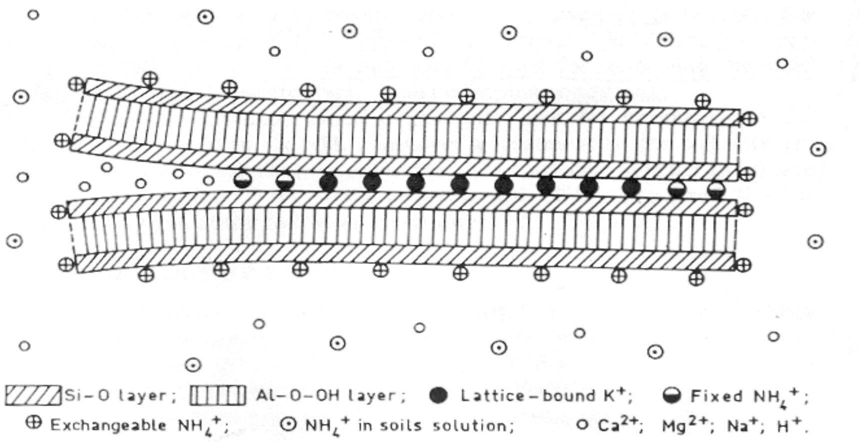

Figure 2. Schematic picture showing the different forms of NH_4^+ on illite (Nömmik & Vathras, 1982).

Several authors have reported that fixation of ammonium can occur rapidly, where a large proportion of the ammonium is fixed within a few days (Nömmik, 1957; Scherer, 1993). Some scientists differentiate between "native" NEA and "recently fixed" NEA. Native NEA is related to parent material while recently fixed NEA corresponds to that of NH_4^+ in soil solution, due to the addition of fertiliser or mineralisation of organic matter (Liu *et al.*, 1997).

The capacity of a soil to fix ammonium is normally estimated by treating a soil with a dilute NH_4^+-salt solution and then removing the easily exchangeable NH_4^+ with KCl. The difference between the amount of added ammonium and that recovered represents the amount fixed. However, this method does not take into account the amounts already present. Several extraction procedures based on the use of hydrofluoric acid (HF) have been developed to determine actual soil contents of NEA. The widely accepted method of Silva and Bremner (1966) involves the removal of exchangeable and organic matter N by treating the soil with KOBr, and washing it with KCl, after which the remaining mineral residue is dissolved with a HF-HCl solution and the liberated NH_4^+ is recovered by distillation after addition of KOH. Several improvements to this method have followed (Zhang & Scherer, 1998; Liang *et al.*, 1999) where the most recent involves a replacement of the acid digestion step with direct measurements of NEA content on an elemental analyser, after the removal of organic and exchangeable N.

As the availability of NH_4^+ in the soil solution affects the contents of exchangeable and non-exchangeable ammonium through ion diffusion, it has been suggested that all three forms of ammonium interact (Nömmik, 1957; Scherer, 1993), e.g.:

$$(NH_4^+{}_{\text{exchangeable}}) \leftrightarrow (NH_4^+{}_{\text{soil solution}}) \leftrightarrow (NH_4^+{}_{\text{non-exchangeable}})$$

Consequently it also follows that when ammonium concentration in the soil solution is low, NEA will diffuse out, or be mobilised. The mobilisation of NEA is dependent on the exchanging cations. The presence of cations in the soil solution that contract the clay minerals, such as K+, which are adsorbed at the edge of the minerals, decrease mobilisation, whereas the presence of ions that promote expansion of the minerals, such as Ca^{2+} and H^+, increases mobilisation. In addition, mobilisation is also promoted by wet conditions, which initiates hydration of the cations.

For NEA to be mobilised, the ammonium concentration in the soil solution must be low; a condition which can result from plant uptake of soil solution and exchangeable ammonium (Scherer, 1993; Scherer & Ahrens, 1997). Most NEA mobilised is considered to be released from the recently fixed pool (Scherer, 1993). There are reports of mobilisation of NEA-N contributing to as much as 11-85% of total plant N uptake (Scherer &Weimar, 1993) or up to 250 kg ha^{-1} yr^{-1} of NEA-N (Scherer, 1993). Seasonal variations in NEA mobilisation are common, and attributed to plant N uptake variations. For example, Mengel & Scherer (1981) report a decrease in NEA content during the beginning of the growing season, from February to March, followed by a slow replenishment of NEA to almost the initial values. This replenishment of the NEA pool at the end of the growing season can function as a way of reducing nitrification, thus also reducing leaching of nitrate.

Factors that affect mobilisation are similar to those that influence fixation: clay mineral composition, soil moisture and cation presence, especially K^+. In addition, it appears that mobilisation is also influenced by plant species (Scherer & Ahrens, 1996), root density (Mengel *et al.*, 1990) and availability of oxidizable organic material (Scherer & Werner, 1996).

The abundance of NEA in soils can range from 0 to more than 1000 ppm (Young & Aldag, 1982; Scherer, 1993) or to as much as 14% of total soil N (Scherer, 1993). NEA has received little attention in Sweden, despite the fact that soils generally have a high clay content (mostly illite) (Wiklander, 1976) and are considered to have a relatively high capacity to fix ammonium (Jansson & Eriksson, 1961; Jansson, 1958). In agronomic terms, a NEA content of 10 mg kg^{-1} in the topsoil layer (0-30 cm) would correspond to 38 kg N per hectare (dry bulk density ρ =1.25 kg dm^{3-}). The abundance and mobilisation of this N source in Swedish agricultural systems could have significant implications for efficient N resource use.

Legume-maize cropping systems in West Africa

It is generally recognised that soil fertility in West Africa is declining. Annual nutrient losses can be as high as 60 kg NPK ha^{-1} $year^{-}1$ (Figure 3) (FAO, 2001). Although data are not from completely overlapping areas, soil C and N contents in the savanna zone of Nigeria in 1975 were 1.1-1.2% C and 0.09-0.1% N (Singh &

Balasubramanian, 1980) compared to 0.6-0.9% C and 0.05-0.07% N in 2000 (Keatinge *et al*., 2001).

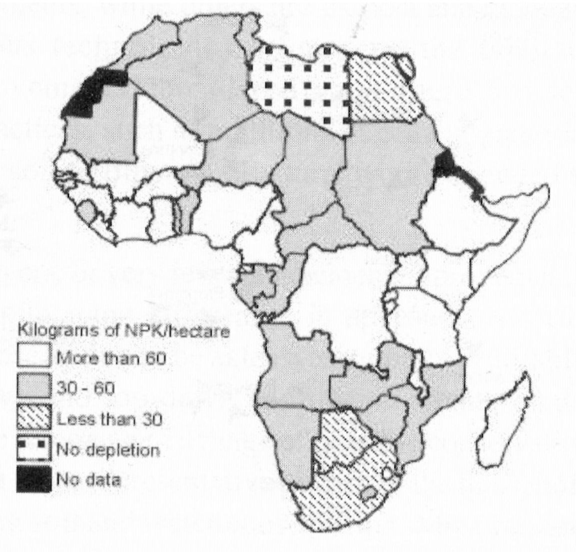

Figure 3. Annual nutrient depletion of NPK in Africa.

To overcome the declining soil fertility status in West Africa, efforts of major research organisations, such as the Consultative Group on International Agricultural Research (CGIAR), World Bank etc. should include promotion of systems where inorganic and organic resources are used in combination (Keatinge et al., 2001). The nutritive value of locally available organic inputs has been researched extensively (Giller & Cadish, 1995; Palm *et al*., 1997). A decision tree, aimed at assisting resource management, has been developed with regards to resource quality. In addition, a farmer-friendly version has been produced (Figure 4).

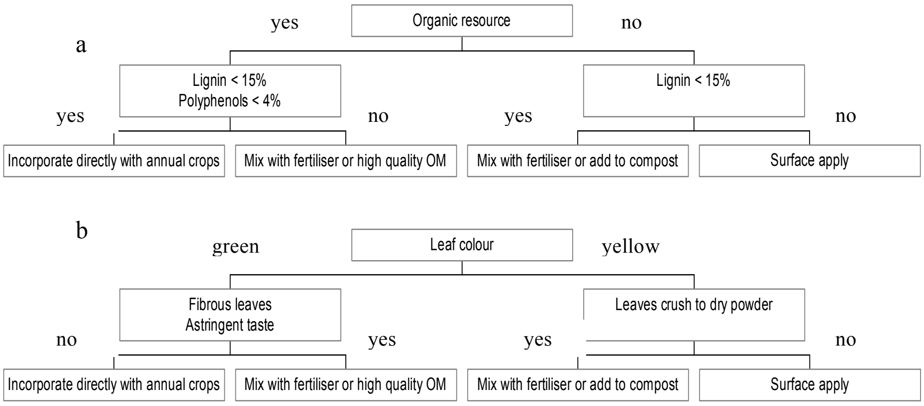

Figure 4. Organic resource management decision tree: a) initial version (modified after Palm *et al*., 1997, b) farmer-friendly version (modified after Giller, 2000).

The use of OM and N-fixing legumes in maize crop rotations has proven a viable option in West Africa. Positive effects on yields, believed to arise from increased synchrony between plant nutrient demand and availability, have been observed when adding organic matter (crop residues, manure) to the soil shortly before planting and then applying inorganic fertiliser (Vanlauwe *et al.*, 2002). Crop yield increases have been reported to be 200-400 % with the addition of OM (Vanlauwe *et al*, 2002) and N fertiliser replacement values between 50-120 kg ha^{-1} have been reported for different legumes (Tian *et al.*, 2000; Schulz *et al.*, 2001). In addition, legumes provide weed (Carsky *et al.*, 1998) and nematode suppressant effects (Bagayako *et al.*, 2000). Although legumes in the tropics can acquire up to 300 kg N ha^{-1} through biological N fixation (Sanginga *et al*, 2001; Tian *et al*, 2002, Carsky *et al*, 2001, Giller & Cadisch*,* 2001), only 10-30 % of the legume N is recovered in the following crop in such rotations and losses are attributed to erosion, leaching and gaseous emissions (Giller & Cadisch, 1995). However, we should not that not recovered in the crop does not equal loss, as parts of the N may enter the soil organic N pool.

Fallow legume and maize cultivars with different characteristics (grain yield, biomass yield, duration) have been developed and tested. For example, a dual-purpose variety of *Glycine max* (soybean) has been developed with high biomass production as well as high grain yield, and several disease resistant maize cultivars, with low N requirements, have been developed and are now used throughout the region.

Maize-legume crop rotations have been proven to be successful in increasing yields and profitability while restoring soil fertility and are being adopted by farmers, yet awareness of the problems with blanket recommendations for agricultural systems is increasing. At the International Institute of Tropical Agriculture, one of the 16 CGIAR research centres, research efforts are aimed at providing farmers with a “basket of options”, which includes combinations of short season/long season cultivars, disease and weed resistance, and OM management systems and fertiliser applications. Some constraints with the *ex situ* legume OM system have been recognized, such as the time and labour consuming ‘cut-and carry’ method and the problems with having sufficient OM available at the right time, as farmers struggle to preserve the crop residues throughout the dry season (Iwuafor *et a.l*, 2002). *In situ* production of legume OM could overcome a number of these constraints and provide additional benefits. As part of the overall goal of increasing sustainable food production in West Africa, the potential of the *in situ* OM production system needs to be assessed and optimised.

N_2O fluxes from tropical cropping systems

Gaseous N fluxes from tropical agricultural systems are receiving increasing attention not only due to the potential loss of plant available N, but also due to their impact on global warming. Climate change due to increased CO_2

concentrations, greenhouse gas emissions and a decreasing ozone layer has long been a global concern. The recent "Kyoto Protocol" deals with mitigating conventions related to carbon sequestration and climate change. The United Nations Framework Convention on Climate Change (UNFCCC) requires that inventories of anthropogenic emissions of greenhouse gases are updated regularly using common methodologies. The Intergovernmental Panel on Climate Change (IPCC) has been coordinating the methodology development.

Nitrous oxide, N_2O, which is one of the greenhouse gases (H_2O, CO_2, CH_4, O_3, CFCs and N_2O), is estimated to be 300 times as potent as CO_2, and has increased steadily in modern times (Table 2) (Grantham, 1989). The gas is a concern for several reasons; it absorbs thermal radiation in the troposphere and contributes to global warming; it contributes to the depletion of the ozone layer in the stratosphere ($N_2O \rightarrow NO + O_3 \rightarrow NO_2 + O_2$) (Mosier *et al.*, 1998) and is long lasting in the stratosphere (Grantham, 1989).

Table 2. *Some greenhouse gas properties*

	ppmv		Absorption per
Gas	1940	1989	mole relative to CO_2
CO_2	300	351	1
N_2O	0.29	0.31	296[1]
CH_4	1.0	1.7	23[1]
Tropospheric O_3	0.01	0.02	2000
CFCs	0	0.001	10000

Modified after Grantham, 1989.

[1] www.ipcc.ch, 100 year perspective.

N transformation processes involved in N_2O production are nitrification, denitrification, and chemodenitrification (Sahrawat & Keeney, 1986). Denitrification was previously believed to be the main source of N_2O emissions, but recent investigations have shown that N_2O is produced in substantial amounts during the nitrification process (Bremner, 1997). As mentioned earlier, there are several strains of nitrifying hetero- and autotrophic bacteria that can produce N_2O. The autotroph *Nitrosomonas europaea* is the most well known. Other examples of heterotrophs are *Bacillus subtilis*, *Escherichia coli, Aspergillus flavus* and *Penicillum atrovenetum* (Sahrawat & Keeney, 1986; Bremner, 1997). Nitrification and N_2O production increases with soil pH, (dissolved) organic matter content, soil moisture content, soil temperature, and availability of nitrifiable forms of mineral (fertiliser) and organic N (plant residue, FYM) (Brady, 1990).

Denitrification is promoted by high soil moisture, neutral pH, high temperatures, and availability of nitrate and soluble organic matter (Saharawat & Keeney, 1986). Bacterial species involved are mainly from the genera *Pseudomonas, Bacillus* and *Paracoccus* (Bouwman, 1996). Although little is known about the significance, some other bacteria not involved in nitrification/denitrification also have the

ability to produce N_2O, of which *Rhizobium* spp. probably are the most important ones.
Methods for measuring N_2O fluxes include micrometeorological methods and open and closed chamber methods (IAEA, 1992). The micrometeorological method involves rapid measurements of vertical concentration gradients over a large area of land. In the chamber methods, N_2O fluxes are measured directly as concentration change over time. The chambers, which are placed over the soil in such a way that normal fluxes are unaffected, can either be fully closed, or vented. A brief introduction to the closed chamber method will be given here. For a description of the different measurement methods, see IAEA (1992).

The vented closed chamber system was designed to allow pressure equilibration in order to avoid alteration of atmospheric pressure at the soil surface (Hutchinson & Mosier, 1981). As concentration of N_2O in the chamber can accumulate to levels that reduce soil emission rates, short collection intervals are recommended. Temperature differences within and outside the chamber can be reduced by use of reflective materials or insulation of the chamber. It is recommended that gas samples, which are taken from the chamber using a syringe, are transferred to evacuated vials with rubber septa for storage (IAEA, 1992).

It is estimated that about 90% of global N_2O emissions come from soils (Bouwman, 1996) and that 20-50% of the emissions come from tropical soils (Davidson & Kingerlee, 1997). About 20-70% of anthropogenic N_2O emissions are estimated to come from agriculture (Mosier *et al*, 1998). As IPCC (Mosier *et al.*, 1998) have suggested that estimates of N_2O emissions have been underestimated, sources of this greenhouse gas have received increased attention (Mosier *et al.*, 1998). Previous estimates of N_2O emissions, which only included direct emissions from agricultural fields where mineral N fertiliser had been applied, were revised to include direct emissions from mineral and organic N sources (fertilisers, FYM, crop residues and biological fixation). Several studies now estimate that 1.25 ± 1.0 % of added N is lost as N_2O (Mosier *et al.*, 1998). Most of the information on N_2O fluxes comes from studies in temperate regions, and several authors have indicated the need for information on N_2O fluxes from tropical soils (Mosier *et al.*, 1998, Erickson & Keller, 1997). Fluxes have been reported to range from 1-2000 $\mu g\ N\ m^{-2}\ h^{-1}$ in tropical regions (Erickson & Keller, 1997; Dick *et al.*, 2001; Erickson & Keller, 1997; Weitz *et al.*, 2001)

In Africa, for example, the population pressure is forcing the conversion of forest land to agricultural production. Although several authors have suggested large increases in fluxes of N_2O following land use changes (Erickson & Keller, 1997), my work focuses on N_2O emissions from agricultural lands. For a discussion of N_2O emissions from soils, please refer to Mosier (1998).

The warm climate, soil moisture conditions and agricultural practises in the moist tropics are believed to stimulate N_2O production. Several studies have recognized the positive effect of temperature on nitrification and N_2O emissions (Breuer *et al.*, 2002). Rainfall patterns also influence N_2O emissions (Dick *et al.*, 2000; Weitz *et al.*, 2001, Nobre *et al.*, 2001; Khalil *et al.*, 2002, Breuer, 2002, ,). Although its is recognized that tillage regimes influence soil oxygen levels and porosity, the effects on N_2O emissions are ambiguous, as Baggs *et al.* (2003) found higher emissions from no-till systems compared with conventional tillage systems, whereas Choudhary *et al.* (2002) found no differences.

Although the use of fertilisers is limited in most developing countries in the tropics, application increases emissions (Baggs *et al.*, 2003, Khalil *et al.*, 2002, Nobre *et al.*, 2001). The use of organic amendments is however common, and organic matter quality, quantity and placement play an important role in the control of N_2O fluxes (Baggs *et al.*, 2003; Nobre *et al.*, 2001; Weitz *et al.*, 2001; Larsson *et al.*, 1998). Information on N_2O fluxes from systems where mineral fertilisers are combined with organic amendments in tropical systems is scarce, but based on temperate studies it has been suggested that the management practices can either increase or decrease emissions (Baggs *et al.*, 2002).

Sequestration of C in the soil has been recognized as having mitigating effects on climate change. Naturally, emission of greenhouse gases counteracts the effects of C sequestration. Any given system will therefore have to be analysed with respect to potential C accumulation versus potential greenhouse gas emission. More knowledge about N_2O emissions from tropical agricultural systems will facilitate mitigation of the negative effects on the environment, through manipulation of agricultural measures affecting N_2O-producing N transformations.

Materials and Methods

Swedish soils

Long-term field experiments in Sweden

Soils from eight locations and 22 treatments from four Swedish long-term field experimental series, initiated 1957-1981, were examined. The soils represent various long-term management features, such as crop rotation, crop residue treatment, inorganic N application levels and K application levels (Table 3). Agricultural productivity data are collected annually in all experimental series and soil characteristics are documented at least once per crop rotation.

Table 3. *Main management features of experimental series in Sweden*

Exp. series	R3-9001	R3-0020	R3-0021	R3-2037
Crop rotation[1]	Livestock Cash-crop	Cereals	Ley	Livestock
Crop residues	Removed Returned	Removed Returned	Removed	Removed
FYM	Yes	No	No	Yes
Inorganic N[2]	0-150	0-120	0-150	0-200
K[3]	0-80	replacement	replacement	0-80
Region	Southern Central	Southern Central Northern	Southern Central Northern	Northern

[1] Crop rotations are four to seven years, depending on experimental series and location. Crop rotations in experimental series R3-9001 and R3-2037 represent typical livestock (cereals and ley) and cash crop (cereals, root and tuber and oilseed crops) rotations of the respective regions.

[2] Average kg N ha^{-1} yr^{-}

[3] Kg K ha^{-1} yr^{-1}

The locations include a range of clay and organic matter contents and climatic conditions representative of Swedish soils (Figure 5).

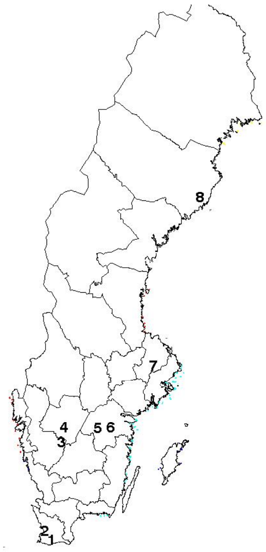

Figure 5. Locations and some soil characteristics. 1 = Fjärdingslöv (clay 14%, pH_{aq} 7.5, C 1.2-1.4 %), 2 = Lönnstorp (clay 25 %, pH_{aq}, C 1.3-1.7 %), 3 = Bjertorp (clay 30 %, pH_{aq} 6.4, C 1.8-2.1 %), 4 = Lanna (clay 36 %, pH_{aq} 6.5, C 1.8-2.3 %), 5 = Högåsa (clay 10 %, pH_{aq} 5.9, C 1.9-2.1 %), 6 = Vreta Kloster (clay 48%, pH_{aq} 6.7, C 2.1 %), 7 = Kungsängen (clay 56 %, pH_{aq} 7.1, C 2.1 %), 8 = Röbäcksdalen (clay 10%, pH_{aq} 6.5, C 1.7-2.5 %).

N mineralisation and soil organic matter in Swedish soils

Plant N uptake in a pot experiment (Paper I)

N mineralisation capacity was estimated in a pot experiment as N uptake by ryegrass (*Lolium perenne*). Topsoil samples (0-20 cm) were collected plot-wise in the spring of 1997 from R3-9001, R3-0020 and R3-0021 from six sites (Fjärdingslöv, Lönnstorp, Lanna, Bjertorp, Högåsa and Röbäcksdalen). Soils were collected from treatments that had received zero N and the highest inorganic N dose. Sub-samples were collected for analysis of total C and N. Soils were then passed through a 0.5 cm sieve and thoroughly mixed into composite samples of each experimental combination and then placed in Mitscherlich pots in three replications. Total number of pots was 90. Approximate replacement levels of P and K were applied. No inorganic N was applied. Ryegrass was then sown and harvested three times at 8-week intervals. Soil organic C and N, and aboveground plant N contents, were determined by dry combustion with a LECO CNS 2000 analyser.

‘Forced’ mineralisation incubation experiment

Net N mineralisation and microbial activity was measured in a ‘forced’ mineralisation experiment. Topsoil samples (0-20 cm), from treatments that had not received inorganic fertiliser, were collected plot-wise in the spring of 1998 from four experiments (R3-0020, R3-0021, R3-9001 and R3-2037) from four sites (Lönnstorp, Lanna, Bjertorp and Röbäcksdalen). Prior to the incubation study, the soils were freeze-milled and then wetted to 30-50% of their water holding capacity (WHC). One kilogram of each soil was incubated in 3-litre glass jars for three cycles of approximately three weeks at constant temperature (20ºC). To ensure augmented, or ‘forced’ mineralisation, the soils were passed through a 0.5 cm sieve prior to every cycle. Mineral N contents were analysed on sub-samples at the start of the experiment and at the end of every cycle. Microbial activity was measured as CO_2-evolution using CO_2-traps containing 0.5 M NaOH, which were titrated with HCl on day 2, 5, 10, 15 and 21 of every cycle.

SOM fractionation

In order to estimate long-term management effects on SOM fractions, soils from two long-term experiments at Lanna and Lönnstorp were fractionated in three replicates according to the conceptual framework developed by Six et al. (2002). Topsoil samples (0-20 cm), from treatments that had not received inorganic fertiliser, were collected plot-wise in the spring of 1998 from R3-0020 and R3-0021. Soil from this batch had previously been used in the ‘forced’ mineralisation incubation experiment.

This work was performed together with Professor Jakob Magid, at the Royal Veterinary and Agricultural University, Copenhagen, Denmark. Approximately 100 g FW of soil was used per replicate. Firstly the soil was dispersed in an end-over-end shaker (45 min., 30 rev. min^{-1}) using sodium hexametaphosphate (5 ‰

w/v), because, apart from facilitating dispersion, it also removes some complexed calcium ions that otherwise would form insoluble calcium polytungstate salts during the density separation. Thereafter, the soil was transferred to a set of sieves (1000 μm, 100 μm and 53 μm), and carefully washed with additional dispersal agent. The 4000-1000 μm and 1000-100 μm fractions were separated by density at normal gravity in three fractions. Firstly distilled water was added to the size separates and floating material ($\rho < 1.0$ g cm^{-3}) was transferred to a small sieve. Secondly a mixture of sodium polytungstate and water ($\rho = 1.85$ g cm^{-3}) was added to the remnant size separates. Upon repeated decantation of floating material ($\rho < 1.85$ g cm^{-3}) the heavier remaining material ($\rho > 1.85$ g cm^{-3}) was washed with distilled water on a sieve. Before further examination and analysis, the materials were dried (70 °C, 40 h). The 100-53 μm and the <53 μm fractions were separated at 10000 *g*, by centrifugation in a mixture of sodium polytungstate and water ($\rho = 1.85$ g cm^{-3}). The supernatant, containing material < 1.85 g cm^{-3} was filtered through a binder free glass fibre filter (Whatman, GFF) after the filter was washed with water. The pellet was washed by re-suspending in water and then centrifuged and dried (70 °C, 40 h).

All POM fractions were oven-dried at 70^{o}C for 24 hours. Dry samples were weighed, the material was ground, and analyzed for total C and N using an elemental analyser.

The procedure resulted in 10 fractions per replicate:

1. big (> 1 mm) and light ($\rho < 1.0$ g cm^{3-})
2. big (> 1 mm) and medium density (1.0 g cm^{3-}) < ρ < 1.85 g cm^{3-}))
3. big (> 1 mm) and heavy ($\rho > 1.85$ g cm^{3-}))
4. medium size (< 1 mm > 0.1 mm) and light ($\rho < 1.0$ g cm^{3-})
5. medium size (< 1 mm > 0.1 mm) and medium density (1.0 g cm^{3-} < ρ < 1.85 g cm^{3-})
6. medium size (< 1 mm > 0.1 mm) and heavy ($\rho > 1.85$ g cm^{3-})
7. small (< 0.1 mm > 0.056 mm) and medium density (1.0 g cm^{3-}< ρ < 1.85 g cm^{3-})
8. small (< 0.1 mm > 0.056 mm) and heavy ($\rho > 1.85$ g cm^{3-})
9. very small (< 0.056 mm) and medium density (1.0 g cm^{3-}< ρ < 1.85 g cm^{3-})
10. very small (< 0.056 mm) and heavy ($\rho > 1.85$ g cm^{3-})

Non-exchangeable ammonium in Swedish soils (Paper II)

For the measurements of abundance of NEA in Swedish soils, topsoil samples (0-20 cm) were collected plot-wise in the spring of 1997 from experimental series R3-9001 and R3-2037 from five locations (Fjärdingslöv, Bjertorp, Vreta Kloster, Kungsängen and Röbäcksdalen). Soils were collected from treatments that had received zero and the highest dose of K. Sub-samples were collected and analysed for a) AL-extractable and HCl-extractable K content, according to standardised methods at the laboratory at the Department of Soil Sciences, SLU. and b) NEA content, where sub-samples were passed through a 0.5 cm sieve, dried and then passed through a 0.125 µm sieve and analysed for N by dry combustion, according to the method of Liang *et al*. (1999), using a LECO CNS 2000 analyser.

Mobilisation of NEA was estimated in a pot experiment where ryegrass (*Lolium perenne*) was grown, using soils described previously. Plot-wise samples were passed through a 0.5 cm sieve, thoroughly mixed into composite samples of each experimental combination and then placed in Mitscherlich pots in three replications. Total number of pots was 102. Replacement levels of N and P were applied. No K was applied. Ryegrass was then sown, and harvested three times at 8-week intervals on day 56, 112 and 168 after planting. Soil core (Ø 1 cm) sub-samples were collected from the pots in conjunction with the ryegrass harvests. These samples were then dried, passed through a 0.125 µm sieve and analysed for NEA content by dry combustion, according to the method of Liang *et al.* (1999), using a LECO CNS 2000 analyser.

Nigerian soils

Field trial

A field trial was established at the International Institute of Tropical Agriculture (IITA), Ibadan, Nigeria (7°30′ N, 3°54′ E), on a Ferric Lixisol (FAO, 1991) in May 2000 and repeated in an adjacent site in May 2001 (Figure 6).

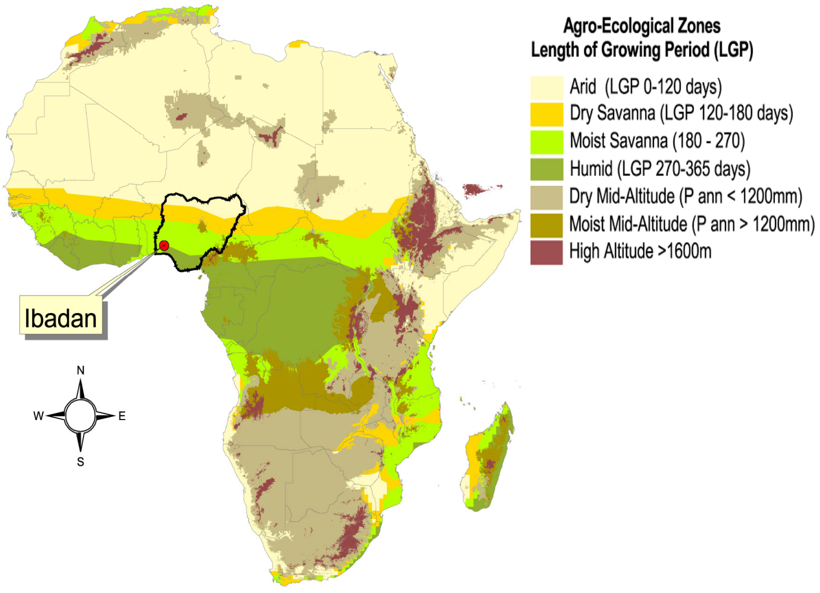

Figure 6. Location of field trial site at IITA in Ibadan, Nigeria. P= precipitation. Source: IITA.

The region is characterised by a mean annual rainfall of 1200 mm, distributed bi-modally, with a dry season from November to March (Figure 7).

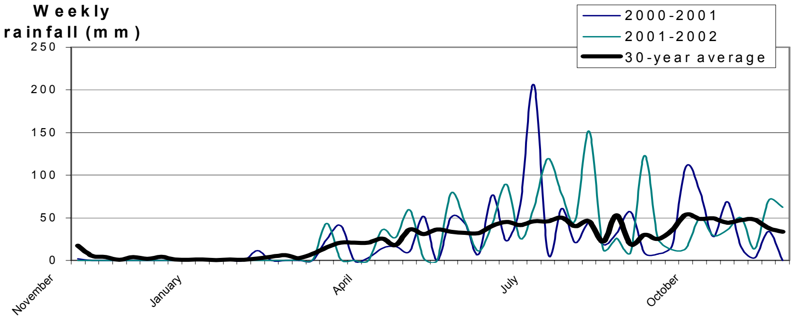

Figure 7. Measured weekly rainfall during the two seasons, and 30-year average.

Prior to trial establishment, the land had been fallowed for two and three years, respectively, before which it had been used for seed production. Topsoil (0-30 cm) was sampled prior to establishment and analysed for baseline soil data (Table 4) according to IITA laboratory procedures.

Table 4. *Some topsoil characteristics of the experimental site in Ibadan, Nigeria*

pH_{aq}	C^1 (%)	N^2 (%)	P^3 (ppm)	$ECEC^4$ cmol kg^{-1})
5.6 (0.2)	0.75 (0.03)	0.1 (0.02)	31 (3)	4.7 (0.3)

Numbers in brackets indicate standard errors of the mean. Values are presented as averages of the 2000 and 2001 baseline soil data sampling from the two adjacent sites.

[1] Chromic acid digestion (Heanes, 1984).

[2] Kjeldahl-N (Bremner & Mulvaney, 1982)

[3] Mehlich 3 extraction (Mehlich, 1984).

[4] Anderson & Ingram, 1993.

Five legumes were investigated in this trial; *Glycine max, Vigna unguiculata, Cajanus cajan, Mucuna pruriens, Pueraria phaseoloides.* Natural fallow, mainly consisting of ‘Guinea grass’, (*Panicum maximum)*, was used as a control. The legumes were selected on the basis of their potential as improved dry season fallows, and biomass production, drought tolerance and grain yield were considered. Main features of the legumes are given in Table 5.

Table 5. *Main features of legumes*

Legume	Common name	Type	Dry season duration[1]	Cropping systems
G. max	Soyabean	Grain	Short	Dual purpose[2]
V. unguiculata	Cowpea	Grain	Short	Dual purpose [2]
M. pruriens		Herbaceous	Medium	Cover crop[3]
P. phaseoloides		Herbaceous	Long	Cover crop[3]
C. cajan	Pigeon pea	Herbaceous	Long	

[1] Drought tolerance, e.g. ability to grow during the dry season.
[2] Biomass and grain production.
[3] Cover crops are mainly used for their weed suppressant effects.

Pictures of the different fallow crops are presented in Figure 8.

Figure 8. Pictures of a) *G. max* (Soyabean), b) *V. unguiculata* (Cowpea), c) *M. pruriens*, d) *P. phaseoloides*, e) *C. cajan* (Pigeon pea) and f) natural fallow. Photo: K. Röing.

The trial was designed in a split-split plot design, in three blocks, with the different legumes species as main plots, three residue treatments (early incorporation, early mulching, late incorporation) and two levels of inorganic fertiliser application (0 and 45 kg urea-N ha^{-1}) as split and split-split plots, respectively. Total number of plots was 108.

The first maize crop, which established a common baseline, was planted manually in May 2000 (0.75 m between rows, and 0.25 m between plants in rows). The legumes were then relay-cropped in between the maize, on plots of 8 x 9 m (net plot size 5 x 6.25 m.) The first maize crop was harvested manually at the end of the cropping season. Early incorporation and early mulching of legume residues occurred at legume maturity, which differed between the species. Legumes were slashed, using the traditional cutlass, and where applicable, incorporated manually using the traditional hoe. Late incorporation of legume residues occurred before planting of the second maize crop, in the beginning of the following wet season, in the same way as the early incorporation. Urea, which is the most commonly used mineral fertiliser in the region, was applied by broadcasting to the second maize crop at time of planting (15 kg urea-N ha^{-1}), and four weeks thereafter (30 kg urea-N ha^{-1}), where applicable. A schematic presentation of activities is given in Figure 9.

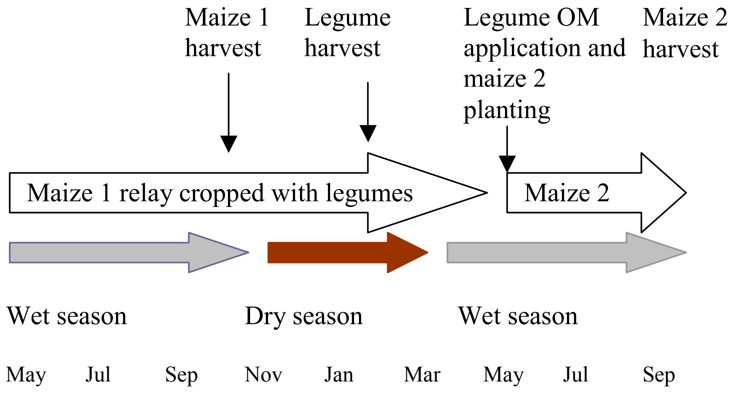

Figure 9. Schematic presentation of activities.

The two maize crops and the legumes were manually weeded on a regular basis. The second maize crop was harvested manually at the end of the wet season. Soils (0-30 cm) and biomass (legume and second maize crop) were sampled on a monthly basis.

Fertiliser yield increase in maize-legume rotations in Nigeria (Paper III)

Fertiliser yield increase (FYI) was established experimentally in maize comparing the effects of adding *P. phaseoloides*, *M. pruriens* and *C. cajan* organic matter (OM) in three different OM management systems (early and late incorporation, mulching). FYI was calculated as kg maize dry matter (DM) yield increase per kg of added fertiliser N. Maize grain and stover yields were determined by cutting biomass from a 2 x 2 m plot at harvest. DM yields were measured by drying samples at 60ºC and weighing them, after which samples were ground and also analysed for N content according to standard procedures at IITA.

Legume biomass yields were estimated on a monthly basis until legume application by cutting biomass from a 0.75 x 0.75 m quadrant per plot. Concurrently, the amount of litter, if present, was measured. The legume biomass was dried at 60º C and weighed to determine dry matter yields. Samples were then ground and sub-samples were analysed for N, lignin and polyphenol contents, according to IITA laboratory procedures (Anderson & Ingram, 1993).

N_2O fluxes in maize-legume systems in Nigeria (Paper IV)

Gaseous N_2O fluxes were measured during two wet seasons (June-September 2001, May-September 2002) and one dry season (March-June 2002) in treatments where *P. phaseoloides* OM was incorporated late. The treatment where fallow OM was incorporated late was used as a comparison.

For the wet season N_2O dynamics, gaseous N_2O fluxes were measured 1, 3, 5, 8 and 15 days after maize planting and incorporation of the fallow and legume OM, and then every four weeks until maize harvest. A vented closed chamber system (Hutchinson & Mosier, 1981), with two replicates per plot, was used. A picture of the set-up is presented in Figure 10.

Figure 10. Picture of vented closed chamber system. Next to the chamber a thermometer is inserted into the soil. Photo: K. Röing.

Sampling of N_2O fluxes started at 9 a.m. every sampling day. The chambers were inserted 5 cm into the soil, and gas samples were taken at time 0 (background), 30 and 60 min. Gas samples were analysed for N_2O concentration on a Shimadzu 14B ECD gas chromatograph fitted with an electron capture detector. Fluxes were estimated as changes in N_2O-N concentration over time. Soil and air temperature was measured at every sampling occasion.

For the dry season N_2O dynamics, gaseous N_2O fluxes were measured 1, 3, 5, 8 and 15 days after incorporation of OM, and then every four weeks until maize planting in June. Soil and air temperature was measured at every sampling occasion.

Legume biomass yields were measured on a monthly basis until legume application by cutting biomass from a 0.75 x 0.75 m quadrant per plot. When present, the amount of litter was measured. Legume biomass was weighed, and dried at 60º C and then weighed again to determine dry matter yields. Samples were then ground and sub-samples were analysed for N, lignin and polyphenol contents, according to IITA laboratory procedures (Anderson & Ingram, 1993).

From each plot, three soil samples were collected from the 0-30 cm, 30-60 cm and 60-90 cm layer, using soil cores (Ø 2 cm), giving 9 replicates per treatment combination. These samples were then analysed for mineral N and soil moisture contents according to IITA laboratory procedures (Kalra & Maynard, 1991; Anderson & Ingram, 1993). These samples were collected concurrently with the gas samples on day 0, day 15, day 28 and then every four weeks until maize harvest.

Results and discussion

N mineralisation, SOM and agricultural management

The results from the first study indicated that N mineralisation capacity, estimated as aboveground ryegrass N uptake in a pot experiment, was higher in soils from ley rotations than in soils from the cereal rotations. These observations are similar to those in other investigations (Jarvis *et al*., 1996). Leys, particularly at ley break, input high amounts of N-rich, high quality OM. This, in combination with less soil disturbance (less frequent ploughing) and more transpiration, results in SOM accumulation (Kätterer & Andrén, 1999), which is positively correlated with N mineralisation capacity (Jarvis *et al*., 1996). This accumulation is also reflected by the higher SOC concentrations observed in the ley rotations (Paper I).

Crop residue return (straw left in the field) had no significant effect on plant N uptake or SOC concentrations. Other studies have found the effects of crop residue return on SOC contents to be positive, negative or non-existent (Kätterer & Andrén, 1999).

Application of inorganic N tended to increase plant N uptake compared with soils where no N was applied, although only significantly so in one soil from the cash crop rotation. In the livestock crop rotation, the inclusion of N-fixing legumes in the leys and application of FYM will result in additional N input, reducing the relative effect of N fertilisation. Application of inorganic N also tended to yield higher SOC concentrations, although not significantly so. Powlson (1997) noted that the addition of inorganic N stimulates crop growth and increases the OM input in the form of N-rich crop residues and under-ground OM, resulting in increased N mineralisation potential.

Differences in plant N uptake in relation to crop rotation were thus observed in the pot experiment. In order to further investigate management-related effects on SOM and N mineralisation, the 'forced' mineralisation incubation study and SOM fractionation followed. Analysis of the SOM fractionation results are however preliminary, and are only briefly discussed. In the 'forced- mineralisation study, all soils exhibited typical patterns of mineralisation, with an increase in nitrate content over time (Figure 11).

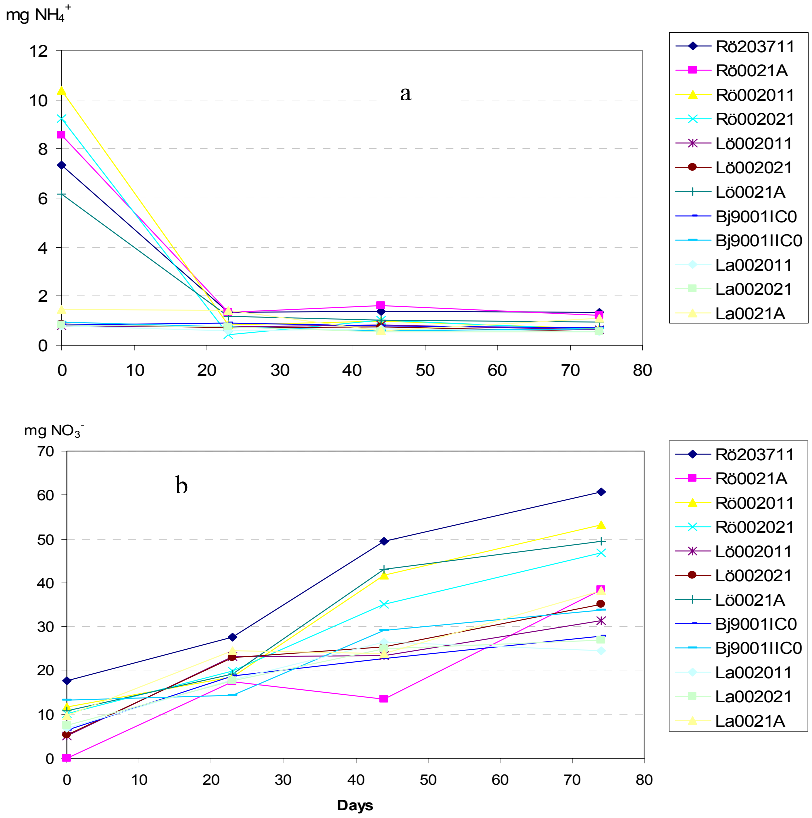

Figure 11. Mineral N concentrations for a) NH_4^+ and b) NO_3^- in soils of the forced mineralisation experiment. For explanation of treatment legend, see Table 3 and Figure 5.

Net N mineralisation, estimated as the difference between soil content of mineral N on day 0 and at the end of the experiment, varied between 17.4-37.0 mg N kg^{-1} (Table 6). Net mineralisation was generally higher in soils from crop rotations with high OM input such as ley or FYM, in line with the observed results from the pot experiment. At Röbäcksdalen, the highest mineralisation was found in the 'Northern livestock' crop rotation, in the treatment that had received FYM. Crop residue treatment appeared to have no significant effect on net mineralisation.

Table 6. *Net N mineralisation (mg kg^{-1}) and C-to-N ratio of mineralized SOM during the incubation study in soils from four locations in Sweden*

Location	Experimental series	Crop residue treatment	Net mineralisation	ΔC-to-ΔN[1]
Röbäcksdalen	Livestock	Returned	37.0^a	21.7
	Ley		31.1^b	nd
	Cereals	Removed	31.0^b	13.2
	Cereals	Returned	27.4^b	17.5
		Mean	31.6	
Lönnstorp	Ley		33.5^a	11.0
	Cereals	Removed	26.1^c	8.4
	Cereals	Returned	29.5^b	10.1
		Mean	29.7	
Bjertorp	Livestock	Returned	21.4^a	12.1
	Cereals	Removed	20.4^a	9.3
		Mean	20.9	
Lanna	Ley		28.0^a	20.0
	Cereals	Removed	17.4^b	6.7
	Cereals	Returned	19.1^b	7.9
		Mean	21.5	

Significant differences are denoted with different letters.

[1] mg of C mineralised (evolved as CO_2) per mg of N mineralised during two cycles.

The ΔC-to-ΔN ratios of the mineralised SOM were not well correlated with net mineralisation, indicating that the pools of SOM in the different soils behave differently.

SOM fractionation was undertaken in soils from Lanna and Lönnstorp, where the extreme treatments of ley, here denoted as ‘21’, and cereals where crop residues where removed, here denoted as ‘20', were selected (Figure 12). Preliminary analysis of the results indicate that the C-to-N ratios of the different fractions vary between 8 and 50, and that the larger, lighter fraction (Aa), has a lower C-to-N ratio in the high-mineralising ley soils than in the cereal soils.

Statistical analysis indicates that the fractions are sensitive to the treatments in the following order: C-to-N ratio > amount of N > N concentrations > amount of C >> C concentrations in fraction. Obviously the fractions are highly sensitive to fraction class, which merely indicates that the different fractions isolate different types of organic matter.

C-to-N ratios consistently decrease with fraction-size, and low ratios (~9) were found in the smallest organo-mineral fraction, indicating that this is a decomposed, mainly microbial source. The smaller ‘non mineral associated’ fractions (Cb and Db) contain high amounts of soil carbon, yet they are relatively unaffected in N content (data not shown), thus qualifying them as relatively ‘inert’ fractions, possibly related to charcoal-content. Further analysis relating these SOM fractions to N mineralisation is pending.

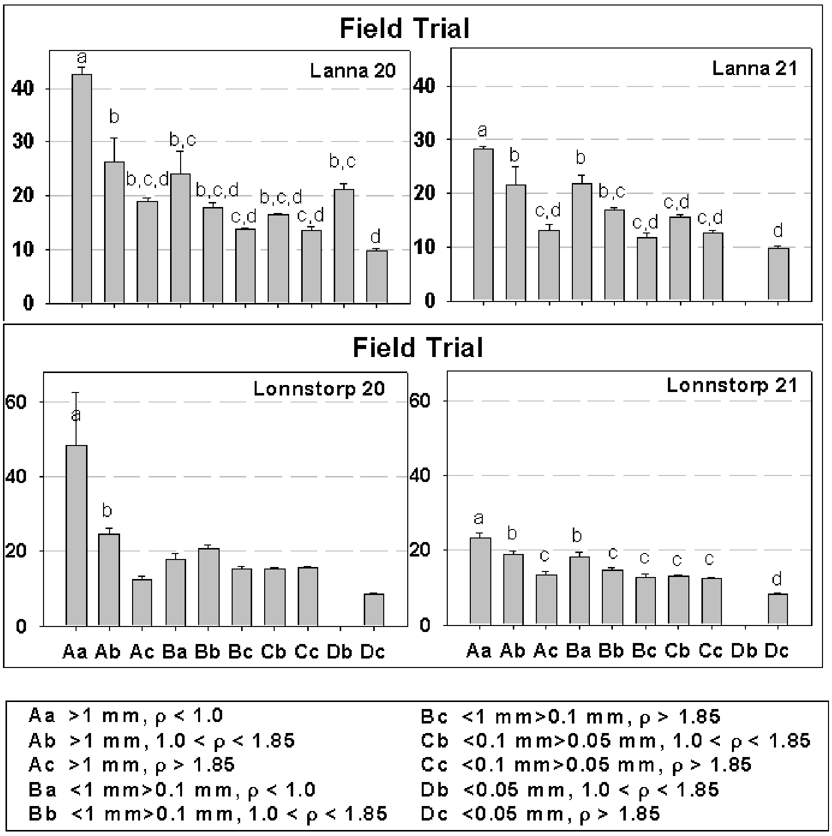

Figure 12. C-to-N ratios of SOM fractions of Lanna and Lönnstorp soils. Significant differences are denoted with different letters.

Non-exchangeable ammonium in Swedish soils

The NEA content of Swedish topsoils used in this study ranged from 21-217 mg kg^{-1} sieved soil (Table 2 in Paper II), which is comparable to other reports of NEA contents that vary between 20-500 mg kg^{-1} in agricultural soils (Osborne, 1976; Scherer, 1993; Scherer & Weimar, 1993; Liu *et al.*, 1997; Soon, 1998). A summary of the results are presented in Table 7.

The measured NEA content correlated relatively well with soil clay content: Kungsängen (56% clay of which 55% is illite and 0% vermiculite) > Vreta Kloster (48% clay with 45% illite and 9% vermiculite) > Fjärdingslöv (14% clay with 33 % illite and 6% vermiculite) = Bjertorp (30% clay, mineralogy unknown) > Röbäcksdalen (10% clay, mineralogy unknown) (Kirchmann, 1991, Kirchmann *et al.*, 1999, Kirchmann *et al.* in press). This is in accordance with other observations (Nömmik & Vathras, 1982; Scherer, 1993). Further investigation of correlation between vermiculite and NEA content would have been interesting, but was unfortunately not possible due to lack of data. Between 0.1-6% of total soil N was estimated to be in the form of NEA.

Table 7. *Averages of NEA (mg kg^{-1} sieved soil) and total N (%) contents in Swedish soils*

Location	Fjärdingslöv	Bjertorp	Vreta Kloster	Kungsängen	Röbäcksdalen
NEA	83^c	65^c	118^b	196^a	23^d
Total N	0.14^d	0.16^c	0.18^b	0.22^a	0.21^a
NEA/total N	1.0^c	1.2^c	2.9^b	5.1^a	0.1^d

Significant differences between sites ($p<0.05$) are denoted by different letters. NEA/total N was calculated taking into account the fraction of sieved soil of total soil.

Long-term additions of K fertiliser resulted in increases in the AL-extractable K content, but the HCl-extractable K content was unaffected. Unexpectedly, there was no significant correlation between K content and NEA content. Timing of K fertiliser application could be responsible for this, as application of K prior to NH_4^+ can depress fixation, yet simultaneous addition of N and K can increase fixation (Jansson, 1958, Nömmik & Vathras, 1982). In these field experiments, K fertiliser had been added both prior to and simultaneously with "Nitrochalk" fertiliser, so a clear correlation might be difficult to find.

In general, NEA mobilisation was correlated with rye grass growth and N uptake, which was greatest between day 0 and day 112 (Paper II, Figure 4). Other studies indicate seasonal variations of NEA contents, also related to crop growth and plant N uptake by roots (Mengel & Scherer, 1981, Mengel *et a.l*, 1990, Scherer & Ahrens, 1996). Increases in NEA content after harvest, at the end of the growing season, similar to the observed increase on day 168 have been reported (Mengel & Scherer, 1981, Mengel *et al.*, 1990). The increase is attributed to fixation of recently ammonified organic N. Between 25-58% of NEA was mobilised, which could have substantial effects on crop N dynamics.

Further studies are needed to estimate the short-term agronomic effects of K- and NH_4^+-containing fertiliser applications on NEA fixation and mobilisation in typical Swedish cropping systems.

Dry season legume fallows in maize-legume systems in Nigeria

The dry season legume fallow was evaluated in terms of biomass production, N contribution, OM quality and effect on following maize crop. OM from the legumes generally had higher N content and contributed more to the N input than the natural fallow, with the exception of soybean (Table 8).

Table 8. *Some properties of the dry season fallow crops*

	Soybean	Cowpea	Mucuna	Pueraria	Pigeon pea	NF
N (%)	1.47	2.48	2.41	2.23	2.81	2.14
N input (kg ha^{-1})	14	76	91	103	89	48
Lignin (%)	6.9	6.6	12.4	11.8	15.4	8.5
Polyphenol (%)	1.6	1.1	1.8	2.0	2.6	1.3

Data are presented as averages over the two seasons. Due to missing values, data on soybean are mainly from the first season. NF= Natural fallow.

Dry season legume biomass production, which ranged from 1000 to 8300 kg ha^{-1}, was greater than the natural fallow control 800-2300 kg ha^{-1} (Figure 13), although legume biomass yields were lower than under rainy season conditions, where biomass yields up to 10 000 kg ha^{-1} have been reported (Muhr *et al.*, 1999a). The production of OM for application to the soil has long been regarded as a bottleneck (Vanlauwe, 2004), however, the potential adoption of a technology with an OM production phase is regarded as high when the production phase also results in a commercially viable product, such as grain legumes (Sanginga *et al.*, 2001).

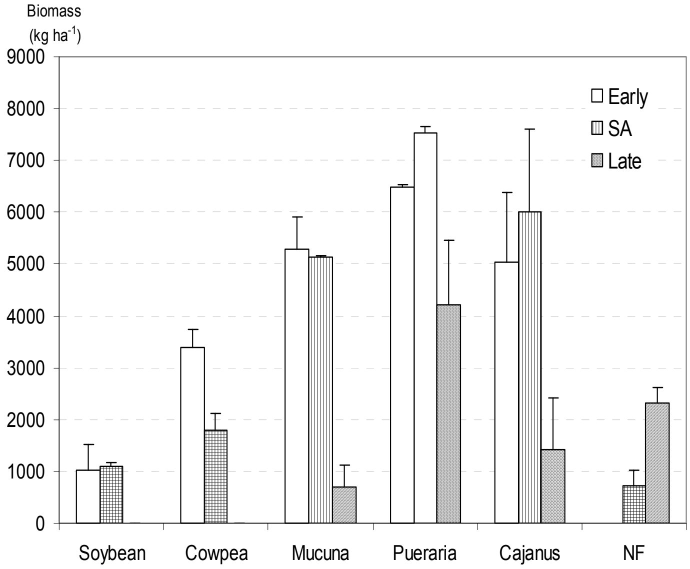

Figure 13. Legume biomass yields. Data are presented as averages over the two seasons. Error bars indicate standard errors of the mean. NF= Natural fallow, SA= Surface application.

Dry season legume biomass produced *in situ* and applied as fallow OM resulted in yield increases of 10-35 % on the following maize crop compared with natural fallow (Figure 14). Almost all legume treatments resulted in maize grain yields greater than 1000 kg ha^{-1}, with the majority of treatments resulting in grain yields between 1500-2000 kg ha^{-1}. Vanlauwe *et al.* (2001) report of maize grain increases up to 140 %, which where negatively correlated with soil fertility status, indicating that the effect of adding OM was reduced under good soil fertility conditions. Additional benefits of including legumes in the crop rotation could be improved soil phosphorous (P) status through rhizosphere processes, reduction in pest and disease pressure and improved soil physical properties (Vanlauwe, 2004).

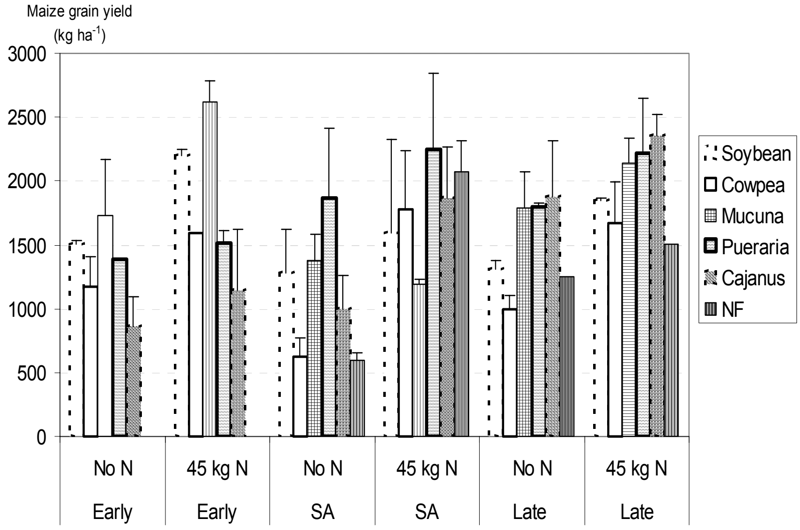

Figure 14. Maize grain yields. Data are presented as averages over the two seasons. Error bars indicate standard errors of the mean. NF= Natural fallow, SA= Surface application.

Maize stover is used as animal fodder in agricultural systems in West Africa and thus deserves mentioning here. Stover yields varied between 1400 – 4400 kg ha^{-1}, although there were no significant differences in yields between preceding fallow crops, treatments or fertiliser application.

In addition to maize grain and stover yields, these dry season fallow legume systems also need to consider the legume grain yield. Legume grains, such as soybean and cowpea, are an important source of protein for many people in sub-Saharan Africa and soybean and cowpea are examples where legume grains have successfully been incorporated into local food practices (Manyong *et al.,* 2000). Soybean and cowpea grain yields varied between 250-725 kg ha^{-1} and 81-310 kg ha^{-1}, respectively.

Although the legumes were of similar quality (N, lignin and polyphenol contents), the synergistic effect of combining dry season-produced legume OM and fertiliser could be manipulated by use of different legumes and management systems. For every kg of fertiliser added, maize grain yields could be increased by up to ca 25 kg (Figure 15). In West African systems where no OM was added, typical maize grain increases per kg of fertiliser added were around 15 kg (FAO, 2001).

The results suggest that application of *C. cajan* OM is not as time dependent as that of *P. phaseoloides* or *M. pruriens,* where highest fertiliser yield increase correlates with time of highest biomass production. This suggests that proper management of dry season OM resources could give farmers an opportunity to increase crop productivity.

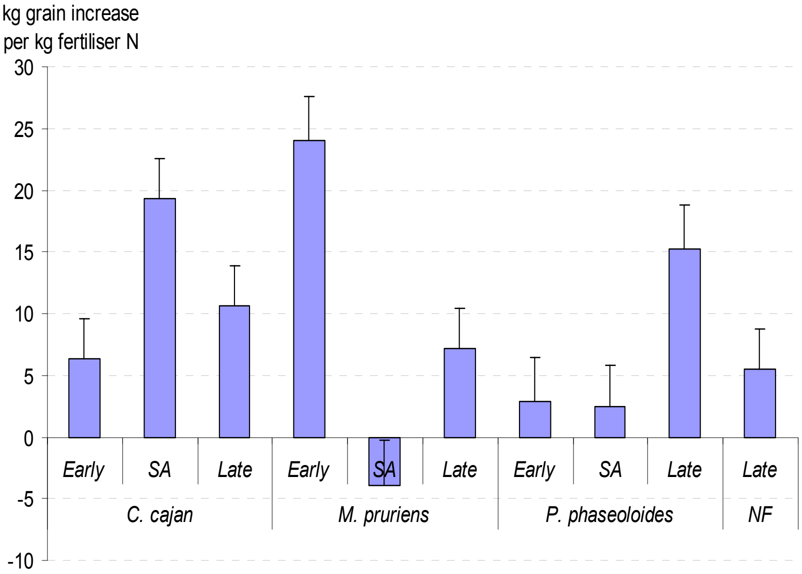

Figure 15. Maize grain-yield increase per kilogram of added fertiliser urea-N under the different fallow crops and management systems. Data are presented as averages of the two seasons. Error bars indicate standard errors of the mean. SA= Surface application, NF= Natural fallow.

Dry season legume fallow systems, with high biomass production, maize grain yield increases and additional benefits of legume grain production, could be a viable option for resource-poor farmers in West Africa to increase maize grain yields while providing a “basket of options”. Investigations of the long-term effects of such a crop rotation on soil properties, as well as a detailed analysis of its appropriateness and effects on household economy would have to be undertaken for a full understanding.

N_2O fluxes in maize-legume systems in Nigeria

N_2O fluxes up to 138 μg N m^{-2} h^{-1} were observed (Table 9). Mean N_2O fluxes during the three sampling periods were 21 and 13 μg N m^{-2} h^{-1} for *P. phaseoloides* and natural fallow, respectively, in the treatments where no fertiliser was applied, and 28 and 21 μg N m^{-2} h^{-1}, respectively, in the treatments where 45 kg ha^{-1} of urea-N was applied. There were no significant differences between N_2O fluxes from soil where *P. phaseoloides* and natural fallow had been applied.

Flux rates in tropical forest-based systems have been found to range from 0 to 90 $\mu g\ N\ m^{-2}\ h^{-1}$ and from 0 to 100 $\mu g\ N\ m^{-2}\ h^{-1}$ in improved tropical fallow systems (Erickson & Keller, 1997; Nobre *et al.*, 2001; Weitz *et al.*, 2001; Baggs *et al.,* 2002; Palm *et al.*, in press). Although difficult to compare between different studies, due to variations in method reliability, calculations and spatial and temporal disparity, greater flux rates in tropical high- and low-input cropping systems compared to forest-based systems have been suggested (Baggs *et al.*, 2002; Palm *et al.*, in press).

Table 9. *Mean and range of N_2O fluxes ($\mu g\ N\ m^{-2}\ h^{-1}$) during the two wet seasons (WS 01 and WS 02) and the dry season (DS 02) from treatments with incorporated P. phaseoloides (Pu) and natural fallow (NF) OM where 0 kg urea-N ha^{-1} (-F) and 45 kg urea-N ha^{-1} (+F) has been applied*

	WS 01				WS 02[1]				DS 02	
	Pu		NF		Pu		NF		Pu	NF
	-F	+F	-F	+F	-F	+F	-F	+F	-F	-F
Min.	26	18	13	3	-0.6	-5	0	-10	-0.1	-0.2
Max.	114	138	59	80	64	20	92	36	4	1.4
Mean	56	51	32	37	11	5	13	5	1	0.5

[1] An extra sampling date was included in WS 02, after a heavy rainfall, but only in the treatment where no urea-N had been applied.

Fluxes from treatments where N fertiliser had been added were significantly different from treatments where no fertiliser had been added, which is consistent with other findings (Baggs *et al.,* 2003, Khalil *et al.*, 2002, Nobre *et al.,* 2001).

Dick et al. (2000) report of peak fluxes under controlled conditions of up to 2000 $\mu g\ N\ m^{-2}\ h^{-1}$ after heavy rainfall in a Ugandan soil, which was correlated with high soil moisture contents. Our results indicate that fluxes were significantly correlated with soil content of NO_3^- although not related to soil moisture content, suggesting that nitrification plays a more significant role than denitrification. Fluxes varied significantly with time and generally peaked within the first couple of weeks after incorporating the OM (see Figure 6, 7, 8 in Paper IV), indicating a correlation with the decomposition of the added OM material. However, the erratic nature of rainfall and soil moisture conditions in the tropics increases the complexity of factors that contribute to N_2O emissions and makes interpretations difficult.

Due to the great variation in fluxes, it is difficult to quantify the loss of N from the cropping system. To give a very rough estimate, taking into account the seasonal variations of four months of dry season and eight months of wet season, annual N_2O-N emissions are roughly estimated to potentially range from 0 to 8 kg N ha^{-1}, with mean emissions of 1-2 kg N ha^{-1} from soil where natural fallow and *P. phaseoloides*, plant residues were incorporated. Although perhaps not of great agronomic significance, these N_2O-N losses could have substantial effects on climate change and C sequestration potential.

Conclusions

N transformation processes are central to efficient, sustainable crop production in all agricultural systems. This thesis has explored some of the impacts of N inputs and agricultural management on crop productivity in Swedish and Nigerian agricultural systems.

The main conclusions concerning N mineralisation and soil organic matter in temperate agricultural systems (Theme 1) are:

- long-term ley crop rotations in Sweden result in higher plant N uptake, net N mineralisation and topsoil C content than cereal crop rotations
- long-term return of crop residues in Sweden has no significant effect on plant N uptake, net mineralisation or topsoil C properties

The main conclusions of the impact of NEA on N availability in temperate soils (Theme 2) are:

- Swedish agricultural soils contain 20-200 ppm NEA and 0.1 to 6 % of total soil N is in the form of NEA
- substantial amounts of NEA in Swedish soils can become plant available during the cropping season, suggesting a need for re-evaluation of N models

The main conclusions from N inputs and losses in tropical soils (Theme 3) are:

- application of *in situ* dry season produced legume OM resulted in maize grain yield increases up to 35% compared with natural fallow
- N_2O fluxes from a maize-legume crop rotation in the derived savanna zone of Nigeria were up to 138 μg N m^{-2} h^{-1}

The ability to estimate and manage the N pools and N fluxes in a given soil will hopefully result in increased productivity through increased synchrony between N availability and plant N demand. The results presented here indicate that a farmer's management decisions, be it in Sweden or Nigeria, can significantly affect N fluxes, which will in turn affect long-term agricultural and environmental sustainability.

References

Ambus, P., Jensen, E.S., Robertson, G.P. 2001. Nitrous oxide and water mediated N-losses from agricultural soils: influence of crop residue particle size, quality and placement. *Phyton (Austria)*, 41, 7-15.

Anderson, J.M. & Ingram, J.S.I. (Eds.) 1993. *Tropical soil biology and fertility: A handbook of methods*. 221 pp.

Andrén, O. & Kätterer, T. 1997. ICBM – the Introductory Carbon Balance Model for exploration of soil carbon balances. *Ecological Applications*, 7, 1226-1236.

Andrén, O., Lindberg, T., Boström, U., Clarholm, M., Hansson, A-C., Johansson, G., Lagerlöf, J., Paustian, K., Persson, J., Pettersson, R., Schnürer, J., Sohlenius, B., Wivstad, M. 1989. Chapter 5. Organic carbon and nitrogen flows. In: Andrén, O., Lindberg, T., Paustian, K., Rosswall, T. (Eds.) *Ecology of arable land – organisms, carbon and nitrogen cycling.* Ecological Bulletins. (Copenhagen) 40, 85-126

Bagayako, M., Buerkert, A., Lung, G., Bationo, A., Römheld, V. 2000. Cereal/legume rotation effects on cereal growth in Sudano-Sahelian West Africa: soil mineral nitrogen, mycorrhizae and nematodes. *Plant and Soil*, 218, 103-116.

Baggs, E.M., Millar, N., Ndufa, J.K., Cadisch, G. 2001. Effect of residue quality on N2O emissions from tropical soils, pp. 120-125. *In* R.M. Rees, B.C. Ball, C.D. Campbell and C.A. Watson (Eds). *Sustainable management of soil organic matter.* CAB International.

Baggs, E., Cadisch, G., Verchot, L., Millar, N., Ndufa, J. 2002. Environmental impacts of tropical agricultural systems.- N_2O emissions and organic matter management. Proceedings from the 17th World Congress of soil Sciences, Bangkok, Thailand, 14-18 August, 2002.

Baggs, E.M., Stevenson, M., Pihlatie, M. Regar, A., Cook, H., Cadisch, G. 2003. Nitrous oxide emissions following application of residues and fertiliser under zero and conventional tillage. *Plant and Soil*. 254, 361-370.

Bosatta, E. & Ågren, G.I. 1985. Theroretical analysis of decomposition of heterogeneous substrates. *Soil Biology and Biochemistry*, 24, 275-277.

Bouwman, A.F. 1996. Direct emissions of nitrous oxide form agricultural soils. *Nutrient cycling in agroecosystems*, 46, 53-70.

Brady, N.C. 1990. *The nature and properties of soils*. 10th edition. Macmillan Publishing company, NY.

Bremner, J.M., Mulvaney, C.S. 1982. Nitrogen- Total. In A.L. Page, R.H. Miller, and D.R. Keeney (Eds.) *Methods of soil analysis*. Part 2, Agronomy 9, 595-624.

Bremner, J.M. 1997. Sources of nitrous oxide in soils. *Nutrient Cycling in agroecosystems*, 49, 7-16.

Breuer, L., Kiese, R., Butterbach-Bahl, K. 2002. Temperature and moisture effects on nitrification rates in tropical rain-forest soils. *Soil Science Society of America Journal*, 66, 834-844.

Cambardella, C.A. & Elliot, E.T. 1992. Particulate soil organic matter changes across a grassland cultivation sequence. *Soil Science Society of America Journal*, 56, 777-783.

Carlgren, K. & Mattsson, L. 2001. Swedish Soil Fertility Experiments. *Acta Agriculturae Scandinavica*, 1, 49-78.

Carsky, R.J, Hayashi, Y., Tian, G. 1998. Benefits of mulching in the sub-humid savannah zone: Research needs and technology targeting. Resource and Crop Management. Research Monograph No. 26. IITA

Carsky, R.J., Oyewole, B., Tian, G. 2001. Effect of phosphorous application in legume cover crop rotation on subsequent maize in the savanna zone of West Africa. *Nutrient cycling in agroecosystems*, 59, 151-159.

Carsky, R.J., Becker, M., Hauser, S. 2002. Mucuna cover crop fallow systems: potential and limitations. In: *Sustaining Soil Fertility in West Africa*. Soil Science Society of America. Special publication no. 58.

Choudhary, M.A., Akramkhanov, A., Saggar, S. 2002. Nitrous oxide emissions from a New Zealand cropped soil: tillage effects, spatial and seasonal variability. *Agriculture, Ecosystems and the Environment*, 93(1-3), 33-43.

Christensen, S., Ambus, P., Arah, J.R.M., Clayton, H., Galle, B., Griffith, D.W.T., Hargreaves, K.J., Klemedtsson, L., Lind, A.M., Scott, A., Skiba, U., Smith, K.A., Welling, M., Wienhold, F.G. 1996. Nitrous oxide emission from an agricultural field: Comparison between measurements by flux chamber and micrometerological techniques. *Atmospheric Environment*, 30(24), 4183-4190.

Davidson, E.A., Matson, P.A., Brooks, P.D. 1996. Nitrous oxide emissions controls and inorganic nitrogen dynamics in fertilized tropical soils. *Soil Science Society of America Journal*, 60, 1145-1152.

Davidson, E.A., & Kingerlee, W. 1997. A global inventory of nitric oxide emissions from soils. *Nutrient cycling in agroecosystems*, 48, 37-50.

Dick, J., Skiba, U., Wilson, J. 2000. The effect of rainfall on NO and N_2O emissions from Ugandan agroforest soils. *Phyton: Annales rei botanicae*, 4(3), 73-80.

Erickson, H. & Keller, M. 1997. Tropical land use change and soil emissions of nitrogen oxides. *Soil use and management,* 13, 278-287.

FAO, 1991. Soil Taxonomy. Rome.

FAO, 2001. The economics of soil productivity in sub-Saharan Africa. Rome.

FAO. http://www.fao.org/waicent/portal/statistics_en.asp; (accesses 28 January 2005)

Feigen, A. & Yaalon, D.H. 1974. Non-exchangeable ammonium in soils of Israel and its relation to clay and parent material. *Journal of Soil Science*, 25(3), 384-397.

Freney, J.R. 1997. Emissions of nitrous oxide from soils used for agriculture. *Nutrient cycling in agroecosystems*. 49, 1-6.

Gigou, J. & Bredoumy, S.K. 2002. Yield trends, soil nitrogen and organic matter content during 20 years of continous maize cultivation. In: Vanlauwe, B., Diels, J., Sanginga, N., Merckx, R. (Eds.), *Integrated plant nutrient management in sub-Saharan Africa: From concept to practice*. CAB International, Wallingford, Oxon, UK., pp 199-208

Giller, K.E. & Cadisch, G. 1995. Future benefits from biological nitrogen fixation: An ecological approach to agriculture. *Plant and Soil*, 174, 255-277.

Giller, K.E. 2000. Translating science into action for agricultural development in the tropics: an example from decomposition studies. *Applied soil ecology*, 14, 1-3.

Giller, K.E. & Cadisch, G. 2001. *Nitrogen fixation in tropical cropping systems*. 2nd edition. CAB international.

Golchin, A., Baldock, J.A., Oades, J.M. 1998. A model linking organic matter decomposition, chemistry and aggregate dynamics. In Lal, R., Kimble, J.M., Follett, R.F., & Stewart, B.A. (Eds.) *Soil processes and the Carbon Cycle*, CRC Press, Boca Raton, Boston, New York, Washington, London. pp. 245-266.

Granli, T. & Böckman, O. 1995. Nitrous oxide (N_2O) emissions from soils in warm climates. *Fertiliser Research*, 42, 159-163.

Grantham, R. 1989. Approaches to correcting the global greenhouse drift in managing trooical ecosystems. *Tropical Ecology*, 30(2), 157-174.

Hassink, J. 1994. Active organic matter fractions and microbial biomass as predictors of N mineralization. *European Journal of Agronomy*, 3(4), 257-265.

Hassink, J., Whitmore, A.P., Kubát, J. 1997. Size and density fractionation of soil organic matter and the physical capacity of soils to protect organic matter. *European Journal of Agronomy*, 7, 189-199.

Heanes D. L. 1984. Determination of total organic carbon in soils by an improved Chromic acid digestion and Spectrophotometric procedure. *Communications in Soil Science and and plant analysis*. 15:1191-1213

Herrmann, A. 2003. *Predicting Nitrogen Mineralisation from Soil Organic Matter – a Chimera?* Acta Universitatis Agriculturae Sueciae, Agraria 429.

Hutchinson, G.L., & Mosier, A.R., Improved soil cover method for field measurements of nitrous oxide fluxes. *Soil Science Society of America Journal*, 45, 311-316.

IAEA. 1992. Manual on measurement of methane and nitrous oxide emissions from agriculture. IAEA-TECDOC-674.

ISRIC. 1993. *Procedures for soil analysis*. ISRIC Technical paper no. 9.

Iwuafor, E.N.O., Aihou, K., Jaryum, J.S., Vanlauwe, B., Diels, J., Sanginga, N., Lyasse, O., Deckers, J., Mercks, R. 2002. On-farm evaluation of the contribution of sole and mixed applications of organic matter and urea to maize grain production in the savannah. In: *Integrated plant nutrient management in sub-Saharan Africa: From concept to practice*. CAB International, Wallingford, Oxon, UK., pp. 185-197.

Jansson, S.L. 1958. Tracer studies on nitrogen transfprmation in soil with special attention to mineralisation-immobilization relationships. *Kungliga Lantbrukshögskolans Annualer*, 24, 101-361.

Jansson, S.L., & Eriksson, J. 1961. Kväve-och kaliumproblem i skånsk växtodling. En preliminär redogörelse. *Socker Handlaren*, 17, 9-21. (In Swedish)

Jansson, S. L. & Persson, J. 1982. Mineralization and Immobilization of Soil Nitrogen. In Stevenson, F. J. (ed) *Nitrogen in Agricultural soils*, Agronomy 22, 229-252.

Jarvis, S.C., Stockdale, E.A., Shepherd, M.A., Powlson, D.S. 1996. Nitrogen mineralisation in temperate agricultural soils: processes and measurement. *Advances in Agronomy*, 57, 187-235.

Johnsson, H., Bergström, L., Jansson, P-E., Paustian, K. 1987. Simulated nitrogen dynamics and losses in a layered agricultural soil. *Agriculture, Ecosystems and the Environment*, 18, 333-356.

Jordbruksverket, 2004. Jordbruksstatistisk årsbok, 2004. SCB-Tryck, Örebro.

Kalra, Y.P. & Maynard, D.G. 1991. *Methods manual for forest soil and plant analysis*. Northwest Region Information Report NOR-X-319, Forestry, Canada.

Karlsson, T., Andrén, O., Kätterer, T. 2003. Management effects on topsoil carbon and nitrogen in Swedish long-term experiments – budget calculations with and without humus pool dynamics*. European Journal of Agronomy*, 20, 137-147.

Khalil, M., Rosenani, A., Van Cleemput, O., Boeckx, P., Shamshuddin, J., Fauziah, C. 2002. Nitrous oxide production from an ultisol of the humid tropics treated with different nitrogen sources and moisture regimes. *Biology and Fertility of Soils*, 36, 59-65.

Kirchmann, H. 1991. Properties and classification of soils of the Swedish long-term fertility experiments: I. Sites at Fors and Kungsängen. *Acta Agriculturae Scandinavica*, 41, 227-242.

Kirchmann, H., Persson, J., Carlgren, K. 1994. *The Ultuna long-term soil organic matter experiment, 1956-1991*. Swedish University of Agricultural Sciences, Department of Soil Sciences, Reports and Dissertations, 17.

Kirchmann, H. Eriksson, J. Snäll, S. 1999. Properties and classification of soils of the Swedish long-term fertility experiments: IV. Sites at Ekebo and Fjärdingslöv. *Acta Agriculturae Scandinavica*, 49, 25-38.

Kirchmann, H. Snäll, S., Eriksson, J., Mattsson, L. Properties and classification of soils of the Swedish long-term fertility experiments: V. Sites at Vreta Kloster and Högåsa. *Acta Agriculturae Scandinavica* (In press).

Keatinge, J.D.H., Breman, H., Manyong, V.M., Vanlauwe, B., Wendt, J. 2001. Sustaining soil fertility in West Africa in the face of rapidly increasing pressure for agricultural intensification. In: *Sustaining Soil Fertility in West Africa*. Soil Science Society of America, Special publication no. 58.

Kätterer, T. & Andrén, O. 1996. Measured and simulated nitrogen dynamics in winter wheat and a clay soil subjected to drought stress or daily irrigation and fertilization. Fertil. Res. 44, 51-63.

Kätterer, T. & Andrén, O. 1999. Long-term agricultural experiments in northern Europe: analysis of the influence of management on soil carbon stocks using the ICBM model. *Agriculture, Ecosystems and the Environment*, 72, 165-179.

Kätterer, T. & Andrén, O. 2001. The ICBM family of analytically solved models of soils carbon, nitrogen and microbial biomass dynamics – descriptions and application examples. *Ecological Modelling* 136, 191-201.

Larsson, L.; Ferm, M., Kasimir-Klemedtsson, Å., Klemedtsson, L. 1998. Ammonia and nitrous oxide emissions from grass and alfalfa mulches. *Nutrient cycling in agroecosystems, 51, 41-46.*

Liang B.C. Mackenzie, A.F. Gregorich, E.G. 1999. Measurement of fixed ammonia and nitrogen isotope ratios using dry combustion. *Soil Science Society of America Journal*, 63, 1667-1669.

Littell, R.C., Milliken, G.A., Stroup, W.W., Wolfinger, R.D. 1996. *SAS® System for mixed models*, Cary, NC: SAS Institute Inc. 1996. 633 pp.

Liu, Y.J., Laird, D.A., Barak, P. 1997. Release and fixation of ammonium and potassium under long-term fertility management. *Soil Science Society of America Journal*, 61, 310-314.

Magid, J., Gorissen, A., Giller, K.E. 1996. In search of the elusive ”active” fraction of soil organic matter: three size-density fractionation methods for tracing the fate of homogenously ^{14}C-labelled plant materials. *Soil Biology and Biochemistry*, 28(1), 89-99.

Magid, J., Stoumann Jensen, L., Mueller, T., Nielsen, N.E., 1997. Size-density fractionation for *in situ* measurements of rape straw decomposition – an alternative to the litterbag approach? *Soil Biology and Biochemistry*, 29 (7), 1125-1133.

Manyong, V., Smith, J., Weber, G.K., Hagtap, S.S., Oyewole, B. 2000. *Macrocharacterisation of agricultural systems in West Africa: An Overview*. Resource and crop management division, International Institute of Tropical Agriculture, Monograph no. 21.

Mattsson, L. 1999. *Soil organic matter and N mineralization in arable land*. Swedish University of Agricultural Sciences, Dept. of Soil Sciences, Division of Soil Fertility, Report nr. 201 (In Swedish).

Mattsson, L. 2002. Soil organic C development in cereal and ley systems. Data from 20 years old Swedish field experiments. Arch. Acker. Pfl. Boden., 48, 107-115.

Mehlich, A. 1984. Mehlich 3 soil test extractant: A modification of Mehlich 2 extractant. Commun. *Soil Science and Plant Analysis*, 15(12), 1409-1416.

Meijboom,, F.W., Hassink, J., Van Noordwijk, M. 1995. Density fractionation of soil macroorganic matter using a silica suspension. *Soil Biology and Biochemistry*, 27(8), 1109-111.

Mengel, K. & Scherer, H.W. 1981. Release of non-exchangeable (fixed) soil ammonium under field conditions during the growing season. *Soil Science*, 131(4), 226-232.

Mengel, K., Horn, D., Tributh, H. 1990. Availability of interlayer ammonium as related to root vicinity and mineral type. Soil Science, 149(3), 131-137.

Muhr, L., Tarawali, S.A., Peters, M., Schultze-Kraft, R. 1999 a. Forage legumes for improved fallows in agropastoral systems of subhumid West Africa. I. Establishment, herbage yield and nutritive value of legumes as dry season forage. *Tropical grasslands*, 33, 222-233.

Muhr, L., Tarawali, S.A., Peters, M., Schultze-Kraft, R. 1999 b. Forage legumes for improved fallows in agropastoral systems of subhumid West Africa. II. Green manure production and decomposition after incorporation into the soil. *Tropical grasslands*, 33, 234-244.

Muhr, L., Tarawali, S.A., Peters, M., Schultze-Kraft, R. 1999 c. Forage legumes for improved fallows in agropastoral systems of subhumid West Africa. III. Nutrient import and export by forage legumes and their rotational effects on subsequent maize. *Tropical grasslands*, 33, 245-256.

Mosier, A.R., Duxbury, J.M., Freney, J.R., Heinemeyer, O., Minami, K. 1998. Assessing and mitigating N_2O emissions from agricultural soils. *Climatic Change*. 40, 7-38.

Mosier, A., Kroeze, C., Nevison, C., Oenema, O., Seitzinger, S., van Cleemput, O. 1998. Closing the global N2O budget: nitrous oxide emissions through the agricultural nitrogen cycle. *Nutrient Cycling in Agroecosystems*, 52, 225-248.

Nelson, D.W. 1982. Gaseous losses of nitrogen other than through denitrification. In Stevenson, F. J. (ed) *Nitrogen in Agricultural soils*, Agronomy 22, 327-347.

Nobre, A.D., Keller, M., Crill, P.M., Harriss, R.C. 2001. Short-term nitrous oxide profile dynamics and emissions response to water, nitrogen and carbon additions in two tropical soils. *Biology and Fertility of Soils*, 34, 363-373.

Nömmik, H. 1957. Fixation and defixation of ammonium in soils. *Acta Agriculturae Scandinavica*, 7, 395-436.

Nömmik, H., & Vathras, K. 1982. Retention and fixation of ammonium and ammonia in soils. In: Stevenson, F.J. (Ed.), *Nitrogen in Agricultural soils*, Agronomy, 22, 123-169.

Osborne, G.J., 1976. The extraction and definition of non-exchangeable ammonium in some soils from Southern New South Wales. *Australian Journal of Soil Research*, 14, 373-380.

Palm, C., Myers, R.J.K., and Nandwa, S. 1997. Combined use of organic and inorganic nutrient sources for soil fertility maintenance and nutrient replenishment.IN: Buresh, R.J. and Sanchez, P.A. (eds.) Replenishing soil fertility in Africa. ASSA, CSSA, SSSA, Madison, WI, USA, pp. 193-217.

Palm, C., Alegre, J., Arevalo, L., Mutuo, P., Mosier, A., Coe, R. Nitrous oxide and methane fluxes in six different land use systems in the Peruvian Amazon. Submitted to Global Geochemical cycles (In press).

Palm, C.A., Giller, K.E., Mafongoya, P.L., Swift, M.J. 2001. Management of organic matter in the tropics: translating theory into practice. *Nutrient cycling in agroecosystem*, 61, 63-75.

Powlson, D.S. 1997. Integrating agricultural nutrient management with environmental objectives: current state and future prospects. *Proceedings of the Fertiliser Society*, 402.

Recous, S., Mary, B., & Faurie, G. 1990. Microbial immobilization of ammonium and nitrate in cultivated soils. *Soil Biology and Biochemistry* 22, 913-133.

Robertson, G.P., Eldor, A.P., Harwood, R.R. 2000. Greenhouse gases in intensive agriculture: Contributions of individual gases to the radiative forcing of the atmosphere. *Science*, 289, 1922-1930.

Rodhe, H. 1990. A comparison of the contribution of various gases to the greehouse effect. *Science*, 248, 1217-1219.

Rosswall, T., Berg, P., Bergström, L., Ferm, M., Johansson, C., Klemedtsson, L., Svensson, B.H., 1989. Chapter 6. Inorganic nitrogen cycling processes and flows. In: Andrén, O., Lindberg, T., Paustian, K., Rosswall, T. (Eds.) *Ecology of arable land – organisms, carbon and nitrogen cycling*. Ecological Bulletins. (Copenhagen) 40, 85-126

Röing, K. 1997. Kvävenivåns, skörderesternas och växtföljdens långsiktiga inflytande på markens kol- och kvävehalt. No. 107. Department of Soil Sciences, Swedish University of Agricultural Sciences (In Swedish)

Sahrawat, K.L. & Keeney, D.R. 1986. Nitrous oxide emissions from soils. *Advances in Soil Science*, 4, 103-148.

Sanginga, N., Okogun, J.A., Vanlauwe, B., Diels, J., Carsky, R.J., Dashiell, K.E. 2001. Nitrogen contribution of promiscuous soybeans in maize based cropping systems. In: *Sustaining soil fertility in West Africa*. Tian, G., Ishida, F., Keatinge, D. (Eds.) pp. 157-178. Soil Science Society of America, Special publication No. 58, Madison, Wisconsin.

SAS Institute. 1999. *SAS release 8.1*. SAS Inst., Cary, NC.

Scherer, H.W. 1993. Dynamics and availability of the nonexchangeable NH_4^+-N – a review. *European Journal of Agronomy*, 2(3), 149-160.

Scherer, H.W., & Weimar, S. 1993. Release of non-exchangeable NH_4^+-N after planting of ryegrass in relation to soil content and as affected by nitrate supply. *Zum Pflanzenenernährung Bodenkunde*, 156, 143-148.

Scherer, H.W., & Ahrens, G. 1996. Depletion of non-exchangeable NH_4-N in the soil root interface in relation to clay mineral composition and plant species. *European Journal of Agronomy*, 5, 1-7.

Scherer, H.W., Werner, W. 1996. Significance of soil microorganisms for the mobilization of non-exchangeable ammonium. *Biology and Fertility of Soils*, 22, 248-251.

Schulz, S. Carsky, R.J., Tarawali, S.A. 2001. Herbaceous legumes: The panacea for West African soil fertility problems? In: *Sustaining Soil Fertility in West Africa*. Soil Science of America Special publication no. 58.

Sharma, C., Prabhat, K. G., Parashar, D.C. 1996. Atmospheric nitrous oxide: Sources and sinks. *Tropical Ecology*, 37(2), 153-166.

Sing, A. & Balasubramanian, V. 1980. Nitrogen cycling in the savanna zone of Nigeria. In: *Nitrogen cycling in West African Ecosystems*. Rosswall, T. (Ed.). 377-391.

Six, J., Elliot, E.T., Paustian, K. 2000. Soil macroaggregate turnover and microaggregate formation: a mechanism for C sequestration under no-tillage agriculture. *Soil Biology and Biochemistry*, 32, 2099-2103.

Six, J., Conant, R.T., Paul, E.A., Paustian, K. 2002. Stabilization mechanisms of soil organic matter: implications for C-saturation of soils. *Plant and Soil*, 241, 155-176.

Silva, J.A., & Bremner, J.M. 1966. Determination and iso-tope ration analysis of different forms of nitrogen in soils. 5. Fixed ammonium. Soil Science Society of America Proceedings, 30, 587-594.

Smith, S.J., Schepers, J.S., & Porter, L.K. 1990. *Assessing and managing agricultural nitrogen losses to the environment*. Advances in Soil Science, vol. 14. Springer-Verlag NY Inc.

Soon, Y.K. 1998. Nitrogen cycling involving non-exchangeable ammonium in a gray luvisol. Biology and Fertility of Soils, 27, 425-429.

Steffens, D. & Sparks, D.L. 1997. Kinetics of non-exchangeable ammonium release from soils. *Soil Science Society of America Journal*, 61, 455-462.

Stevenson, F.J. 1982. Origin and distribution of N in soil. In Stevenson, F. J. (ed) *Nitrogen in Agricultural soils*, Agronomy 22, 229-252.

Tate, R.L. 1995. *Soil microbiology*. John Wiley & Sons, NY.

Tian, G., Kolowole, G., Kang, B.T., Kirchhof, G. 2000. Nitrogen fertiliser replacement index of legume cover crops in the derived savannah of West Africa. *Plant and Soil*, 224, 287-296.

Tian, G. Hauser, S., Koutika, L-S., Ishida, F., Chianu, J. 2002. Pueraria cover crop fallow systems: Benefits and applicability. In: *Sustaining Soil Fertility in West Africa*. Soil Science of America Special publication no. 58.

Vanlauwe, B., Aihou, K., Iwuafor, E.N.O., Houungnaden, P., Diels, J., Manyong, V.M., Sanginga, N. 2000. Recent developments in soil fertility management of maize-based systems: The role of legumes in N and P nutrition of maize in the moist savanna zone of West Africa. Proceeding from the BNMS workshop, 2000.

Vanlauwe, B., Aihou, K., Aman, S., Iwuafor, E.N.O., Tossah, B.K., Diels, J., Sanginga, N., Lyasse, O., Merckx, R., Deckers, J. 2001. Maize yield as affected by organic inputs and urea in the West African moist savanna. *Agronomy Journal*, 93(6), 1191-1199

Vanlauwe, B. Wendt, J., Diels, J. 2001. Combined application of organic matter and fertiliser. In Sustaining soil fertility in West Africa (Eds. G. Tian, F. Ishida and JDH Keatinge), Soil Science of America Special publication no. 58.

Vanlauwe, B., Diels, J., Lyasse, O., Aihou, K., Iwuafor, E.N.O., Sanginga, N., Merckx, R., Deckers, J. 2002. Fertility status of soils of the derived savanna and northern guinea savanna and respone to major plant nutrients, as influenced by soil type and land use management. *Nutrient cycling in agroecosystems*, 62, 139-150.

Vanlauwe, B. 2004. Integrated Soil Fertility management research at TSBF: The framework, the principles and their application. In: Bationo (Ed), *Managing nutrient cycles to sustain soil fertility in sub-saharan Africa*. Academy Science Publishers, 608 pp.

Wehrmann, J. & Coldewey-Zum Eschenhoff, H. 1986. Distribution of nitrate and non-exchangeable ammonium in the soil-root interface. *Plant and Soil*, 91, 421-424.

Weitz, A., Linder, E., Frolking, S., Crill, P., Keller, M. 2001. N_2O emissions from humid tropical agricultural soils: effect of soil moisture, texture and nitrogen availability. *Soil Biology and Biochemistry*, 33, 1077-1093.

Vermoesen, A., de Groot, C-J., Nollet, L., Boeckx, P., van Cleemput, O. 1996. Effect of ammonium and nitrate application on the NO and N_2O emission out of different soils. *Plant and Soil*, 181, 153-162.

Vermoesen, A., Van Cleemput, O., Hofman, G. 1996. Long-term measurements of N_2O emissions. *Energy Conversion Management*, 37, 1279-1284.

Wiklander, L. 1976. *Marklära*. Uppsala. (In Swedish)

Young, J.L. & Aldag, R.W. 1982. Inorganic forms of nitrogen in soil. In: Stevenson, F. J. (Ed.), *Nitrogen in Agricultural soils, Agronomy* 22, 229-252.

Zhang, Y. & Scherer, H.W. 1998. Simplification of the standard method for determination of non-exchangeable NH_4-N in soil. *Zum Pflanzenenernährung Bodenkunde*, 161, 191-103.

Acknowledgements

Ultuna, Skåne, Västergötland, Östergötland, Norrland, Köpenhamn, Ibadan, Nigeria, Benin, Togo, Ghana, Kenya, Australia, Belgium, Thailand ...

First of all, I would like to say that this has been an adventure. An adventure that has taken me all over Sweden, all over Africa and all over the world. I have had the opportunity to learn so many things, not only about being a scientist but also about myself. How many PhD-students can say that they've thrown up in the gutter outside the conference hall in Tamale (Northern Ghana), horribly sick from malaria …?!

The start

I would like to express my sincerest gratitude to professor emeritus Jan Persson and professor Gyula Simán for initially taking me on as a PhD-student. Despite many changes of supervisor, due to retirements, your continued interest and support in my work has been uplifting.

The work

Many tears! Many laughs! Mountains of thanx to the staff at the Dep. of Soil sciences (Pia, Laima, Lolita, Anne, Harriet, Thomas, Kerstin, Inger, Allan, Morgan, Rosemarie, …), the staff at IITA (Sanginga, Jan, Bernard, Dyno, Bob, Rodo, Nicoline, Jackie, Muyiwa, Joseph x2, Bukky, Robert, Ole, Maj, Aman, Boru …), the staff and students at KVL (Jakob and Jane) and my fellow PhD students at SLU and IITA. You helped me get through the day!

Coming full circle

My sincerest gratitude goes to Professor Olle Andrén, who agreed to take over as my main supervisor in 1999. Without your continued support, scientific sharpness and ability to force me to focus, I would never have been able to finish this thesis. I would also like to thank you for your never-ending support of my many tangent activities and that you had the courage to come to IITA in Nigeria.

Thanx also to Dr. Lennart Mattsson, who patiently answered my many questions about the Swedish long-term field fertility experiments and to Dr. Jakob Magid, who ensured the success of the SLU-KVL collaboration!

Research funding

This work was in part funded by the Swedish Farmers Foundation for Agricultural Research (SLF), Skogs-och-Jordbrukets Forskningsråd (SJFR) and the Swedish International Development Cooperation Agency (Sida).

Not just work

My friends and family in Sweden– thanks ever so much for helping me get through this. A special mention goes to my mother Marta and my sister Anna, for helping me sieve 1500 kgs of soil, my father Christer for financial support during moments of crisis (which seemed to occur on a monthly basis !!!), Josefine, for helping me harvest (manually cut with scissors!) 750 pots of ryegrass, and Åsa and Paul, for helping me freeze-mill 250 soils. You guys …! If you ever need help, just call!

My friends in Nigeria; Karen, Danny, Ade, Polly, Vassily, Claudia, Leye – although I love Ibadan, I must admit that it was great to be able to discuss the madness of it on occasion.

Almost last but not least …

For those of you that know me, you know how important Bilbo, Olga, Synti, Breitling, and Spot are to me.

That special someone

Thanks for everything! Don’t forget to dream!