Ecology and Development Series No. 4, 2002

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# The potential benefit of green manures and inorganic fertilizers in cereal production on contrasting soils in eastern Uganda

Cuvillier Verlag Göttingen

# ABSTRACT

Nitrogen is the most limiting nutrient in farming systems of Uganda. Research was conducted in E. Uganda at six sites on a transect from Mt. Elgon (high altitude zone), through the medium altitude zone to low the altitude zone. The aim of this study was to evaluate the alternatives of using Velvet bean (*Mucuna pruriens*) as a green manure and using inorganic N fertilizer in improving maize production. The medium and high altitude zones are high-potential agricultural areas, with much more reliable rainfall and soils with high-productivity rating than the low-altitude zone, which is a low-potential area with lower, unreliable rainfall and soils with low-productivity rating. In addition, two more sites (Doho and Nakisenye) with contrasting rice production systems were included in the study to evaluate the benefits of either a mucuna – green manure, or an *Azolla* – green manure as well as inorganic fertilizers in rice production. Farmers in the Doho grow two rice crops in a year due to irrigation facilities. In contrast, Nakisenye farmers grow one rice crop a year during the long rains. As green manuring benefits are derived in the subsequent season, this study evaluated the benefits of the alternative systems over a two-season cycle.

Mucuna dry matter production and N accumulation was in the range 2.6 – 11.6 t ha$^{-1}$ (80 - 350 kg N ha$^{-1}$) and affected by altitude. The estimated quantity of N fixed was 34 - 150 kg ha$^{-1}$, with a local value of US \$ 26 - 115. In the subsequent season, a maize crop was used to evaluate the effects of the green-manure-N as compared to 40 and 80 kg N ha$^{-1}$. The site mean maize yield of the farmers practice (without inputs) was used to distinguish two types of fields at each site: low- and high-productivity, the yield from the former fields was below, and from the latter fields above the site mean. Significant ($P < 0.05$) differences in maize yield between the two groups of fields were attributed to differences in measurable chemical soil properties, except for Odwarat, where they were explained by the number of seasons the fields have been under cultivation, as a proxy for soil fertility differences not detectable by chemical methods.

There was a significant increase ($P < 0.05$) in maize yield in response to the alternative N strategies. The increase above that of the farmers′ practice was in the range 0.3 – 1.1 t ha$^{-1}$ for low-potential, and 0.8 – 2.6 t ha$^{-1}$ for high-potential agro-ecological zones. Application of P and K fertilizers with the alternative N strategies resulted in a significant increase ($P < 0.05$) in maize yield, with the greatest effect in low-potential agro-ecological zones, and at high levels of N (80 kg N or mucuna) across the agro-ecological zones. The aggregated maize yield over two seasons indicated highest yield increment of 2.7 t ha $^{-1}$ with the application of inorganic fertilizers, and of 1.9 t ha$^{-1}$ with a preceding mucuna relay on high-productivity fields in high-potential agro-ecological zones, compared to 1.3 t ha$^{-1}$obtained with both strategies on the low-productivity fields across the agro-ecological zones. The increase in maize grain yield in response to the application of P and K fertilizers when combined with the alternative N strategies was in the range 1.2 – 2.1 t ha$^{-1}$ for low potential, and 1.5 – 3.3 t ha$^{-1}$ for high potential agro-ecological zones. Mucuna as a fallow is effective in compensating for the yield loss during the period when the fields were under fallow across the agro-ecological zones.

There was a significant ($P = 0.05$) increase of 0.8 t ha$^{-1}$ grain in response to a preceding mucuna crop and to the application of inorganic N at Nakisenye. At Doho, the use of *Azolla* or the application of inorganic N was equally effective, resulting in an

increase of 1.4 t $ha^{-1}$ of grain; application of P and K fertilizers resulted in an additional 0.9 t $ha^{-1}$ of grain. The use of inorganic N fertilizers, mucuna and *Azolla* is economically viable in the rice farming systems.

Economic benefits are obtained with the use of alternative N strategies on highly productive fields in high-potential agro-ecological zones. For the poorer soils, only the mucuna relay gives economic benefits above that of the farmers' practice; other strategies are equally beneficial as the farmers practice. On the less-productive soils, in low-potential agro-ecological zones, none of the fertilizer-based strategies were economically viable at the current fertilizer prices. Only the relay cropping of mucuna would slightly improve the farmer's economic situation. To at least recover the extra cost of fertilizer use on low-productivity fields (for the 40, 80 kg N $ha^{-1}$ and the mucuna plus P relay), fertilizer prices would have to reduce by 10 - 40% in the low-potential areas, compared to 70 – 90% in high-potential areas. Therefore, irrespective of the technology applied, better returns will be obtained on more productive soils in high productive areas, while low-cost inputs like mucuna should be used in areas with low-productivity soils mainly to ensure food security, and to reduce nitrogen imbalance and farmer encroachment on to marginal lands. Variation in farmers' assessment of the strategies emphasizes the need to provide multi-purpose green manures, which can be tailored to prevailing conditions.

# KURZFASSUNG

Stickstoff ist der limitierende Nährstoff in den landwirtschaftlichen Anbausystemen Ugandas. Das Ziel der Untersuchung war, verschiedene Möglichkeiten der Anwendung von Mucuna (*Mucuna pruriens*, Samtbohne; als Gründünger) und anorganischer Düngemittel zur Steigerung der Maisproduktion zu bewerten. Die Forschungen wurden an sechs verschiedenen Standorten Ost-Ugandas, entlang eines Transektes vom Mt. Elgon (Hochlandzone) über die mittleren Höhenlagen bis in die Tieflandzone durchgeführt. Sowohl die mittleren Höhenlagen als auch die Hochlandzone gehören zu den ackerbaulichen Gunstgebieten mit regelmäßigen Regenfällen und fruchtbaren Böden. Die Tieflandzone ist ein ackerbauliches Ungunstgebiet mit geringeren und unregelmäßigen Niederschlägen sowie mit weniger fruchtbaren Böden. Zusätzlich wurden zwei weitere Standorte (Doho und Nakisenye) mit differierenden Reisanbausystemen in die Untersuchung mit einbezogen, um den Nutzen zweier als Gründünger verwendeter Pflanzen, Mucuna oder *Azolla*, und von anorganischen Düngemitteln, auf die Reisproduktion zu beurteilen. Die Landwirte in Doho bauen unter Nutzung von Bewässerungssystemen zweimal im Jahr Reis an. Demgegenüber erzielen die Landwirte in Nakisenye, während der Zeiten ausgiebiger Regenfälle, eine Reisernte im Jahr. Da der Nutzen der Gründüngung erst in der folgenden Anbauperiode erlangt wird, wurden in dieser Untersuchung die Auswirkungen der verschiedenen Systeme der Nährstoffanreicherung über zwei Anbauperioden hinweg er-forscht.

Die Trockemasseproduktion von Mucuna wurde von der Höhenlage beeinflußt und lag zwischen 2.6 und 11.6 t ha$^{-1}$, die der Stickstoffakkumulation zwischen 80 – 350 kg N ha$^{-1}$. Die geschätzte Menge fixierten Stickstoffs lag zwischen 34 und 150 kg ha$^{-1}$, was einem lokalen Wert von US $ 26 – 115 entspricht. In der folgenden Anbauperiode mit Mais ließen sich die Auswirkungen des Stickstoffs aus der Mucuna-Gründüngung mit denen einer Düngung durch 40 und 80 kg N ha$^{-1}$ vergleichen. Die durchschnittliche Maisernte bei der üblichen landwirtschaftlichen Praxis, also ohne Zusatz von Dünger, wurde herangezogen, um an dem jeweiligen Standort zwei Typen von Feldern zu unterscheiden: wenig produktive Felder bei einer unter dem Durchschnitt liegenden Ernte und hoch produktive Felder bei einer über dem Durchschnitt liegenden Ernte. Signifikante Unterschiede ($P < 0.05$) im Maisertrag bei den beiden Feldtypen sind zurückzuführen auf unterschiedliche, durch Messungen nachweisbare, Bodenbedingungen - mit Ausnahme des Standorts Odwarat, wo die Unterschiede im Ernteertrag auf die Anzahl der Anbaujahre, die den Untersuchungen vorausgegangen sind, beruhen.

Die verschiedenen Strategien der Stickstoffanreicherung hatten, verglichen mit der Ernte bei der üblichen landwirtschaftlichen Praxis, einen signifikanten Anstieg ($P < 0.05$) der Maisernte zur Folge. Der Anstieg lag zwischen 0.3 und 1.1 t ha$^{-1}$ in den agrarökologischen Ungunstgebieten und zwischen 0.8 und 2.6 t ha$^{-1}$ in den agrarökologischen Gunstgebieten. Ein signifikanter Anstieg ($P < 0.05$) der Maisernte wurde auch bei Anwendung von Phosphor-Kalium-Düngern, wenn sie mit weiteren N-Anreicherungsstrategien kombiniert wurden, verzeichnet. In den agrarökologischen Ungunstgebieten waren die Zunahmen im Ernteertrag am höchsten, wobei bei hoher Stickstoff-Dosierung (80 kg N oder Mucuna) eine Steigerung in allen agrarökologischen Zonen beobachtet werden konnte. Die über zwei Anbauperioden summierten Maiserträge zeigen bei der Verwendung von anorganischen Düngern mit 2.7 t ha$^{-1}$ den höchsten Ernteanstieg. Bei vorhergehendem Anbau mit Mucuna liegt der Anstieg bei 1.9 t ha$^{-1}$ auf den hoch produktiven Feldern in den agrarökologischen Gunstgebieten, während bei der Anwendung beider Strategien, auf den weniger produktiven

Feldern der Anstieg bei 1.3 t $ha^{-1}$ liegt. Die Verwendung von PK-Düngern, in Kombination mit anderen Stickstoff-Anreicherungsstrategien, wirkte sich auf die Steigerung des Maisertrages in den agrarökologischen Ungunstgebieten mit einem Anstieg zwischen 1.2 und 2.1 t $ha^{-1}$, in den Gunstgebieten mit einem Anstieg zwischen 1.5 und 3.3 t $ha^{-1}$ aus. In allen agrarökologischen Zonen hat sich die Verwendung von Mucuna als wirksam erwiesen, um den Ernteverlust der Bracheperiode auszugleichen.

Das Reisanbausystem in Nakisenye zeigte nach einem vorhergehenden Mucuna-Anbau und dem Aufbringen von anorganischen Stickstoff mit 0.8 t $ha^{-1}$ einen signifikanten Anstieg ($P = 0.05$) des Kornertrags. In Doho erwies sich die Verwendung von *Azolla* als genauso effektvoll wie das Aufbringen anorganischen Stickstoffs. Es erbrachte einen Anstieg der Erntemenge um 1.4 t $ha^{-1}$, während die Verwendung von PK-Düngern noch einmal eine Steigerung von 0.9 t $ha^{-1}$ bewirkte. Die Verwendung von anorganischem Stickstoffdünger, Mucuna und *Azolla* erwies sich in den Reisanbausystemen als ökonomisch vertretbar.

Ein wirtschaftlicher Gewinn wurde durch die Verwendung der verschiedenen N-Anreicherungsstrategien auf den hoch produktiven Feldern in den agrarökologischen Gunstgebieten erzielt. Auf den ärmeren Böden lässt sich der Gewinn, im Vergleich zur üblichen landwirtschaftlichen Praxis, nur durch die Verwendung von Mucuna steigern. Die anderen Anreicherungsstrategien sind genauso rentabel wie die derzeit angewandten Techniken. Bei den derzeitigen Düngemittelpreisen erwies sich auf den weniger produktiven Böden der agrarökologischen Ungunstgebiete keine der auf der Verwendung von Dünger basierenden Strategien als ökonomisch entwicklungsfähig. Lediglich der gleichzeitige Anbau von Mucuna unter Mais würde die wirtschaftliche Situation der Kleinbauern ein wenig verbessern. Um zumindest die Zusatzkosten für den Gebrauch von Düngemitteln auf den weniger produktiven Feldern wieder auszugleichen, müssten die Düngemittelpreise in den Ungunstgebieten zwischen 10 und 40%, bzw. zwischen 70 und 90 % in den Gunstgebieten, unter dem Normalpreis für 40, 80 Kg N $ha^{-1}$ bzw. für Mucuna incl. Phosphat, liegen. Folglich werden, unabhängig von der verwendeten Technologie, auf den hoch produktiven Böden der agrarökologischen Gunstgebiete die besseren Ernten erzielt, während die preiswerten Methoden der Nährstoffzufuhr, wie die Verwendung von Mucuna, in den Gebieten mit wenig produktiven Böden genutzt werden sollten, um die Nahrungsmittelproduktion zu sichern, Unausgewogenheiten der Stickstoffversorgung zu reduzieren und das Vordringen der Kleinbauern auf Grenzertragsstandorte zu verhindern. Die Variationsbreite der Einschätzung der verschiedenen Anreicherungsstrategien durch der Kleinbauern macht den Bedarf an vielseitig nutzbaren Gründüngungspflanzen, deren Verwendung an verschiedene aktuelle Bedingungen angepasst werden kann, deutlich.

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# LIST OF ABBREVIATIONS

| | |
|---|---|
| ANOVA | Analysis of variance |
| ARDC | Agricultural Research and Development Centre |
| BMZ | Bundesministerium für Wirtschaftliche Zusammenarbeit und Entwicklung |
| BNF | Biological Nitrogen Fixation |
| B/C | Benefit to cost ratio |
| Ca | Calcium |
| CEC | Cation-exchange capacity |
| CGIAR | Consultative Group of International Agricultural Research |
| CIMMYT | International Maize and Wheat Improvement Centre |
| cmolc $kg^{-1}$ | centimole per kilogram |
| C/N | carbon to nitrogen ratio |
| DAAD | Deutscher Akademischer Austauschdienst |
| DM | Dry matter |
| FAO | Food and Agriculture Organisation |
| IAEA | International Atomic Energy Agency |
| LSD | Least Significant Difference |
| K | Potassium |
| KARI | Kawanda Agricultural Research Institute |
| kg $ha^{-1}$ | kilogram per hectare |
| $k_m$ | mass loss constant |
| $k_N$ | Nitrogen release constant |
| mg $kg^{-1}$ | milligram per kilogram |
| N | Nitrogen |
| NARO | National Agricultural Research Organisation |
| Ndfa | N derived from air |
| Ndff | N derived from fertilizer |
| Ndfr | N derived from mucuna residues |
| $Ndff_F$ | N derived from fertilizer by fixing plant |
| $Ndff_{NF}$ | N derived from fertilizer by non-fixing plant |
| OM | organic matter |
| P | Phosphorus |
| t $ha^{-1}$ | tons per hectare |
| TVC | Technology verification centre |
| UNESCO | United Nations Education Scientific and Cultural Organisation |
| UgShs | Uganda Shillings |
| US$ | United States of America Dollar |
| Ø | diameter |

# 1 INTRODUCTION

Per capita agricultural production and crop yields per unit area of production in Uganda, like in other sub-Saharan African countries, is declining (IBSRAM 1994; Sanchez et al. 1996; FAO 1999). The main contributing biophysical factors are low inherent soil fertility, particularly nitrogen (N) and phosphorus (P) deficiencies (Nye and Greenland, 1960; Ssali et al. 1986; Bekunda et al. 1997), exacerbated by nutrient/soil fertility depletion (Vlek 1993; Sanchez et al. 1997a). In addition, a large number of the poorest people in sub-Saharan Africa live in marginal areas where markedly increased land, and labour productivity is unlikely (Vlek 1990).

A soil survey conducted in the late 1950's revealed that about a tenth of the total land area had soils with a productivity rating above medium, more than a quarter had soils rated as unproductive, hence leaving about one half of the land surface with soils rated as medium (Harrop 1970). A medium rating implies that the soils will only yield good crops under good management (Harrop 1970; Stephens 1970). The soil fertility is associated with soil organic matter (Foster 1981) and is found mainly in the top 0 - 30 cm. If topsoil is lost through erosion, the fertility and productivity are permanently lost (Stephen 1970). However, loss of nutrients as components of crop harvests as well as through runoff and soil erosion is on the increase in many of the farming systems. Smallholder farmers are unable to compensate for these losses by using crop residues and manures or purchasing mineral fertilizers, resulting in the negative nutrient balances reported at the national level for sub-Saharan Africa countries (Stoorvogel and Smaling 1990) and at the regional scale for the farming systems of eastern and central Uganda (Wortmann and Kaizzi 1998).

Smallholder farmers use low-input production technologies without appropriate soil and water management practices. They sustain their households through extensive production of food crops using most of the available land and labour resources (Vlek 1990). The farmers lack financial resources to purchase fertilizers to correct the inherent low fertility levels and replace the nutrients removed from the fields. Yet farmers either abandoned the traditional systems of restoring and sustaining soil fertility such as leaving land under fallow, use of animal manure and proper crop rotation, or, where these are being used, they are no longer able to cope with the rate of soil fertility decline.

Replenishing and enhancing soil N, P and K is essential for sustained productivity and for the rehabilitation of eroded and depleted soils. Soil fertility replenishment and enhancement will result in positive benefits such as increased soil cover with protective vegetation, and increased soil biological activity associated with enhanced crop production (Sanchez et al. 1997b). Soil fertility replenishment can be achieved through the use of inorganic fertilizers, organic fertilizers or their combination. Inorganic fertilizers are the only option available to improve and balance the loss of P and K. For N it can be achieved through the use of both inorganic fertilizers and Biological Nitrogen Fixation (BNF).

Unfortunately, social and economic factors do not favour the use of inorganic fertilizers by the smallholder farmers. In sub–Saharan Africa, inorganic fertilizers cost two to six times as much as those in Europe (Bumb and Baanante 1996; Sanchez 2002) mainly due to transport costs, and other charges (Vlek 1990). In addition, the profitability of fertilizer use is highly variable and dependent on agro-climatic and economic conditions at local and regional levels (Vlek 1990). Most farmers do not have access to credit, and the returns to fertilizers are low and variable (Badiane and Delgado 1995; Heisley and Mwangi 1996). Inorganic fertilizers are mainly used on cash crops such as tobacco, tea, and sugarcane, which can be marketed on a profitable basis (Vlek 1990). In addition, farmers are not aware of the forms of fertilizers, methods of their use and the potential benefits accruing from their use (Bekunda et al. 1997).

There are also constraints limiting the use of organic materials, including labor for collecting and applying the materials as in the case of biomass transfer (Ruhigwa et al. 1995), limited quantities and variation in quality of organic materials (Palm et al. 1997), and the demand for crop residues as fuel and fodder (Palm 1995). In the case of green manure or in-situ biomass production, farmers have to sacrifice land by keeping it out of food production (Giller et al. 1997), which they cannot afford especially in areas with high population density. Organic materials are not only frequently in limited supply, where they are used alone, the quantities may not provide the productivity boost needed by the smallholder farmers. Hence a judicious combination of available organic materials with inorganic fertilizers may be an appropriate option.

Cereals are important crops for the smallholder farmers in Uganda, and N is one of the factors limiting cereal production in the region. Only with a secure N supply can farmers increase cereal production and contribute to food security for the smallholder farmers. Their main concern to date is having enough food to take them up to the next harvest.

The strategies investigated in this study include the use of inorganic N fertilizers and the exploitation of BNF through the use of *Azolla* and Velvet bean (*Mucuna pruriens*), either as relay crops, or as an improved fallow. Since the study covered contrasting agro-ecological zones and contrasting soils, application of P and K fertilizers was required especially for poor soils and at high levels of N. The agronomic and economic benefits of these different strategies were evaluated in a series of production environments comprised of low and high productivity soils in favorable and marginal agro-ecological zones. Thus, the overall objective of the study was to determine the most suitable strategy for soil fertility maintenance for resource poor-farmers in eastern Uganda cultivating maize and rice on contrasting soils, and in contrasting agro-ecological zones. Specifically this study aims:

1. To determine mucuna biomass production and BNF with and without P fertilizers, on contrasting soils and in contrasting agro-ecological zones
2. To determine the decomposition and N release pattern of mucuna residues in these contrasting agro-ecological environments
3. To determine the N balance following the application of mucuna and inorganic fertilizer N on contrasting soils
4. To determine maize yield in response to the application of inorganic-N, and to a preceding mucuna fallow or relay crop on contrasting soils in contrasting agro-ecological zones
5. To evaluate rice yield in response to *Azolla,* mucuna or inorganic N fertilizers in contrasting rice production systems
6. To determine the economic benefits of using mucuna, *Azolla* and inorganic N fertilizers as N replenishment strategies for cereal production on contrasting soils in key agro-ecological zones of eastern Uganda

# 2 LITERATURE REVIEW

The wide-spread problems of low inherent soil fertility, declining soil fertility, and agricultural expansion to marginal areas call for urgent attention to ensure food security for the increasing population. Smallholder farmers are faced with several constraints which prevent them from using inorganic fertilizers, organic fertilizers, or their combination in soil fertility management. It is important that farmers make every effort to prevent nutrient depletion and conserve nutrients within the farming systems through proper soil and water conservation. Nitrogen is the main nutrient considered in this study, and response to N fertilizers by maize was reported in eastern Uganda (Foster 1973). Nitrogen can be replaced through the use of both inorganic fertilizers and by Biological Nitrogen Fixation (BNF). The BNF systems considered include the use of *Azolla* and herbaceous legume (mucuna) as green manure either in relay cropping or as an improved fallow both for maize and rice production systems.

## 2.1 Inorganic fertilizers

Bekunda et al. (1997) reviewed several fertility experiments in sub-Saharan Africa, and the results indicate positive yield response to one or more nutrients added as inorganic fertilizers, which highlights their effectiveness in increasing crop yields in arable farming within the region. Mokwunye and Vlek (1986) reported that yields of cereals are often tripled or quadrupled in response to fertilizers in sub-Saharan Africa. In addition, there are reports that application of K or S in combination with N and P increases crop yields, suggesting an increased need for inputs of these nutrients as N and P deficiencies are alleviated (Vlek 1990). This emphasises the need for greater use of inputs to remedy the nutrient deficiencies in sub-Saharan Africa. In areas where fertility depletion is already high, inorganic fertilizers are the only meaningful source for building up nutrients in the soil, because only small amounts of crop residue and animal manure are available (Bekunda et al. 1997).

## 2.2 Organic fertilizers

Organic materials play an important role in soil management. Palm et al. (1997) reported that organic materials serve as sources of nutrients, influence nutrient availability, serve as precursors to soil organic matter, and affect the release pattern of plant available nutrients. In addition, the organic matter added in manure or fallow vegetation is critically important to the sustainability of the traditional agricultural systems since it increases water entry and retention, counteracts adverse phenomena like structure degradation and a decreasing cation-exchange capacity (CEC). Foster (1981) reported that the CEC of the soils in Uganda is largely dependent on soil organic matter content.

### 2.2.1 Biological nitrogen fixation

Biological nitrogen fixation (BNF) as a nitrogen source can be exploited for increased productivity through the use of grain-, herbaceous-, forage-, and woody-legumes, and the aquatic fern *Azolla* in the farming systems of sub-Saharan Africa. Giller and Cadisch (1995) reported that BNF contributes to productivity both directly, when the fixed N is harvested in grain or other food for human or animal consumption or indirectly by adding N to the soil and thus contributing to the maintenance or enhancement of soil fertility in the agricultural system. Under favorable environmental conditions of good supply of nutrients, moisture availability and good pH (Thomas 1995; Wani et al. 1995; Peoples et al. 1995) BNF can meet N requirements and sustain tropical agriculture (Giller et al. 1994, 1997).

Economic considerations make BNF an attractive N source for resource-poor farmers (Giller and Wilson 1991) and the most practical solution for the low-input cropping systems typical in sub-Saharan Africa (Van Cleemput 1995). However, for biological N fixing systems to provide a substantial amount of N to the system, it is essential to ensure good legume growth, which also may require the use of fertilizers (Giller and Wilson 1991; Giller and Cadisch 1995). Phosphorus deficiency is sometimes a constraint to the realization of the potential of N fixation by legumes as it reduces yield, and lowers tissue-%N (Thomas 1995; Houngnandan et al. 2001). Phosphorus fertilization can be necessary for effective growth and N fixation by legumes (Ssali and Keya 1986),

### 2.2.2 Decomposition and N release

The N accumulated by legumes is in the organic form as part of the legume biomass and can be made available to associated cereal crops through the mineralisation process in the soil. The decomposition and nutrient release patterns are determined by climatic, edaphic and chemical characteristics of the organic materials (Swift et al. 1979). The N release pattern is related to chemical characteristics of the organic material (Heal et al. 1997). High quality materials have a low lignin content < 15% (Palm 1995), a low polyphenol content < 3 – 4% (Palm and Sanchez 1990), low (polyphenol/N) ratio (Palm and Sanchez 1991; Oglesby and Fownes 1992), low (lignin/N) ratio (Melillo et al. 1982; Kachaka et al. 1993) and low (lignin + polyphenol)/N ratio (Fox et al. 1990). Lignin and polyphenols are particularly important modifiers of N release from the fresh, non-senescent leaves of high-quality materials (Constantinides and Fownes 1994).

### 2.2.3 Synchronisation

Most leguminous materials are of high quality (Heal et al. 1997), decompose quickly and rapidly release their nutrients (Giller et al. 1997). Approximately 70-95% of the added residue N is released during the first cropping season under tropical conditions. However, the N recovery by the first crop is usually in the range 6-28% in the case of green manures (Giller and Cadisch 1995). The poor N uptake is associated with gaseous losses or leaching, and due to lack of synchrony between crop N demand and N release. Sanchez et al. (1989) and Schroth et al. (1992) emphasized the need for synchronising the nutrient release with plant demand so as to increase both the N uptake by plants and the overall recovery within the system. However, the nutrients released at times of lower plant demand are not necessarily lost from the system; some of the N released is immobilized in the soil microbial biomass, which is both a dynamic sink and a source of nutrients, and thus contributes to the reduction in nutrient loss.

## 2.3 Legumes as green manure

Herbaceous legumes, like mucuna, can be used in farming as green manure in relay systems or improved fallows. Under such circumstances they are grown specifically for use as organic manure. However, little research has been conducted specifically on N fixation by legume green manure (Giller 2001). Under favorable conditions, it is estimated that herbaceous legumes can accumulate 100 to 200 kg N ha$^{-1}$ in 100 - 150 days in the tropics with a significant portion derived from BNF (Giller et al. 1994). In West Africa, Sanginga et al. (1996), Becker and Johnson (1998), Ibewiro et al. (2000), and Houngnandan et al. (2000) reported N fixation by mucuna in the range of 55-86%

of the total N accumulated by mucuna, while in East Africa, 68% of the total N in mucuna was derived from BNF (Wortmann et al. 2000).

Significant crop response to green manure from preceding short-term legume fallow has been reported in sub-Saharan Africa by several authors. In West Africa, Versteeg et al. (1998) reported a 70% increase in maize grain yield following mucuna fallow. This increase was attributed to the large amount of N fixed by mucuna (Sanginga et al. 1996; Ibewiro et al. 2000; Tian et al. 2000). Becker and Johnson (1998) reported a 30% increase in the grain yield of rice following a legume fallow.

Research conducted in Uganda during the 1920's at Bukalasa (Intensive Banana-coffee lakeshore farming system) and Serere (Teso farming system) indicated that crop yields following shifting cultivation were higher than following mucuna, crotalaria, centrosema and leucaena (Martin and Biggs 1937). However, significant yield increases in response to preceding green manures were obtained in recent trials in the country. In a bi-modal rainfall zone of Uganda, mean maize grain yields following *Crotalaria ochroleuca* were 80% higher than after maize (Wortmann et al. 1994; Fischler 1997; Fischler et al. 1999), and 60% higher following mucuna (Fischler 1997), indicating that with the shortening of the fallow period, green manure plays a role in soil fertility improvement.

## 2.4 *Azolla* as green manure

The aquatic fern *Azolla* has been used widely in rice systems. It can accumulate 40-90 kg N ha$^{-1}$ within a period of 30 - 46 days (Watanabe 1982) of which more than 80% is derived from BNF (Kikuchi et al. 1984; Watanabe et al. 1991). Results from 12 sites in Asia indicated that *Azolla* increased rice grain yield on average by 500 kg ha$^{-1}$, equivalent to the addition of 30 kg N ha$^{-1}$ as urea (Kumarasinghe and Eskew 1991, 1993) and by 600-750 kg ha$^{-1}$ in a series of 1500 experiments in China (Lumpkin and Plucknett 1982). In addition, the presence of a dense mat of *Azolla* on the surface of the floodwater lowers the pH, and reduce losses of fertilizer N through ammonia volatilization resulting in increased N fertilizer recovery by rice (Kumarasinghe and Eskew 1993; Vlek et al. 1995). The main limiting agronomic factors for the use of *Azolla* are low phosphorus availability, lack of water, insect pests, and inhibition of growth by high temperatures (Boddey et al. 1997; Giller 2001).

## 2.5 Decline in green manure use

The use of legumes and the aquatic fern *Azolla* for maintenance of soil fertility as green manures has declined in many countries where N fertilizers are widely available (Giller and Cadisch 1995). This is partly attributed to the additional labor required for using green manures, and the intensification of cropping systems leading to land being continually required for production. Green manure has potential in the agricultural systems of the smallholder farmers in Uganda, because it is of low external input type.

## 2.6 Remaining gaps

Smallholder farmers in Uganda are faced with the problem of low inherent and declining soil fertility, yet there is a need to increase agricultural production in the country for food security. Research conducted on the use of green manure focused in the Lake Victoria Crescent agro-ecological zone. However, no effort has been made to quantify the potential benefits of green manures and inorganic fertilizers in cereal production on contrasting soils and in contrasting agro-ecological zones. In addition, *Azolla* is abundant at the Doho irrigation scheme, where farmers consider it an obnoxious weed. They remove it from the field, which is a waste of a potential source of N in the low-input systems.

Due to several constraints hindering the use of both organic and inorganic fertilizers, and the scarcity of resources, it is important to understand the fertilizer (organic or inorganic) requirements in different soils and cropping systems, to determine the benefits of the alternative strategies, and to come up with the most cost-effective strategy to meet the N requirement of cereals on contrasting soils in Uganda.

Therefore, a study to evaluate the benefits of inorganic fertilizers, *Azolla* and mucuna in cereal production and to quantify the amount of N fixed by Mucuna on contrasting soils in Eastern Uganda is timely.

# 3 MATERIALS AND METHODS

**Sites and types of trials**

The study was conducted at eight sites in three agro-ecological zones, with variability in altitude, soil productivity, land-use intensity, and agricultural potential. Two types of trials were conducted, on-station (researcher-managed) and on-farm (farmer-managed) trials, using maize as the test crop. The six sites under the maize production system run from high altitude, through mid-altitude to low-altitude. The two sites under rice captured two contrasting rice production systems, with one site growing rice throughout the year due to the availability of irrigation water, compared to the other site where rice growing is only possible during the long rains.

## 3.1 Researcher-managed trials

### 3.1.1 Site description

Researcher-managed trials were conducted at two sites in eastern Uganda namely: Kibale Technology Verification Center (TVC) and Bulegeni Agricultural Research and Development Center (ARDC). The sites are located on contrasting soils and in contrasting agro-ecological zones; hence they are representative of the sites used for on-farm trials. Bulegeni ARDC represents high and medium altitude zones of high agricultural potential, and Kibale TVC represents lower altitude zone of low agricultural potential. The agricultural potential is determined primarily by the quantity and variability in rainfall, FAO-UNESCO soil classes and the parent materials of the soils. The purpose of the trials was to generate information to be used in explaining the data obtained in parallel on-farm trials. Prior to the commencement of the trials, composite soil samples were collected for analysis. The characteristics of the sites are indicated in Table 1.

Table 1: Site characteristics for Kibale and Bulegeni

| | Location | |
|---|---|---|
| | Kibale TVC | Bulegeni ARDC |
| Location | | |
| Altitude (m asl) | 1132 | 1430 |
| Latitude | 1° 12’ N | 1° 18’ N |
| Longitude | 33° 47’E | 34° 20’E |
| Mean annual precipitation (mm) | 1370 | 1850 |
| Agro-ecological zone | Southern and eastern Lake Kyoga basin | Jinja and Mbale farmlands |
| FAO-UNESCO classification[a] | Ferralsols | Andosols |
| Mapping unit[b] | Buruli catena | Sipi catena |
| Productivity rating[b] | Low – medium | High |
| Parent material[b] | B.C gneiss & granite | Volcanic ash & rocks |

[a]Source: Ssali (2000) [b]Harrop (1970)

### 3.1.2 Experimental description

**The first season (2000B)**

***Mucuna biomass production***

The second rainy season of 2000 (2000B season) was used mainly for growing mucuna that would be used in the trials of the first season in 2001 (2001A season). The biomass production of mucuna fallow was assessed as well as its productivity and effect on maize in a relay crop.

The field at Kibale TVC was prepared using ox-ploughs, whereas a tractor was used at Bulegeni ARDC. The individual plot size was 6 m x 4.5 m, with six rows each 6 m long. The trials were laid out in a randomized complete block design using three replicates at Kibale TVC and four replicates at Bulegeni ARDC.

The treatments during the 2000B season (August – December) were (i) maize - control (farmer practice), (ii) maize, (iii) maize, (iv) maize, (v) maize, (vi) maize, (vii) maize + mucuna (relay), (viii) maize + mucuna (relay) + 25 kg P ha$^{-1}$, (ix) mucuna fallow, and (x) weedy fallow. Phosphorus fertilizer (25 kg ha$^{-1}$) was applied at planting.

“Longe 1”, an open-pollinated maize variety was planted at the recommended spacing of 75 cm x 60 cm on 8th August 2000 at Bulegeni ARDC and on 12th August 2000 at Kibale TVC and thinned after germination leaving two plants per hill. Beta-cyfluthrin 0.05-2.5% (Bulldock) was applied 3-4 weeks after the maize had germinated to control the maize stalk borer, and Chloropyrifos 5% (Dursban) was used whenever there were signs of termite attack.

Mucuna was planted on 14th September 2000 at Bulegeni ARDC and on 15th September 2000 at Kibale TVC, at a spacing of 75 cm x 60 cm under sole crop production, whereas in an intercrop it was planted between two maize rows. Weeds were controlled using hand hoes.

**Data collection.** Maize (grain and stover) yield was determined by harvesting a 3 m x 4.2 m area (middle 4 rows 4.2 m long) at maturity. Sub-samples were collected for moisture determination and the grain yield was adjusted to 14% moisture content.

Mucuna biomass production was determined after 22 weeks by harvesting an area equivalent to $3m^2$ using a $1m^2$ quadrant placed randomly at three different places. All materials within the quadrant including litter were collected and weighed. Sub-samples (including leaves, pods and vines) were dried at 70° to a constant weight for moisture determination and ground for N, P and K determination at the KARI soils and plant-tissue laboratory.

### *Estimation of biological nitrogen fixation*

The experiment was conducted at Kibale TVC and Bulegeni ARDC, using a main plot size of 6 m x 4.5m, with micro plots of 3 m x 2.4 m, laid out in a randomized complete block design with three replicates. The treatments were (i) mucuna (ii) mucuna + 25 kg P $ha^{-1}$ and (iii) Luffa (*Luffa cylindrical* (L.) Roem.). Luffa was used as reference plant. Mucuna and Luffa were planted at a spacing of 75 cm x 60 cm on 14th September 2000 and 16th September 2000 at Kibale TVC and Bulegeni ARDC, respectively. Twenty kg N $ha^{-1}$ with 5 at. % excess $^{15}N$ was applied to mucuna, while 100 kg N $ha^{-1}$ with 1 at. % excess $^{15}N$ was applied to luffa. The labeled fertilizers were prepared from a stock of ammonium sulphate fertilizer with 10.19% $^{15}N$ abundance.

The fertilizers were calculated using the equation (IAEA 1990):

$$m_1 = \left( \frac{(m_1 + m_2)a'}{a'_1} \right) \tag{1}$$

where:

$m_1$ = quantity of fertilizer with 10.19% $^{15}$N abundance

$m_2$ = quantity of fertilizer at natural abundance

$a'_1$ = % $^{15}$N excess of material of higher $^{15}$N enrichment (9.824)

$a'$= % $^{15}$N excess desired in the final mixture

Phosphorus fertilizer was applied at planting. Labeled N fertilizers were applied to the soil in solution in four equal splits at 2-week intervals with the first dose at planting.

Plants were sampled after 22 weeks using a 1m$^2$ quadrant placed in the centre of the micro plot. The biomass in the quadrant was separated into three components (vines, leaves and pods) and weighed in the field. Sub-samples were collected, dried at 70°C, weighed, and ground for $^{15}$N analysis. $^{15}$N was determined at the Institute of Agricultural Chemistry, University of Bonn, by mass spectrometry using an ANCA-SL coupled to 20 – 20 stable isotope analyzer IRMS - PDZ Europa. The biomass produced by mucuna and luffa was determined in a similar way for the designated harvest areas. The amount of N fixed by mucuna was estimated by using the isotope dilution method (IAEA 2001).

The percentage of N derived from the air (%Ndfa) was calculated using the equations (2) to (5) below (IAEA 2001):

$$\%Ndfa = 100\left(1 - \frac{\%Ndff_F}{n\%Ndff_{NF}}\right) + \%Ndff_F\left(\frac{1}{n-1}\right) \tag{2}$$

$$n = \left( \frac{\text{Amount of fertilizer applied to a fixing crop}}{\text{Amount of fertilizer applied to a non - fixing crop}} \right) \tag{3}$$

The percentage of N in the plant derived from fertilizers (%Ndff) was calculated using the equation (4) below (IAEA 2001):

$$\%Ndff = \left( \frac{Atom\,\%\ {}^{15}N\ excess\ of\ the\ plant}{Atom\,\%\ {}^{15}N\ excess\ of\ fertilizer} \right) \times 100 \tag{4}$$

The amount N fixed (Ndfa) and N yield were calculated according to the equations (5) to (8) below (IAEA 2001):

$$Ndfa\ (kg\ ha^{-1}) = \left( \frac{\%\ Ndfa\ x\ total\ N\ in\ plant}{100} \right) \tag{5}$$

$$N\ yield\ (kg\ ha^{-1})\ of\ each\ plant\ part = \left( \frac{Dry\ matter\ yield\ of\ each\ plant\ part\ x\ \%N}{100} \right) \tag{6}$$

$$\text{N fertilizer yield (kg ha}^{-1}\text{)} = \left( \frac{\text{(N yield (kg ha}^{-1}\text{) x \%Ndff}}{100} \right) \tag{7}$$

$$\%Ndff\ (weighted\ average) = \left( \frac{Total\ N\ fertilizer\ yield}{Total\ N\ yield} \right) \times 100 \tag{8}$$

where:

Ndfa = N derived from air (kg ha$^{-1}$)

%Ndff = percentage of N in plant derived from fertilizer

%Ndff$_F$ = percentage of N derived from fertilizer by fixing plant

%Ndff$_{NF}$ = percentage of N derived from fertilizer by non-fixing plant

### *Production of $^{15}$N-labeled mucuna*

The $^{15}$N-labeled mucuna for use in the N uptake and balance study at Bulegeni ARDC and Kibale TVC during the 2001A season was produced at Kawanda Agricultural

Research Institute (KARI), Ssenge farm (0°24'N, 32°31'E), at an altitude of 1200 m above sea level. The soil at the site is classified as Rhodic Kandhapludalf, with the following surface (0-20 cm) soil properties: pH of 5.0; organic carbon, 1.7%; available P, 2.25 mg kg$^{-1}$; exchangeable Ca 3.18 cmol$_c$ kg$^{-1}$, and exchangeable K 0.20 cmol$_c$ kg$^{-1}$.

Mucuna was planted on 3rd September 2000 in a field 26 m x 25 m, split into five equal strips and received 100 kg N ha$^{-1}$ with 5 at. % excess $^{15}$N prepared from ammonium sulphate fertilizer stock of 10.19% $^{15}$N abundance. The fertilizer was applied in solution in two equal splits at 2-week intervals. The amount of fertilizers required was calculated using equation (1) in the previous section.

Mucuna was harvested after 16 weeks, dried in the field, and stored at KARI until the time for its application at Kibale TVC and Bulegeni ARDC. To check for the uniformity of $^{15}$N labeling, the mucuna field was split into 5 strips, and 3 samples were collected from each strip, giving a total of 15 samples from the entire field. The samples were dried, finely ground and analyzed for total N and $^{15}$N at the Institute of Agricultural Chemistry, University of Bonn, by mass spectrometry using an ANCA-SL coupled to 20-20 stable Isotope analyzer IRMS -PDZ Europa.

### The second season (2001A)

#### *Mucuna decomposition and N release*

Hundred grams (oven dry weight) of mucuna residues were placed in 30 cm x 30 cm polyethylene litterbags with a mesh size of 5 mm, allowing access by soil meso- and micro fauna (Swift et al. 1979). The litterbags were randomly placed between rows of maize on the soil surface in treatments (vii) to (ix) at Kibale TVC, Bulegeni ARDC and (iv) to (vi) at Kongta, that was previously under mucuna. Four litterbags were retrieved at each sampling time per site. The contents were cleaned by hand to remove roots and mineral soil, weighed, ground and total N content determined by Kjeldahl digestion (Anderson and Ingram 1993). Sub-samples were combusted in a muffle furnace at 550°C for 4 hours to correct for mixing with mineral soil. Ash weights were determined, and subtracted from the original dry weights of the sub-sample to determine the amount of plant material in the sub-sample on ash-free weight basis. The amount of N remaining was determined as the weight of the material multiplied by the N content.

The single exponential equation, $Y = e^{-kt}$, was used to calculate the decomposition and N release rate constants, $k$, at each site, where $Y$ is the percentage of initial weight of material, or N remaining at time $t$ in weeks (Wieder and Lang 1982). The rate constants were subjected to ANOVA to test for differences in decomposition rates at the different sites.

***Maize response to alternative treatments in preceding season***

During the 2001A season, maize was planted in the field used in 2000B season. The fields were prepared using hand hoes. The 2001A treatments were superimposed on those of the previous season. The treatments are listed in Table 2 below.

Table 2: Treatments during 2000B and 2001A seasons at Bulegeni and Kibale

| Number | Season | |
|---|---|---|
| | 2000B | 2001A |
| I | Maize | Maize |
| ii | Maize | Maize + 40 kg N ha$^{-1}$ |
| iii | Maize | Maize + 80 kg N ha$^{-1}$ |
| iv | Maize | Maize + 25 kg P ha$^{-1}$ |
| v | Maize | Maize+ (40 kg N + 25 kg P) ha$^{-1}$ |
| vi | Maize | Maize+ (80 kg N + 25 kg P) ha$^{-1}$ |
| vii | Mucuna relay | Maize |
| viii | Mucuna relay + 25 kg P ha$^{-1}$ | Maize |
| ix | Mucuna fallow | Maize |
| x | Weedy fallow | Maize |

The mucuna residues were chopped into pieces 12 cm long and placed on the soil surface. The residues were applied on the surface at rates of 12 t ha$^{-1}$ at Bulegeni ARDC and 8 t ha$^{-1}$ at Kibale TVC, corresponding to the site mean biomass yield of mucuna. “PANNAR 67”, a maize hybrid, was planted at the higher altitude/agricultural potential site (Bulegeni ARDC), receiving more rainfall. “Longe 1”, an open pollinated variety (OPV), was planted at the lower altitude/agricultural potential site (Kibale TVC), which receives less rainfall. Maize was planted in the thick mulch of mucuna on 17th March 2001 at Kibale and on 23rd March 2001 at Bulegeni. Phosphorus (25 kg P ha$^{-1}$), and the first split of N (20 and 40 kg N ha$^{-1}$) were applied to the targeted plot at planting, and the second N split (20 and 40 kg N ha$^{-1}$) applied when the maize was 1m high. Beta-cyfluthrin 0.05-2.5% (Bulldock) was applied 3-4 weeks after the maize had germinated to prevent damage by the maize stalk borer, and Chloropyrifos 5% (Dursban) was used for controlling the termites.

**Data collection.** Maize (grain and stover) yield was determined by harvesting an area 3 m x 4.2 m (middle 4 rows, 4.2 m long) at maturity (130 and 165 days for "Longe 1" and "PANNAR", respectively). The maize stover was left in the field. Sub-samples were collected for moisture determination and the grain yield was adjusted to 14% moisture content.

***N balance study (Fate of applied N)***

To study the fate of applied inorganic and mucuna N in the soil-plant system, 40 kg N ha$^{-1}$ ammonium sulphate labeled with 5 at. % excess $^{15}$N and $^{15}$N-labeled mucuna residues were applied to micro plots of 3.0 m x 2.4 m, installed in the center of the main plots for treatments (ii), (v), (viii), and (ix) described above. The micro plots were enclosed in aluminium sheet borders driven 50 cm deep into the soil, with 10 cm remaining above the ground to prevent lateral movement of labeled N and to confine the maize roots within the micro plots (Stumpe et al. 1989). The area outside the micro plots received unlabeled fertilizer at the equivalent N rate (40 kg N ha$^{-1}$), while those for mucuna treatments received equivalent quantities of unlabeled mucuna residues.

The inorganic-N was applied in two splits first at planting, and again when the maize was 1m high. The labeled fertilizer was applied in a furrow (8 cm deep) and 10 cm from the maize row and covered with soil. The mucuna residues from the previous crop were removed from the micro plot areas only and replaced with the $^{15}$N-labeled residues, which was also applied as mulch at planting.

**Data collection.** At maturity, eight maize plants in the center of the micro plot (four plants from two central maize rows) were harvested and separated into two components (grain and stover), dried at 70°C, weighed, and ground for $^{15}$N analysis.

Soil samples were taken from the center of the micro plot in an area of 1m$^2$. The entire top layer (0-15 cm) of soil was removed and mixed, and a composite sample was taken for $^{15}$N analysis. Samples were taken from the 15 – 30 cm and 30 – 60 cm soil layers by auguring (five 2.5 cm Ø cores for each layer). Soil bulk density was determined for each of the soil layers. The soil samples were air-dried and ground to pass a 2 mm sieve. Soil and plant $^{15}$N was determined at the Institute of Agricultural Chemistry, University of Bonn, by mass spectrometry using an ANCA-SL coupled to

20 – 20 stable isotope analyzer IRMS - PDZ Europa. The $^{15}$N was used to estimate plant uptake of inorganic fertilizer-N, of N mineralised from mucuna residues, and the amount of N remaining in the soil at harvest and the N balance.

The percentage N in maize derived from mucuna residues % (Ndfr) was calculated according to the equation (9) below (IAEA 2001):

$$\%Ndfr = \left( \frac{Atom\,\%^{15}N\ excess\ in\ the\ crop}{Atom\,\%^{15}N\ excess\ in\ the\ mucuna\ residues\ added} \right) \times 100 \tag{9}$$

The quantity of N derived from the mucuna residues (Nrec) was calculated according to equation (10) below (IAEA 2001):

$$Nrec.(kg) = \left( \frac{\%Ndfr\ x\ total\ N\ in\ maize}{100} \right) \tag{10}$$

Percentage recovery of N from mucuna residues (%Nrec) was calculated according to equation (11) below (IAEA 2001):

$$\%Nrec. = \left( \frac{Ndfr\ (kg)}{Amount\ of\ N\ added\ in\ mucuna\ residues} \right) \times 100 \tag{11}$$

The percentage of N in maize derived from fertilizers (%Ndff) was calculated according to the equation (12) below (IAEA 2001):

$$\%Ndff = \left( \frac{Atom\,\%\ ^{15}N\ excess\ in\ the\ maize}{Atom\,\%\ ^{15}N\ excess\ of\ the\ fertiliser} \right) \times 100 \tag{12}$$

The quantity of N derived from fertilizers (Ndff) was calculated according to equation (13) below (IAEA 2001):

$$Ndff\,(kg) = \left( \frac{\%Ndff\ x\ total\ N\ in\ maize}{100} \right) \tag{13}$$

Percentage recovery of fertilizer N calculated according to equation (14) below (IAEA 2001):

$$Nrec. = \left( \frac{Ndff\ (kg)}{Amount\ of\ \ fertiliser\ N\ added} \right) \times 100 \tag{14}$$

where: Ndfr = amount of N derived from mucuna residues

Ndff = amount of N derived from fertilizer

Equivalent calculations were done to trace $^{15}$N in the soil (IAEA 2001).

### 3.1.3 Laboratory analysis

**Soil and plant analysis**

Soil samples were air-dried and ground to pass a 2 mm sieve and analysed at KARI according to the Foster (1971) methodology. Extractable P, K and Ca were measured in a single ammonium lactate/acetic acid extract buffered at pH 3.8. Soil pH was measured using a soil to water ratio of 1:2.5.

Plant samples were dried in an oven at 70˚C, ground to pass a 0.5 mm sieve and analysed for total N, P and K by Kjeldahl digestion with concentrated sulphuric acid (Anderson and Ingram 1993). P was determined calorimetrically, and K by flame photometry.

Plant and soil samples from the BNF and N balance studies were sent for total N and $^{15}$N analysis at the Institute of Agricultural Chemistry, University of Bonn, by mass spectrometry using an ANCA-SL coupled to 20-20 stable isotope analyzer IRMS - PDZ Europa.

### 3.1.4 Statistical analysis

Data was examined by ANOVA using the general linear model, and comparisons of treatment means were made by least significant difference (LSD) using Statistix V.2.0 (Statistix for Windows, Analytical Software, 1998).

## 3.2 On-farm (farmer-managed) trials

### 3.2.1 Maize system

### 3.2.1.1 Site description

On-farm research was conducted at four sites in Eastern Uganda namely: Kongta, Nemba/Kasheshe, Agonyo II, and Odwarat. The sites are located along a transect which captures variability in altitude, soil productivity, land use intensity and agricultural potential, and covering three agro-ecological zones namely: Mt. Elgon High Farmlands; Jinja and Mbale Farmlands; and Southern and Eastern Lake Kyoga basin.

The characteristics of the sites are listed in Table 3.

Table 3: Site characteristics for Kongta, Nemba/Kasheshe, Odwarat and Agonyo II

| | Site | | | |
|---|---|---|---|---|
| | Kongta | Nemba/Kasheshe | Odwarat | Agonyo II |
| Location | | | | |
| Altitude (m asl) | 1890 | 1432 | 1071 | 1060 |
| Latitude | 1° 18'N | 1° 19'N | 1° 27'N | 1° 30'N |
| Longitude | 34° 48'E | 34° 20'E | 33° 48'E | 33° 24'E |
| Mean annual precipitation (mm) | 2000 | 1850 | 1310 | 1350 |
| Agro-ecological zone | Mt. Elgon high farmlands | Jinja and Mbale farmlands | Southern and Eastern Lake Kyoga basin | Southern and Eastern Lake Kyoga basin |
| FAO-UNESCO classification[a] | Humic Andosols | Andosols | Plinthic Ferralsols | Ferralsols |
| Mapping unit[b] | Benet series | Sipi catena | Amuria catena | Buluri catena |
| Productivity rating[b] | Medium | High to medium | Low | Low to medium |
| Parent material[b] | Elgon volcanics | Volcanic ash and rocks | Lake deposits from B.C granite, gneiss | B.C granite, gneiss |

[a]Source: Ssali (2000); [b]Harrop (1970)

### 3.2.1.2 Experimental description

**Characterisation of farmers' fields**

The trials were set up on 20 randomly selected farmers' fields at each site and were managed by farmers, with each farm acting as a replicate. The farmers' fields were characterised through analysis of composite soil samples collected from the 0-20 cm depth prior to the initiation of the trials. The soil was analysed for pH, organic matter, extractable P, K and Ca, as described above.

### The first season treatments (2000B season)

#### *Mucuna biomass production*

The experiment carried out over two seasons aiming at an assessment of overall productivity. The 2000B season was mainly for testing mucuna as an alternative to maize. In the 2001a season, the effects of these alternatives on maize were evaluated. Fields were prepared using ox-ploughs, except in Kasheshe/Nemba where hand hoes were used. The plot size was 6.0 m x 4.5 m, (with 6 maize rows, 6 m long). The treatments during the 2000b season (August – December) were (i) maize - control (farmer practice), (ii) maize, (iii) maize, (iv) maize + mucuna (relay) + 25 kg P ha$^{-1}$, (v) maize + mucuna (relay), (vi) mucuna fallow, and (vii) weedy fallow.

A maize variety ("Longe 1") was planted at the recommended spacing of 75 cm x 60 cm and was thinned after germination leaving 2 plants per hill. Phosphorus fertilizer (25 kg ha$^{-1}$) was applied at planting. Mucuna was planted one month after sowing the maize at a spacing of 75 cm x 60 cm as a sole crop, or in an intercrop between two maize rows. Weeds, maize stalk borer and termite control, and data collection were carried out as at the on-station trials.

#### *Maize response to treatments in the preceding season (2001A season)*

During the subsequent 2001A season (March – July), field preparation was done using hand hoes on all sites. The following treatments were super-imposed on those of the previous season. However, all the plots except the farmer practice were split into two, with one half receiving P (25 kg P ha$^{-1}$) and K (60 kg K ha$^{-1}$) fertilizers, and the other half receiving N either as inorganic fertilizer or mucuna–derived N only. For the preceding mucuna fallow or relay, maize was planted within the mucuna mulch. "PANNAR 67", a maize hybrid, was planted at the higher and mid–altitude, more productive Kongta and Nemba/Kasheshe sites, which received more rainfall. "Longe 1", an open-pollinated variety (OPV), was planted at the lower altitude, less productive Odwarat and Agonyo II sites, which receive less rainfall. The P fertilizers (25 kg ha$^{-1}$), and the first dose of N and K were applied at planting, whereas the second dose of N and K was applied when the maize was 1m high. Weeds and termites were controlled as in the previous season. The treatments are listed in Table 4 below.

Table 4: Treatments during 2000B and 2001A seasons at the different on-farm sites

| | Season | |
|---|---|---|
| Number | 2000B | 2001A |
| i | Maize (farmers' practice) | Maize |
| ii | Maize | Maize + 40 kg N $ha^{-1}$ |
| iii | Maize | Maize + 80 kg N $ha^{-1}$ |
| iv | Mucuna relay + 25 kg P $ha^{-1}$ | Maize |
| v | Mucuna relay | Maize |
| vi | Mucuna fallow | Maize |
| vii | Weedy fallow | Maize |

Maize (grain and stover) yield was determined by harvesting an area 3 m x 2.4 m at maturity (130 and 165 days for Longe 1 and PANNAR, respectively). The maize stover was left in the field. Sub-samples were collected for moisture determination and the grain yield was adjusted to 14% moisture content.

At each site, the farmer's fields were grouped into low and high yielding/productivity groups using the 2001A season mean yield from the farmers' practice (control plot) of the site. Fields with yields above the site mean were designated group I (high yielding/productivity), and those below the site mean were designated as group II (low yielding/productivity) fields.

The sites were divided into two groups using the FAO – UNESCO soil classes, soil productivity, amount of rainfall and its reliability as criteria. Kongta and Kasheshe/Nemba were considered as one group representing high-potential areas, whereas Odwarat and Agonyo II represented low-potential areas. The grouping resulted in four classes of production environments, and allows an evaluation of the tested technologies across these environments, both in agronomic and economic terms.

### *Economic analysis*

The partial budget concept for the different strategies was determined according to the CIMMYT (1988). The costs included maize, rice and mucuna seeds, N, P and K fertilizers, ploughing, labor for applying fertilizers, harvesting, and incorporating *Azolla*. Additional costs for rice included labor for opening up of ridges, guarding rice fields, spraying, pesticides, and transport to mills and milling charges. Family labor was assessed at market value.

The economic benefits were determined for the combined 2000B and 2001A seasons, which are equivalent to one year. The combined maize production during the 2000B and 2001A seasons is used as a reference, since farmers lose a full crop by leaving the land under either a mucuna fallow or weedy fallow. Items included under the partial budget are listed in Table 5.

Table 5: Items used in the partial budget to determine the economic benefits of the alternative strategies

| Item | Description | Notes |
|---|---|---|
| 1 | Average yield (kg $ha^{-1}$) | |
| 2 | Adjusted yield (kg $ha^{-1}$) | The average yield is reduced by 10% to cater for the small plot size used |
| 3 | Field price maize and rice were UgSh 100 and 500 per kg, respectively | Farm gate price |
| 4 | $\text{Gross benefits} = \text{Adjusted yield} \times \text{field price}$ | |
| 5 | Total variable costs | Cost of rice, maize and mucuna seeds, fertilizers, ploughing, labour for applying the fertilizers, weeding, harvesting, and removing mucuna from the maize plants Additional cost under rice include; pesticides, labor for opening ridges, spraying, paddling, guarding rice fields, winnowing, threshing, transport to mill, milling charges |
| 6 | Farm gate prices for 50-kg bags of urea, triple super phosphate and muriate of potash are UgSh.30800, 36000 and 46200, respectively. | 1 US$ = Ug shs 1750 |
| 7 | $\text{Gross margins} = \text{Gross benefits} - \text{total variable costs}$ | Gross margins are not the same as net profit, because not all production costs are considered under the partial budget |
| 8 | $\left(\frac{Benefit}{Cost}\right) = \left(\frac{\text{Gross benefits}}{\text{total variable costs}}\right)$ | A "benefit to cost ratio" equal to one (1), implies that on average for each Shs 1 invested in the total variable costs, farmers recover their Shs. 1. |

The "benefit to cost ratio" (B/C) is the indicator of the profitability of a given strategy. A benefit to cost ratio with a value of one (1) is the break-even point implying that farmers recover the total variable costs, in other words it means 100% recovery of the total variable costs by farmers. The B/C above one (1) implies that farmers recover the total variable and earn some profits. Below one (1) indicate that the practice is not economically viable since farmers are incurring losses.

### 3.2.2 Rice system

#### 3.2.2.1 Site description

On-farm rice research was conducted at two sites in eastern Uganda (Table 6) namely; Nakisenye and Doho rice scheme, respectively, with contrasting rice production systems. The farmers at Doho are in an irrigation scheme that allows the growing of two rice crops in a year, compared to their counterparts at Nakisenye who rely on rainfall, and as a result grow only one rice crop during the long rains. They either plant upland crops or leave their land under fallow during the second season due to insufficient water. The sites are located in Southern and Eastern Lake Kyoga basin agro-ecological zone (Wortmann and Eledu 1999). The characteristics of the sites are indicated in Table 6.

Table 6: Site characteristics for Nakisenye and Doho rice scheme

| | Site | |
|---|---|---|
| | Nakisenye | Doho R.S. (Lubembe) |
| Location | | |
| Altitude (m asl) | 1138 | 1083 |
| Latitude | 1ºN | 0º 56'N |
| Longitude | 34ºE | 34º 02'E |
| Mean annual precipitation (mm) | 1164 | 1164 |
| Agro-ecological zone | Southern and Eastern Lake Kyoga basin | Southern and Eastern Lake Kyoga basin |
| FAO-UNESCO classification[a] | Plinthic Ferralsols | Plinthic Ferralsols |
| Mapping unit[b] | Mazimasa complex | Mazimasa complex |
| Productivity rating[b] | Low | Low |
| Parent material[b] | Lake deposits from B.C granite, gneiss | Lake deposits from B.C granite, gneiss |

[a]Source: Ssali (2000); [b]Harrop (1970)

#### 3.2.2.2 Experimental description

**Characterisation of farmers' fields**

The trials were set up on 20 randomly selected farmers fields at each site and managed by farmers, with each farm acting as a replicate. The farmers' field were characterised through analysis of composite soil samples collected from the 0-20 cm depth prior to the initiation of the trials. The soil was analysed for pH, organic matter, extractable P, K, Ca as described above.

**Nakisenye**

***The first season (2000B season)***

Similar to the experiments for the maize system, first – season treatments (2000B) was mainly for testing various alternatives to maize. In the 2001A season, the impact of the treatments of the preceding season, were evaluated by its effect on rice. The treatments for the 2000B season were the same as those listed under Section 3.2.1.2 for the maize system. The same data were collected as well.

***Rice response to treatments of preceding season (2001A)***

During the 2001A season (March – July) the following treatments were super imposed on those with the equivalent number of the previous season. The treatments are listed in Table 7 below.

Table 7: Treatments during 2000B and 2001A seasons at Nakisenye

| | Season | |
|---|---|---|
| Number | 2000B | 2001A |
| i | Maize (farmers' practice) | Rice |
| ii | Maize | Rice + 60 kg N ha$^{-1}$ |
| iii | Maize | Rice + NPK[a] |
| iv | Mucuna relay | Rice |
| v | Mucuna relay + 25 kg P ha$^{-1}$ | Rice + PK[b] |
| vi | Mucuna fallow | Rice |
| vii | Weedy fallow | Rice |

[a]NPK = (60 kg N + 20 kg P + 25 kg K) ha$^{-1}$
[b]PK = (20 kg P + 25 kg K) ha$^{-1}$

The fields were prepared using hand hoes. The mucuna was partially incorporated into the soil during the time of seedbed preparation. Rice variety "China K87" was direct seeded by broadcasting the seeds (a common practice in the area) from 19th to 21st February 2001. Phosphorus fertilizer (20 kg P ha$^{-1}$) was broadcast at the time of planting, where applicable. Nitrogen (60 kg N ha$^{-1}$) and K (25 kg K ha$^{-1}$) fertilizers were applied in three splits, with the first dose (equivalent to 25 %) three weeks after germination, second dose (equivalent to 50%) at tillering, and the third dose (equivalent to 25%) at panicle initiation. Water was drained off all plots/fields three days before and allowed onto the fields two days after fertilizer application. The N and K fertilizers were also broadcasted and covered immediately with some soil, taking care not to damage the plants.

The rice yield (grain and straw) was determined at maturity, from 25th to 28th July 01 using a 1 m by 1 m quadrant placed four times randomly within the plots. Both grain and straw samples were collected for moisture determination. The rice yield was adjusted to 14% moisture content. No analysis for nutrients was carried out.

## Doho irrigation scheme

### *The first (2000B) and second (2001A) season treatments*

The fields were prepared using hand hoes. The plot size was 3 m wide by 17 m long. The plots were separated by raised bunds to control undesired lateral movement and/or spillover of water, *Azolla* and fertilizers between treatments.

The treatments during the 2000B season (August – December), and the superimposed treatments for the 2001A season (March – July) were, (i) rice - control (farmer practice), (ii) rice + (60kg N+ 20 kg P + 25 kg K) $ha^{-1}$, (iii) rice + *Azolla*, (iv) rice + (60kg N+ 20 kg P + 25 kg K) $ha^{-1}$ + *Azolla*, (v) rice + 60kg N $ha^{-1}$. Twenty five (25) day old rice seedlings of variety “China K87” raised in a nursery-bed were transplanted at a spacing of 20 by 20 cm. Two seedlings were transplanted per hill.

Phosphorus fertilizer (20 kg P $ha^{-1}$) was applied at the time of transplanting. Nitrogen (60 kg N $ha^{-1}$) and K (25 kg K $ha^{-1}$) fertilizers were applied in three splits, with the first dose (equivalent to 25 %) at transplanting, second dose (equivalent to 50%) at tillering, and the third dose (equivalent to 25%) at panicle initiation. The fields were drained two days before fertilizer application, the fertilizers were then surface broadcast, covered slightly with soil, taking care not to damage the rice plants, and water was then allowed into the field two days afterwards.

***Azolla* biomass and application.** During the 2000B season, *Azolla* was collected from fields where it was abundant and broadcast as uniformly as possible in the respective treatment plots at an average rate of 1.4 t $ha^{-1}$ (dry weight), determined from the mean *Azolla* biomass in six randomly selected fields, using a 1 m by 1 m quadrant. The *Azolla* in the quadrant was washed, and thoroughly drained before weighing. Samples were collected for moisture and total N determination. The samples were oven dried at 60ºC to a constant weight, ground and analysed for total N. *Azolla* was manually incorporated and trampled into the soil at transplanting. The unincorporated *Azolla* was allowed to re-grow, and incorporated at tillering stage. The process was repeated at panicle initiation stage. Weeds were manually trampled into the soil. Beta-cyfluthrin 0.05-2.5% (Ambush) was used to control stem borers.

The same procedures were repeated during 2001A season, but by this time all target plots (i.e. treatments (iii) and (iv)) had *Azolla* arising from that added during the previous season. The average biomass incorporated at transplanting was 1.27 t $ha^{-1}$.
The yield (grain and straw) was determined at maturity using a 1m by 1m quadrant placed eight times randomly within the plots. Harvest data was collected from a larger area due to the bigger plot size used. Samples were collected for moisture determination. The rice grain yield was adjusted to 14% moisture content.

**Economic analysis**

The partial budgets for the different strategies were determined according to the CIMMYT (1988) methodology. The items considered under the partial budget are listed in Table 5 under Section 3.2.1. The economic benefits of the treatments were determined for the combined 2000B and 2001A seasons, which is equivalent to one year.

### 3.2.3 Farmer evaluation of Mucuna, *Azolla* and inorganic fertilizers

Data on farmers' independent assessment of the alternative strategies was collected during December 2001 through conducting individual interviews with all the farmers who participated in the study using an open-ended questionnaire. Individual interviews were preferred to group interviews to avoid biased responses due to influence by vocal members.

# 4 RESULTS AND DISCUSSION

## 4.1 Researcher-managed trials

### Soil characteristics

Results from the analysis of soil samples from Bulegeni and Kibale are given in Table 8. The two sites had soils of different fertility, the soils at Bulegeni being more fertile than those at Kibale. The values of the soil characteristics at the latter site were below the critical values for Uganda soils according to Foster (1971). This is in agreement with the productivity rating of these soils (Harrop 1970) and their FAO-UNESCO classification (Ssali 2000). The soils at Bulegeni are Andosols, have more plant nutrients, and more productive than the Ferralsols at Kibale.

Table 8: Selected soil properties at Kibale and Bulegeni

| Property | Location | | Critical values[a] |
|---|---|---|---|
| | Kibale TVC | Bulegeni ARDC | |
| pH[b] | 4.8 | 5.6 | 5.2 |
| OM[c] (%) | 2.1 | 5.6 | 3.0 |
| Extractable P (mg $kg^{-1}$) | 2.5 | 14.9 | 5.0 |
| Extractable K ($cmol_c$ $kg^{-1}$)[d] | 0.3 | 1.2 | 0.4 |
| Extractable Ca ($cmol_c$ $kg^{-1}$)[d] | 0.6 | 7.7 | 0.9 |
| Bulk density (kg $m^{-3}$) | 1470 | 1160 | na |
| | | | na |
| Sand (%) | 60 | 16 | na |
| Silt (%) | 12 | 26 | na |
| Clay (%) | 28 | 58 | na |
| Texture class | Sandy clay loam | Clay | na |

[a] Below these values, soils are deficient or poor (Foster 1971); na = not applicable

[b] measured in 1:2.5 (Soil:water) suspension

[c] Walkley – Black method, modified according to Foster (1971)

[d] measured in single ammonium lactate/ acetic acid extract (pH 3.8) according to Foster (1971)

### 4.1.1 The first season (2000B)

***Maize and mucuna biomass production and N, P, K yield***

The mean maize yield and mucuna dry matter production during the 2000B season is given in Table 9. There was no significant difference (p =0.05) in mucuna dry matter production between the relay with and without P, implying that P fertilizers did not have an effect on mucuna dry matter production at both sites. The dry matter production was equally not affected by inter-planting with maize because of the aggressive nature of mucuna it competed favourably with maize for nutrients and other requirements.

Table 9: Mucuna and maize yield (t $ha^{-1}$) at Bulegeni and Kibale during 2000B season

| Treatment | Site | | | | | |
|---|---|---|---|---|---|---|
| | Bulegeni | Kibale | Bulegeni | Kibale | Bulegeni | Kibale |
| | Mucuna | | Maize | | | |
| | Dry matter | | Grain | | Stover | |
| Maize | na | na | 3.0 | 0.9 | 3.8 | 1.4 |
| Maize + Mucuna relay + 25 kg P $ha^{-1}$ | 12.4 | 7.5 | 1.4 | 1.2 | 1.9 | 2.2 |
| Maize + Mucuna relay | 10.6 | 7.9 | 1.3 | 0.7 | 1.7 | 1.1 |
| Mucuna fallow | 11.8 | 9.0 | na | na | na | na |
| Mean | 11.6 | 8.2 | 1.8 | 0.9 | 2.4 | 1.6 |
| $LSD_{5\%}$ | ns | ns | 1.5 | ns | 1.3 | ns |

na = not applicable ns = not significantly different at 5% level

There was a significant reduction (P=0.05) in maize yield in the intercrop compared to the sole crop at Bulegeni attributed to competition for resources between mucuna and maize. Mucuna intertwined and smothered the maize plants. Moreover, efforts to reduce the smothering effect through frequent physical removal and cutting the vines was not effective at Bulegeni because of the vigorous growth, probably due to the high soil fertility. On the other hand, in Kibale, the maize grain yield was hardly affected by a mucuna relay, showing a loss of 200 kg $ha^{-1}$ only. The addition of P in this system largely benefited the maize and caused an increase of 300 kg $ha^{-1}$ in maize grain and 800 kg $ha^{-1}$ in straw yield. Thus, on the basis of a single season it appears that mucuna/maize relay cropping should be restricted to the poorer soils/environments.

**Mucuna N, P, and K yields**

The N, P and K yields by mucuna during 22 weeks are given in Table 10. There was a significant increase (P = 0.05) in the amount of N and P accumulated by the mucuna relay in response to P fertilizers, possibly due to an increased uptake of nutrients due to a better root system in response to P fertilizers, since P is known to improve root growth

(Tisdale et al. 1999). In general, mucuna accumulated disproportionally more N, P and K at Bulegeni than at Kibale, reflecting the higher quality of the mucuna residues at Bulegeni. This is attributed to the more fertile soils at Bulegeni, which have more available plant nutrients than the poorer soils at Kibale, and only partly to the high amount of dry matter produced at the former site.

Table 10: Mucuna N, P and K yields (kg ha$^{-1}$) at Bulegeni and Kibale during 2000B season

| Treatment | Site | | | | | |
|---|---|---|---|---|---|---|
| | Bulegeni | Kibale | Bulegeni | Kibale | Bulegeni | Kibale |
| | N yield | | P yield | | K yield | |
| Mucuna relay + 25 kg P/ha | 430 | 190 | 40 | 8.0 | 370 | 90 |
| Mucuna relay | 290 | 150 | 25 | 8.3 | 260 | 90 |
| Mucuna fallow | 320 | 170 | 28 | 9.5 | 290 | 100 |
| Mean | 350 | 170 | 31 | 8.6 | 310 | 93 |
| LSD$_{5\%}$ | 120 | ns | 11 | ns | ns | ns |

***Biological nitrogen fixation***

The amount of N fixed by mucuna with and without inorganic P fertilizer is indicated in Tables 11a and 11b for Bulegeni and Kibale, respectively.

Table 11a: Nitrogen fixation by mucuna at Bulegeni (means of three replicates)

| | Dry matter yield (t ha$^{-1}$) | N (%) | N yield (kg ha$^{-1}$) | Atom $^{15}$N excess (%) | Ndff (%) | N fert. yield (kg ha$^{-1}$) | Ndfa (%) | Fixed N (kg ha$^{-1}$) |
|---|---|---|---|---|---|---|---|---|
| Mucuna | | | | | | | | |
| 0 kg P ha$^{-1}$ | | | | | | | | |
| Vines | 2.7 | 1.8 | 60 | 0.069 | 2.05 | 1.23 | | |
| Leaves | 2.7 | 3.0 | 80 | 0.084 | 1.67 | 1.34 | | |
| Pods | 2.8 | 2.9 | 80 | 0.075 | 1.49 | 1.19 | | |
| Total | 8.2 | | 220 | | 1.71$^{a}$ | 3.76 | 39 | 86 |
| 25 kg P ha$^{-1}$ | | | | | | | | |
| Vines | 2.8 | 2.1 | 60 | 0.093 | 1.85 | 1.11 | | |
| Leaves | 3.0 | 3.3 | 100 | 0.072 | 1.44 | 1.48 | | |
| Pods | 2.1 | 3.2 | 70 | 0.064 | 1.29 | 0.89 | | |
| Total | 7.9 | | 230 | | 1.50$^{a}$ | | 46 | 106 |
| LSD$_{5\%}$ | | | | | | | ns | |
| Luffa | | | | | | | | |
| Vines | 3.5 | 2.2 | 80 | 0.131 | 13.1 | 10.5 | | |
| Leaves | 2.4 | 2.7 | 60 | 0.122 | 12.2 | 7.3 | | |
| Pods | 1.1 | 2.9 | 30 | 0.116 | 11.6 | 3.5 | | |
| Total | 7.1 | | 170 | | 12.5$^{a}$ | 21.4 | | |

$^{a}$weighted average

The results indicate that mucuna was effective in fixing N at both sites, highlighting the importance of mucuna as a source of N in the low input agriculture common to the smallholder farmers in Uganda. The percentage of N fixed was within the range reported in similar studies in central Uganda by (Wortmann et al. 2000), and in West Africa (Sanginga et al. 1996; Becker and Johnson 1998; Ibewiro et al. 2000; Houngnandan et al. 2000).

There was a significant increase ($P = 0.05$) in N fixation in response to P fertilizers at Kibale, indicating that P was a limiting factor for N fixation. This is in agreement with the reports by several investigators that P fertilizers increase BNF under P limiting conditions (Ssali and Keya 1986; George et al. 1995; Thomas et al. 1995; Wani et al. 1995).

Table 11b: Nitrogen fixation by mucuna at Kibale (means of three replicates)

| | Dry matter yield (t $\text{ha}^{-1}$) | N (%) | N yield (kg $\text{ha}^{-1}$) | Atom $^{15}$N excess (%) | Ndff (%) | N fert. yield (kg $\text{ha}^{-1}$) | Ndfa (%) | Fixed N (kg $\text{ha}^{-1}$) |
|---|---|---|---|---|---|---|---|---|
| Mucuna | | | | | | | | |
| 0 kg P $\text{ha}^{-1}$ | | | | | | | | |
| Vines | 1.3 | 2.5 | 30 | 0.129 | 2.58 | 0.83 | | |
| Leaves | 1.1 | 2.3 | 20 | 0.172 | 2.77 | 0.65 | | |
| Pods | 4.0 | 2.8 | 120 | 0.129 | 2.4 | 2.95 | | |
| Total | 6.4 | | 170 | | 2.61[a] | 4.44 | 54 | 92 |
| 25 kg P $\text{ha}^{-1}$ | | | | | | | | |
| Vines | 1.9 | 2.2 | 40 | 0.118 | 2.35 | 1.0 | | |
| Leaves | 1.5 | 2.3 | 30 | 0.114 | 2.28 | 0.8 | | |
| Pods | 4.6 | 2.8 | 130 | 0.095 | 2.08 | 2.5 | | |
| Total | 8.1 | | 200 | | 2.16[a] | | 60 | 120 |
| $\text{LSD}_{5\%}$ | | | | | | | 5 | |
| Luffa | | | | | | | | |
| Vines | 0.9 | 2.7 | 20 | 0.264 | 26.4 | 5.28 | | |
| Leaves | 0.4 | 2.8 | 10 | 0.187 | 18.7 | 1.87 | | |
| Pods | 0.5 | 2.9 | 10 | 0.161 | 16.1 | 1.61 | | |
| Total | 1.7 | | 40 | | 21.8[a] | | | |

[a] weighted average

Interestingly, the absolute amounts of fixed N were similar for the two sites (within 7 – 12% of each other). Yet, the fraction of mucuna N derived from BNF is substantially (30 – 38%) higher on poorer soils of Kibale. This reflects the lower availability of soil N at this site.

### 4.1.2 The second season (2001A)

***Mucuna decomposition and nitrogen release***

The mass loss ($k_m$) and N release constants ($k_N$) for mucuna under field conditions at Bulegeni, Kibale and Kongta are given in Table 12. Mucuna decomposed and released N rapidly at the three sites, due the high total N (3.5%) of the substrate, well above the

1.5 – 2.0% critical level for net mineralisation (Palm and Sanchez 1991; Constantinides and Fownes 1994). The percentage of N released is within the range (70-95%) reported for tropical conditions (Giller and Cadisch 1995). The decomposition and N release patterns were described well by the single exponential function (Table 12). The decomposition rate constants ($k_m$ *and* $k_N$) are within the range reported for materials of similar composition in the tropics (Tian et al. 1992; Fosu 1999; Kaizzi and Wortmann 2000).

Table 12. Mucuna mass loss ($k_m$) and N release constant ($k_N$), and the percentage loss of original quantities remaining after 25 weeks in the field at Kongta, Bulegeni, and Kibale

| Site | Mass loss | | | N release | | |
|---|---|---|---|---|---|---|
| | $k_m$ (week$^{-1}$) | *$R^2$ | (%) | $k_N$ (week$^{-1}$) | *$R^2$ | (%) |
| Kongta | 0.127 | 0.984 | 94 | 0.130 | 0.989 | 97 |
| Bulegeni ARDC | 0.081 | 0.960 | 80 | 0.065 | 0.908 | 77 |
| Kibale TVC | 0.118 | 0.938 | 95 | 0.130 | 0.989 | 97 |
| $LSD_{1\%}$ | 0.041 | | | 0.064 | | |

* indicate the fit of the decomposition data to the single exponential function

The relatively higher rates for mass loss and N release constants at the Kongta site, which is located at a higher altitude with relatively lower temperatures compared to Bulegeni, was mainly attributed to termite activities. The litterbags had a 5 mm mesh size allowing termite access to the mucuna substrate. The similarity in the mass loss and N release between the Kongta and Kibale sites is equally explained by the high termite activity at both sites. The relatively lower temperatures at Bulegeni and the absence of termite activity explain the difference in the mass loss and N release rates between the Bulegeni and Kibale sites.

### *Maize response to alternative treatments in preceding season*

#### 4.1.2.1 Bulegeni ARDC

Maize yield in response to the different treatments at Bulegeni is presented in Table 13. There was a significant increase (P=0.05) in maize yield of 2.5 – 3.5 t ha$^{-1}$ in response to the application of inorganic N fertilizers, and to a preceding mucuna fallow or relay as compared to the control of continuous maize (farmer practice). This indicates that N was a limiting factor for maize production at the site. Thus, both inorganic N fertilizers and mucuna green manure served as effective N sources for maize. The average increase in maize grain yield (during 2001A season) due to a preceding mucuna treatment was 84%, which is in agreement with results reported by several investigators (Versteeg et al. 1998; Fischler and Wortmann 1999; Tian et al. 2000).

The mucuna–derived N was on average applied at a rate of 350 kg N ha$^{-1}$, and the results from the decomposition study (Table 12), indicate that 270 kg N ha$^{-1}$ (77%) was released and available for uptake by the maize.

Table 13. Maize$^{a}$ yield (t ha$^{-1}$) at Bulegeni during 2000B and 2001A seasons, and the sum of the two seasons (means of four replicates)

| | Grain | | | Stover | | |
|---|---|---|---|---|---|---|
| Treatment | Season | | Total for year | Season | | Total for year |
| | 2000B | 2001A | | 2000B | 2001A | |
| Control (no input) | 3.0 | 4.5 | 7.5 | 3.8 | 5.3 | 9.1 |
| 40 kg N ha$^{-1}$ | 3.0 | 7.3 | 10.3 | 3.8 | 10.0 | 13.8 |
| 80 kg N ha$^{-1}$ | 3.0 | 7.1 | 10.1 | 3.9 | 12.6 | 16.5 |
| 25 kg P ha$^{-1}$ | 3.0 | 5.1 | 8.1 | 3.4 | 6.9 | 10.3 |
| (40 kg N + 25 kg P) ha$^{-1}$ | 3.3 | 7.5 | 10.8 | 4.4 | 14.1 | 18.5 |
| (80 kg N + 25 kg P) ha$^{-1}$ | 3.7 | 7.5 | 11.2 | 4.2 | 10.1 | 14.3 |
| Preceding mucuna relay | 1.3 | 8.0 | 9.3 | 1.7 | 13.4 | 15.1 |
| Preceding mucuna relay + 25 kg P ha$^{-1}$ | 1.4 | 8.0 | 9.4 | 1.9 | 15.4 | 17.3 |
| Preceding mucuna fallow | na | 8.2 | 8.2 | na | 14.5 | 14.5 |
| Preceding weedy fallow | na | 4.7 | 4.7 | na | 7.8 | 7.8 |
| LSD$_{5\%}$ | 1.5 | 1.2 | 1.6 | 1.3 | 3.3 | 5.9 |

na = not applicable
$^{a}$"Longe 1" maize variety during 2000b season and "PANNAR 67" maize variety during 2001a season

Increasing inorganic N from 40 to 80 kg N ha$^{-1}$ did not result in an increase in maize yield, implying that either the lower N rate was sufficient to meet the maize N requirements at the site or another nutrient or the environment became limiting. The better response to mucuna, containing a sweep of other nutrients may confirm this notion. However, the lack of a significant (P = 0.05) increase in maize yield in response to application of 25 kg P ha$^{-1}$ in addition to 40 and 80 kg N ha$^{-1}$ indicates that P is not a limiting factor.

The combined yield of maize for the two seasons indicates a significant (P=0.05) grain yield response to inorganic N fertilizers of 2.6 – 3.7 t ha$^{-1}$ above the control. A preceding mucuna relay increased the yield by 1.8 – 1.9 t ha$^{-1}$. This implies that inorganic fertilizers and preceding mucuna relay are effective strategies for increasing maize yield at the site, but on average inorganic fertilizers give an additional 1.3 t ha$^{-1}$ of grain. The maize grain yield in response to preceding mucuna fallow was not significantly different (P=0.05) from the control, indicating that the mucuna fallow compensated for the yield loss (giving an extra 0.7 t $ha^{-1}$ of grain) when the fields were under fallow. This is in sharp contrast to a significant (P=0.05) yield reduction of 2.8 t $ha^{-1}$ of grain when the fields are left under weedy fallow.

#### 4.1.2.2 Kibale TVC

Maize yield in response to the different treatments at Kibale TVC is presented in Table 14. There was a significant increase (P = 0.05) in maize yield of 0.9 t $ha^{-1}$ in response to the application of 40 kg N $ha^{-1}$ and 25 kg P $ha^{-1}$ compared to control of continuous maize (farmers' practice), and the lack of response to 40 kg N $ha^{-1}$ without P fertilizers indicates that P is a limiting factor at this site.

Table 14: Maize$^{a}$ yield (t $ha^{-1}$) at Kibale during 2000B and 2001A seasons, and the sum of the two seasons (means of three replicates)

| | Grain | | | Stover | | |
|---|---|---|---|---|---|---|
| Treatment | Season | | Total for year | Season | | Total for year |
| | 2000B | 2001A | | 2000B | 2001A | |
| Control (no input) | 0.9 | 0.8 | 1.7 | 1.4 | 1.2 | 2.6 |
| 40 kg N $ha^{-1}$ | 1.1 | 1.1 | 2.2 | 1.2 | 1.3 | 2.5 |
| 80 kg N $ha^{-1}$ | 1.1 | 1.7 | 2.8 | 1.4 | 2.1 | 3.5 |
| 25 kg P $ha^{-1}$ | 0.9 | 1.0 | 1.9 | 1.3 | 1.9 | 3.2 |
| (40 kg N + 25 kg P) $ha^{-1}$ | 1.2 | 1.7 | 2.9 | 1.4 | 2.3 | 3.7 |
| (80 kg N + 25 kg P) $ha^{-1}$ | 1.5 | 2.3 | 3.8 | 1.7 | 3.3 | 5.0 |
| Preceding mucuna relay | 0.7 | 1.5 | 2.2 | 1.1 | 1.8 | 2.9 |
| Preceding mucuna relay + 25 kg P $ha^{-1}$ | 1.5 | 2.3 | 3.5 | 2.2 | 3.7 | 5.9 |
| Preceding mucuna fallow | na | 1.9 | 1.9 | na | 2.8 | 2.8 |
| Preceding weedy fallow | na | 1.2 | 1.2 | na | 2.0 | 2.0 |
| $LSD_{5\%}$ | ns | 0.5 | 0.6 | ns | 1.0 | 1.6 |

na = not applicable $^{a}$"Longe 1" maize variety

There was a significant increase (P=0.05) in maize yield of 0.7 – 1.5 t $ha^{-1}$ in response to the application of 80 kg N $ha^{-1}$ and to a preceding mucuna fallow or relay compared to the control. The maize response to the alternative strategies was similar, indicating that they all served as effective N sources for maize. The mucuna-derived N was on average applied at a rate of 170 kg N $ha^{-1}$, and the results from the decomposition study (reported in Section 4.1.1) indicate that 165 kg N $ha^{-1}$ (97%) N was released, and some was taken up by maize, resulting in the observed response.

There was a significant increase (P=0.05) in maize yield of 0.6 t $ha^{-1}$ in response to the application of 25 kg P $ha^{-1}$ together with 80 kg N $ha^{-1}$ compared to the minus P treatment, confirming further that P was a limiting factor to maize production at this site. This is supported further by the significant increase ($P = 0.05$) in maize yield of 0.8 t $ha^{-1}$ between a preceding mucuna relay, which received P, compared to the minus P treatment. The results are in agreement with the findings of earlier investigators who reported that N and P are limiting cereal production in Uganda (Stephen 1970; Foster 1980b).

The combined yield of maize for the two seasons indicates a significant ($P=0.05$) increase of 1.2 t $ha^{-1}$ of grain above the control in response to 40 kg N with 25 kg P $ha^{-1}$. The 80 kg N $ha^{-1}$ increased grain yield by 1.1 t $ha^{-1}$, application of 25 kg P $ha^{-1}$ resulted in an additional 1.0 t $ha^{-1}$ of grain. Mucuna relay plus 25 kg P $ha^{-1}$ resulted in a significant increase ($P=0.05$) of 1.8 t $ha^{-1}$ of grain. There was no significant increase ($P=0.05$) in maize grain yield in response to the application of 40 kg N $ha^{-1}$ and preceding mucuna fallow or relay without P. The increase in maize grain in response to a preceding mucuna fallow and a yield reduction of 0.5 t $ha^{-1}$ for the weedy fallow were not significantly different ($P=0.05$) to the control treatment for the two seasons, indicating that preceding mucuna and weedy fallow compensated for the yield loss during the season when the fields were under fallow.

## Comparison of treatments between Bulegeni and Kibale

The results in the previous section indicate that inorganic fertilizers and a preceding mucuna are effective N replenishment strategies for maize at Bulegeni and Kibale. The total maize production over two seasons at Bulegeni and Kibale is presented in Table 15. There was a highly significant difference ($P < 0.001$) in maize yield between the two sites, which is largely attributed to the differences in soil fertility. The soils at Bulegeni are of higher fertility than those of Kibale. Secondly, “PANNAR” has a higher yield potential than “Longe 1”, but it would not have given high yields on the low fertility soils of Kibale. The significant increase ($P=0.05$) in maize yield over the two seasons indicates that N was limiting maize production; therefore, inorganic N fertilizer and a preceding mucuna relay were effective N-replenishment strategies at Bulegeni.

The results show that inorganic-N fertilizers and preceding mucuna relay minus P were more effective on the high fertility soil of Bulegeni than on the low fertility soil of Kibale. Application of inorganic-N fertilizers resulted in an average increase of 2.7 t $ha^{-1}$ of grain at Bulegeni compared to 0. 6 for the 40 kg N $ha^{-1}$, and 1.1 t $ha^{-1}$ for the 80 kg N $ha^{-1}$ at Kibale. A preceding mucuna relay increased yield by 1.8 t $ha^{-1}$ at Bulegeni compared to 0.5 t $ha^{-1}$ at Kibale. Supprisingly, a preceding mucuna relay plus P resulted in a 1.8 t $ha^{-1}$ increase at both sites, indicating that P was a limiting factor at Kibale. Equally, application of P fertilizers resulted in an additional 0.7 t $ha^{-1}$ of grain for the 40 kg N $ha^{-1}$, and 1.0 t $ha^{-1}$ for the 80 kg N $ha^{-1}$ at Kibale, compared to an average of 0.7 t $ha^{-1}$ for both N rates at Bulegeni. The results show that application of P in addition to N is essential for increased maize production on low-fertility soils. The mucuna fallow compensated for the yield loss during the season when the fields were under fallow at both sites.

Table 15: Maize yield (t $ha^{-1}$) for two seasons (2000B and 2001A) at Kibale and Bulegeni

| | Grain | | | Stover | | |
|---|---|---|---|---|---|---|
| Treatment | Site | | | Site | | |
| | Bulegeni | Kibale | Prob[a] | Bulegeni | Kibale | Prob[a] |
| Control (no input) | 7.5 | 1.7 | *** | 9.1 | 2.6 | *** |
| 40 kg N $ha^{-1}$ | 10.3 | 2.2 | *** | 13.8 | 2.5 | *** |
| 80 kg N $ha^{-1}$ | 10.1 | 2.8 | *** | 16.5 | 3.5 | *** |
| 25 kg P $ha^{-1}$ | 8.1 | 1.9 | *** | 10.3 | 3.2 | *** |
| (40 kg N + 25 kg P) $ha^{-1}$ | 10.8 | 2.9 | *** | 18.5 | 3.7 | *** |
| (80 kg N + 25 kg P) $ha^{-1}$ | 11.2 | 3.8 | *** | 14.3 | 5.0 | *** |
| Preceding mucuna relay | 9.3 | 2.2 | *** | 15.1 | 2.9 | *** |
| Preceding mucuna relay + 25 kg P $ha^{-1}$ | 9.4 | 3.5 | *** | 17.3 | 5.9 | *** |
| Preceding mucuna fallow | 8.2 | 1.9 | *** | 14.5 | 2.8 | *** |
| Preceding weedy fallow | 4.7 | 1.2 | *** | 7.8 | 2.0 | *** |
| Mean | 9.0 | 2.4 | *** | 13.7 | 3.4 | *** |
| $LSD_{5\%}$ | 1.6 | 0.6 | | 5.9 | 1.6 | |

[a] level of significance for the difference between means of the same treatment at the two sites, *** indicate significant at P = 0.001

***Nitrogen uptake and balance (Fate of applied N)***

Results from the laboratory analysis indicates that labeled mucuna applied in the studies had a total N content of 3.5% with 0.474 at. % excess $^{15}N$. Plant and soil recovery based on $^{15}N$ derived from fertilizer (ammonium sulphate) or mucuna is presented in Tables 16a and 16b for Bulegeni and Kibale, respectively. Between 91 and 96% of the applied fertilizer N was accounted for at Bulegeni, with 17 - 47% and 44 - 74% recovered by plants and in the soil, respectively. The total recovery at Kibale was in the range 53 - 68%, with a plant and soil recovery of 5 – 24% and 39 - 53%, respectively. The percent recovery of mucuna-derived N by the plants (5 - 21%) is within the range (6-28%) reported for leguminous materials in the tropics (Giller and Cadisch 1995).

The low recovery by plants is partly attributed to the excessive amounts of green manure N (approximately 290 and 400 kg N ha$^{-1}$) added, with 280 kg N ha$^{-1}$ expected to have been released during the season at Kibale and 300 kg N ha$^{-1}$ at Bulegeni. The results from the decomposition study indicate rapid release of mucuna–derived N, for instance 110 kg N ha$^{-1}$ (calculated from N release rate constants) were released during the first eight weeks at Kibale and 142 kg N ha$^{-1}$ at Bulegeni. These amounts exceed the needs of the young maize plants, leading to N immobilisation by the microbial biomass and loss through leaching below 60 cm and volatilisation.

Similar amounts of applied inorganic-N were recovered by plants and in the soil at Bulegeni, whereas more was recovered in the soil than taken up by plants at Kibale. This is partly attributed to lower plant demand at the less favorable Kibale site. More mucuna-derived N was recovered in the soil than in plants at both sites due to excessive amounts added, some of which may have been incorporated into the soil microbial biomass. Microbial biomass and activities increase following the addition of organic materials, acting as an active source and sink of plant nutrients (Smith et al. 1993; Becker et al. 1995; Palm et al. 1997).

Table 16a: Nitrogen balance (% recovery) during 2001A season at Bulegeni (means of four replicates)

| | 40 kg N ha$^{-1}$ | | Mucuna | |
|---|---|---|---|---|
| | P kg ha$^{-1}$ | | | |
| | 0 | 25 | 0 | 25 |
| Plant recovery | | | | |
| Grain | 30 | 29 | 8 | 8 |
| Stover | 13 | 18 | 13 | 9 |
| Total ($LSD_{5\%}$ = 9.9) | 43 | 47 | 21 | 17 |
| Soil recovery | | | | |
| Soil layer (cm) | | | | |
| 0-15 | 27 | 28 | 46 | 33 |
| 15-30 | 12 | 8 | 13 | 13 |
| 30-60 | 14 | 8 | 13 | 28 |
| Total ($LSD_{5\%}$ = 9.4) | 53 | 44 | 71 | 74 |
| TOTAL RECOVERY | 96 | 91 | 92 | 91 |

Most of the added N remaining in the soil (62 - 83%) at Bulegeni was found in the top 0 - 30 cm indicating that N loss through leaching might not have been significant.

Relatively more of the applied N was found in the 30 – 60 cm depth at Kibale, indicating that leaching was significant at this site, therefore some of the N was likely lost through this process resulting in unaccounted N fractions of 32 – 47%. The soils at the site are sandy. Any mineral N present in the soil and not taken up by the plants was liable to being lost with the excess rainwater draining through the sandy soils at Kibale. Nitrogen losses are high in permeable, coarse-textured soils as reported by Vlek et al. (1980), and Singh et al. (1991).

Table 16b: Nitrogen balance (% recovery) during 2001A season at Kibale (means of three replicates)

| | 40 kg N ha$^{-1}$ | | Mucuna | |
|---|---|---|---|---|
| | P kg ha$^{-1}$ | | | |
| | 0 | 25 | 0 | 25 |
| Plant recovery | | | | |
| Grain | 15 | 16 | 5 | 3 |
| Stover | 9 | 7 | 5 | 2 |
| Total (LSD$_{5\%}$ = 10) | 24 | 23 | 10 | 5 |
| Soil recovery | | | | |
| Soil layer (cm) | | | | |
| 0-15 | 10 | 9 | 11 | 13 |
| 15-30 | 5 | 11 | 18 | 11 |
| 30-60 | 24 | 25 | 24 | 23 |
| Total (LSD$_{5\%}$ = 27) | 39 | 45 | 53 | 47 |
| OVERALL RECOVERY | 63 | 68 | 63 | 53 |

In general, the higher amount of mucuna-derived N and inorganic–N recovered by plants at Bulegeni compared to Kibale is partly attributed to the higher N demand by maize to produce 21 t ha$^{-1}$ of dry matter compared to 4.2 t ha$^{-1}$ produced at Kibale. The total N recovery is higher at Bulegeni than at Kibale, which is attributed to higher N demand for the production of 21 t ha$^{-1}$ dry matter compared to 4.2 t ha$^{-1}$ and leaching loss differences related to the soil texture of the two sites.

## Summary and conclusion

The mean mucuna biomass production at the medium altitude (high agricultural potential) site at Bulegeni was 11.6 t ha$^{-1}$ with a total N accumulation of 350 kg ha$^{-1}$, with 150 kg ha$^{-1}$ derived from the atmosphere. At the lower altitude (low agricultural potential) site at Kibale, 8.2 t ha $^{-1}$ of mucuna were produced, and the total N accumulation was 170 kg ha$^{-1}$, with 97 kg ha$^{-1}$ N derived from the atmosphere. The amount of N derived from the atmosphere is equivalent to 6.5 and 4.2 bags of urea, with a local value of US $ 115 at Bulegeni and US $ 74 at Kibale. Hence, mucuna has a high potential as a source of N especially for the low input agriculture of the smallholder farmers in eastern Uganda. In addition, mucuna accumulated 31 kg P ha$^{-1}$ and 310 kg K ha$^{-1}$ at Bulegeni, and 9 kg P ha$^{-1}$ and 93 kg K ha$^{-1}$ at Kibale, showing the potential of mucuna in recycling these nutrients.

Mucuna residues decomposed and released N rapidly because of their high quality, with a 3.5% total N content, which was well above the critical level for N mineralisation. The residue decomposition and N release over a period of 25 weeks were in the range 77 - 97%. With N release rate constants of 0.065 and 0.130 week$^{-1}$ at Bulegeni and Kibale, respectively, estimations can be made on the N release within a specified time. For instance, approximately 142 and 110 kg N were released within eight weeks at Bulegeni and Kibale, respectively, which is an excessive amount for the young plants. Some of the N will be taken up by the plants leading to a subsequent increase in yield, but some of the remainding N could be subject to losses.

Inorganic N and mucuna mulch were effective N sources for maize at both sites, their use resulting in significant increase in grain yield. Considering the overall maize production over the two seasons, the results show that inorganic-N fertilizers and preceding mucuna relay minus P were more effective on the high fertility soil of Bulegeni than on the low fertility soil of Kibale. The inorganic-N fertilizers resulted, on average, in an increase of 2.7 t ha$^{-1}$ grain at Bulegeni, compared to 0. 9 t ha$^{-1}$ at Kibale. A preceding mucuna relay increased yield by 1.8 t ha$^{-1}$ at Bulegeni, and 0.5 t ha$^{-1}$ at Kibale. However, preceding mucuna relay plus P resulted in an increase of 1.8 t ha$^{-1}$ at both sites, and application of P fertilizers to inorganic-N resulted, on average, in an additional 0.9 t ha$^{-1}$at Kibale with a non-significant effect at Bulegeni, indicating that P was a limiting factor at Kibale.

Higher amounts of inorganic fertilizers and mucuna–derived N were recovered in the soil/plant system at Bulegeni with an average of 93% compared to an average of 61% at Kibale. This is partly attributed to differences in N demand between the crops, and partly to differences in soil texture. There was a much higher demand for N to produce 21.2 t ha$^{-1}$ dry matter at Bulegeni, than for the 4.2 t ha$^{-1}$ dry matter produced at Kibale. In addition, the soils at Bulegeni are of heavier texture (clay) as compared to the lighter soils (sandy clay loams) at Kibale. Leaching is likely to have been higher for the coarse textured soils at Kibale. The N remaining in the soil can be utilised by the subsequent crop, if planted early enough in the season before it is lost through leaching.

## 4.2 On-farm (farmer-managed) trials

### 4.2.1 Maize system

### 4.2.1.1 Kongta

**Soil characteristics**

The results from the analysis of selected soil properties are given in Table 17. The fields had clay soils with values of the selected chemical properties largely above the low critical values defined by Foster (1971). The results show that the soils are of high productivity and are likely to be good yielding under good management. This is in agreement with the productivity rating given to the soils in this area (Harrop 1970; Ssali 2000).

Table 17: The range and mean values of selected soil properties soil at Konga

| Soil parameter | Range | Mean | Low critical value[a] | Fields below the critical value (%) |
|---|---|---|---|---|
| pH (1 soil:2.5 water) | 4.6 – 6.6 | 5.3 | 5.2 | 35 |
| OM (%) | 4.2 – 7.1 | 5.3 | 3.0 | 0 |
| Extractable P (mg kg$^{-1}$) | 4.5 –58.9 | 16.1 | 5.0 | 29 |
| Extractable K (cmol$_c$ kg$^{-1}$) | 1.1 – 2.0 | 1.6 | 0.4 | 0 |
| Extractable Ca (cmol$_c$ kg$^{-1}$) | 0.5 – 5.8 | 2.4 | 0.9 | 18 |
| Sand (%) | 16 – 30 | 23 | na | na |
| Silt (%) | 13 – 28 | 20 | na | na |
| Clay (%) | 45 – 70 | 57 | na | na |

[a]Below these values, levels are low/deficient (Foster 1971); na = not applicable

***Maize and mucuna yield in first season (2000B)***

Intercropping maize with mucuna did not reduce maize yield, which was partly attributed to the poor growth of mucuna at this high altitude, due to the associated lower temperatures that affected mucuna germination and establishment. In addition, farmers managed the mucuna well and prevented it from smothering the maize. As a result, mucuna accumulated a mere 2.5 – 3.0 t ha$^{-1}$ in dry matter. On average, mucuna accumulated 80 kg N ha$^{-1}$ and, based on the station experiments, it is estimated that 43% was derived from the atmosphere, contributing 34 kg N ha$^{-1}$ to the system. The quantity of N accumulated was below the range reported for green manures in the tropics (Giller et al. 1994), due to poor growth of the mucuna. The maize and mucuna dry matter, as well as the N, P and K yields during the 2000B season are given in Table 18.

Table 18: Maize, Mucuna dry matter, N, P and K yield at Kongta during 2000B season

| Treatment | Maize | | Mucuna | | | |
|---|---|---|---|---|---|---|
| | Grain | Stover | Dry matter | N | P | K |
| | t $ha^{-1}$ | | t $ha^{-1}$ | kg $ha^{-1}$ | | |
| Maize[a] | 2.0 | 5.5 | | | | |
| Maize | 2.3 | 5.9 | | | | |
| Maize | 2.3 | 6.0 | | | | |
| Mucuna relay + 25 kg P $ha^{-1}$ | 2.1 | 4.9 | 2.5 | 74 | 8.5 | 55 |
| Mucuna relay | 2.1 | 6.0 | 2.8 | 82 | 7.0 | 65 |
| Mucuna fallow | | | 2.6 | 76 | 6.5 | 61 |
| $LSD_{5\%}$ | ns | ns | ns | ns | ns | ns |

[a] "Longe 1" maize variety; ns = non significant at 5% level.

**Classifying farmers' fields**

The mean grain yield for the farmers' practice (control) was 1.6 t $ha^{-1}$ for the Kongta site. This yield level was used to group the fields into high and low productivity groups. Group I consisted of the more productive fields and Group II of the less productive ones. The mean maize yield and selected soil properties for the two groups of fields are given in Table 19.

There was a significant difference (P=0.001) in the mean grain yield between the two groups of fields, which was attributed to differences in soil fertility. The soils of Group I fields are of higher fertility status as observed from the significantly higher (P=0.05) values of the means of the soil properties compared to Group II fields. The soils of Group II fields had far lower P and Ca levels, and were more acidic with mean pH below the critical value for Uganda soils (Foster 1980a,b). However, for group I fields, the organic matter, pH and exchangeable Ca were average, while extractable P and exchangeable K indicate sufficient levels in the soil (Foster 1971).

Table 19: Maize yields, and means values of selected soil properties for the two groups of fields

| | Group[a] | | | Critical value[b] |
|---|---|---|---|---|
| | I | II | Prob[c]. | |
| Number of farmers | 7 | 10 | | |
| Maize yield | | | | |
| Grain (t ha$^{-1}$) | 2.2 | 1.1 | *** | |
| Stover (t ha$^{-1}$) | 5.5 | 4.6 | ns | |
| Soil properties | | | | |
| pH | 5.6 | 5.1 | * | 5.2 |
| OM (%) | 5.9 | 4.9 | * | 3.0 |
| Extractable P (mg kg$^{-1}$) | 27.3 | 8.3 | * | 5.0 |
| Extractable K (cmol$_c$ kg$^{-1}$) | 1.6 | 1.7 | ns | 0.4 |
| Extractable Ca (cmol$_c$ kg$^{-1}$) | 3.6 | 1.5 | ** | 0.9 |
| Sand (%) | 22 | 23 | ns | na |
| Clay (%) | 53 | 60 | ** | na |
| Silt (%) | 25 | 17 | *** | na |
| Bulk density (kg m$^{-3}$) | 1200 | 1200 | ns | na |

[a] Group I = high productivity fields; Group II = low productivity fields; na = not applicable

[b] Below these values, levels are low/deficient (Foster 1971)

[c] level of significance for the difference between means of the same soil property

ns, *, **, *** indicate non-significant at $P = 0.05$ and significant at $P = 0.05$, 0.01 and 0.001 levels, respectively

### ***Maize response to alternative treatments in the preceding season (2001A)***

The maize yield (t ha$^{-1}$) in response to applied N or a preceding mucuna crop at Kongta is given in Tables 20a and 20b, without and with P and K fertilizers, respectively. There was a significant increase ($P=0.05$) in maize yield in response to the application of inorganic-N fertilizer and to a preceding mucuna fallow or relay compared to the farmer practice (control) for both groups of fields. The maize response to the application of N in form of fertilizer or green manure was similar for the low-productivity fields (Group II).

However, for Group I the response to the application of inorganic N fertilizers and a preceding mucuna relay or fallow was different. Inorganic fertilizers were more effective than a preceding mucuna as N source for the maize crop, suggesting poor synchronisation of the N released during the decomposition of mucuna residues. Part of the released N was available for uptake by maize. The mucuna-derived N was applied at a rate of only 77 kg ha$^{-1}$. Although it is anticipated that the N will be released since the residues contain 2.9% N, which is above the critical level for N mineralisation (Heal et al. 1997), it is possible that some N deficiency was experienced later in the season. The N release during the decomposition of mucuna residues was confirmed in a parallel study conducted in the area (reported under Section 4.1.2), where it was observed that

97% (75 kg N ha$^{-1}$) of the mucuna–derived N was released within 175 days, some of which was available for plant uptake.

Table 20a: Maize[a] grain yield (t ha$^{-1}$) for the two groups of fields at Kongta during 2001A season (without P and K fertilizers)

| Treatments | Grain yield | | | Stover yield | | |
|---|---|---|---|---|---|---|
| | Group | | | | | |
| | I | II | Prob[b]. | I | II | Prob[b]. |
| Farmers' practice (control) | 2.2 | 1.1 | * | 5.1 | 4.6 | ns |
| 40 kg N ha$^{-1}$ | 6.0 | 2.3 | *** | 12.5 | 6.5 | *** |
| 80 kg N ha$^{-1}$ | 5.1 | 2.9 | *** | 9.7 | 5.8 | * |
| Preceding mucuna relay + 25 kg P ha$^{-1}$ | 4.3 | 2.2 | *** | 8.9 | 6.0 | ns |
| Preceding mucuna relay | 4.3 | 2.1 | *** | 10.6 | 5.5 | ** |
| Preceding mucuna fallow | 5.2 | 2.0 | *** | 10.4 | 4.9 | *** |
| Preceding weedy fallow | 3.1 | 1.5 | *** | 7.0 | 3.7 | * |
| Mean | 4.3 | 2.0 | | 9.2 | 5.3 | |
| LSD$_{5\%}$ | 1.5 | 0.9 | | 4.3 | 2.6 | |

[a]"PANNAR 67" maize variety

[b]level of significance for the difference between means of the same treatment between groups

ns, *, **, *** indicate non-significant at P = 0.05 and significant at P = 0.05, 0.01, 0.001 levels, respectively

Table 20b: Maize[a] grain yield (t ha$^{-1}$) for the two groups of fields at Kongta during 2001A season (with P and K fertilizers)

| Treatments | Grain yield | | | Stover yield | | |
|---|---|---|---|---|---|---|
| | Group | | | | | |
| | I | II | Prob[b]. | I | II | Prob[b]. |
| Farmers' practice (control)[c] | 2.2 | 1.1 | * | 5.1 | 4.6 | ns |
| 40 kg N ha$^{-1}$ | 5.9 | 2.6 | *** | 15.1 | 7.4 | *** |
| 80 kg N ha$^{-1}$ | 6.7 | 3.3 | *** | 13.8 | 6.9 | *** |
| Preceding mucuna relay + 25 kg P ha$^{-1}$ | 3.9 | 2.4 | ** | 10.4 | 7.4 | ns |
| Preceding mucuna relay | 4.9 | 2.2 | *** | 13.5 | 6.4 | *** |
| Preceding mucuna fallow | 4.5 | 2.9 | *** | 13.1 | 5.9 | *** |
| Preceding weedy fallow | 3.4 | 1.4 | *** | 7.8 | 4.7 | ns |
| Mean | 4.5 | 2.3 | | 11.3 | 6.2 | |
| LSD$_{5\%}$ | 1.3 | 0.7 | | 5.2 | 2.3 | |

[a]"PANNAR 67" maize variety

[b]level of significance for the difference between means of the same treatment between groups

ns, *, **, *** indicate non-significant at P = 0.05 and significant at P = 0.05, 0.01, 0.001 levels, respectively

[c]P and K fertilizers not applied under farmers' practice

Doubling the inorganic fertilizer rate from 40 to 80 kg N ha$^{-1}$ did not result in a significant increase in maize yield for both groups of fields. Possibly other nutrient or environmental conditions become limiting factors to maize production at the site after the N deficiency was overcome. The significant increase in maize grain yield (P=0.05) in response to the application of P and K fertilizers to 80 kg N ha$^{-1}$ compared to the same rate without P and K observed for Group-I fields indicate that at high N rate, and high production levels, P and K are important (Appendix A1). Equally for Group-II fields, increasing N from 40 to 80 kg $ha^{-1}$ in combination with P and K fertilizers resulted in a significant increase ($P = 0.05$) of maize yield, showing that P and K are important at high N levels for the low-productivity fields (Appendix A2).

For Group I fields, applying P and K fertilizers significantly increased ($P = 0.05$) maize yield with the 80 kg N $ha^{-1}$ over those with preceding mucuna fallow or relay. Application of P and K fertilizers to 40 kg N $ha^{-1}$ and to preceding mucuna relay or fallow did not result in a significant increase ($P = 0.05$) of maize yield as compared to the same treatment without P and K fertilizers. This implies that P and K were not limiting maize production at the lower N rate. Though mucuna–derived N was approximately 77 kg N $ha^{-1}$, (with 75 kg N $ha^{-1}$ estimated to be released within 175 days), less than 75 kg N $ha^{-1}$ is available for maize uptake because its release is not synchronised with plant demand, which leads to loss of some N. This may explain the observed significant differences between the response to preceding mucuna fallow or relay and to the 80 kg N $ha^{-1}$.

There was no significant difference ($P = 0.05$) between the preceding weedy fallow and control treatments, implying that the one season weedy fallow was not an effective strategy for increasing maize yield for both groups.

## Comparing the two fertility groups of fields

There was a highly significant difference ($P < 0.01$) in maize yield between the two groups of fields (I and II), both with and without P and K fertilizers. This is attributed to differences in soil fertility. The addition of P and K fertilizers together with the different N strategies did not bridge the yield gap between the two groups of fields, indicating that N, P and K were not the only factors responsible for the observed yield differences. There is a possibility that the quantities of nutrients applied to Group II fields might not have been enough to significantly raise their productivity due to the low soil fertility status of these fields. Sanchez et al. (1997a) reported that in situations where the soils are of extremely low fertility, high levels of nutrients are required to bring about significant changes in yield. Also, farmers with Group II fields might be cultivating the sub-soil after the topsoil was lost through erosion. Stephen (1970) reported that the fertility of the soils in Uganda is associated with organic matter and mainly found in the top 0 - 30 cm, and, when this is lost soil fertility and productivity are affected.

**Combined grain yield of the two seasons (1-year period)**

The results in the previous section indicate a significant (P=0.05) increase in maize yield in response to the application of inorganic fertilizers and to a preceding mucuna fallow or relay. However, the use of mucuna in relay rotation reduces the associated maize yield, while as fallow it results in the loss of a complete season crop. Considering the total maize yield over the two seasons can capture these effects. The combined maize yield for the 2000B and 2001A seasons in response to the different treatments is given in Table 21.

Table 21. Total (overall) grain production (t ha$^{-1}$) for the two seasons for the two groups of fields at Kongta (without and with P and K fertilizers)

| Treatments | - (P and K) | | | + (P and K)$^a$ | | |
|---|---|---|---|---|---|---|
| | Group | | | | | |
| | I | II | Prob$^b$ | I | II | Prob$^b$. |
| Farmers' practice (control) | 4.6 | 2.8 | ** | | | |
| 40 kg N ha$^{-1}$ | 8.3 | 4.8 | *** | 8.4 | 4.5 | *** |
| 80 kg N ha$^{-1}$ | 7.6 | 5.5 | *** | 9.1 | 5.0 | *** |
| Preceding mucuna relay + 25 kg P ha$^{-1}$ | 6.7 | 4.5 | *** | 6.1 | 4.2 | *** |
| Preceding mucuna relay | 6.6 | 4.4 | *** | 7.0 | 4.1 | *** |
| Preceding mucuna fallow | 5.2 | 2.0 | *** | 4.5 | 2.9 | ** |
| Preceding weedy fallow | 3.1 | 1.5 | * | 3.4 | 1.4 | *** |
| Mean | 6.2 | 3.8 | *** | 6.0 | 3.5 | *** |
| LSD$_{5\%}$ | 1.6 | 0.9 | | 1.5 | 1.1 | |

[a] P and K fertilizers not applied under farmers practice

[b] level of significance for the difference between means of the same treatment between the two groups

*, **, *** indicate significant at P = 0.05, 0.01, 0.001 levels, respectively

The results show that without P and K fertilizers for high-productivity fields, application of inorganic-N fertilizers resulted in the greatest response in maize grain yield with 3.4 t ha$^{-1}$ above the control, compared to 2.1 t ha$^{-1}$ obtained with preceding mucuna relay. The increase in maize yield in response to preceding mucuna fallow was 0.6 t ha$^{-1}$ above the control, implying that the response to mucuna fallow compensated for the yield loss when the field was under the fallow. The relay cropping sequence performed even better. Application of P and K fertilizers to 80 kg N ha$^{-1}$ resulted in an additional increase of 1.5 t ha$^{-1}$of grain, but no additional yield benefits were observed with other treatments.

For the low-productivity fields, the highest increase in maize grain yield of 2.7 t ha$^{-1}$ above the control was obtained with 80 kg N ha$^{-1}$ compared to 1.6 – 2.0 t ha$^{-1}$ obtained with 40 kg N ha$^{-1}$ and with preceding mucuna relay. As in the high-productivity fields, the mucuna fallow compensated for the yield loss when the fields were under fallow. Therefore, in terms of overall maize grain yield, the farmers best deal is using inorganic fertilizers, followed by mucuna relay.

#### 4.2.1.2 Kasheshe/Nemba

**Soil characteristics**

The results of the soil analysis of selected fields are given in Table 22. The fields had soils with textures varying from loam to clay. The values of selected chemical properties indicate that the majority of the fields had good soils according to criteria used for Uganda soils (Foster 1971). The soils are likely to give good yields under good management, which is in agreement with the productivity rating given to the soils of this area (Harrop 1970; Ssali 2000).

Table 22: The range and mean values of selected soil properties for the fields at Kasheshe/Nemba

| Soil parameter | Range | Mean | Low critical value[a] | Fields below the low critical value (%) |
|---|---|---|---|---|
| pH (1 soil:2.5 water) | 4.8 – 5.9 | 5.4 | 5.2 | 14 |
| OM (%) | 4.8 – 9.0 | 6.9 | 3.0 | 0 |
| Extractable P (mg kg$^{-1}$) | 1.5 – 332 | 112 | 5.0 | 21 |
| Extractable K (cmol$_c$ kg$^{-1}$) | 0.8 – 1.8 | 1.3 | 0.4 | 7 |
| Extractable Ca (cmol$_c$ kg$^{-1}$) | 1.2 – 8.2 | 5.0 | 0.9 | 0 |
| Sand (%) | 15 – 35 | 25 | na | na |
| Silt (%) | 17 – 58 | 39 | na | na |
| Clay (%) | 22 – 66 | 36 | na | na |

[a]Below these values, levels are low/deficient (Foster 1971); na = not applicable

***Maize and mucuna yield in first season (2000B)***

The maize, mucuna dry matter, N, P and K yields during 2000B season are given in Table 23. There was no significant difference (P=0.05) in maize grain yield between the sole crop and the intercrop. The same applies to mucuna dry matter production, due to proper management of mucuna by the farmers. Farmers managed the mucuna well and prevented it from smothering the maize through constant removal of some of the vines. If not controlled mucuna can smother the maize leading to a reduction in maize yield.

On average, mucuna accumulated 200 kg N ha$^{-1}$ i.e., more than double that of Kongta, and, using estimates from station experiments (reported under Section 4.1.1) 86 kg N ha$^{-1}$ was derived from the atmosphere. This is a significant contribution to N input into the system.

Table 23: Maize[a], Mucuna dry matter, N, P and K yields at Kasheshe/Nemba during the 2000B season

| Treatment | Maize | | Mucuna | | | |
|---|---|---|---|---|---|---|
| | Grain | Stover | Dry matter | N | P | K |
| | t ha$^{-1}$ | | t ha$^{-1}$ | kg ha$^{-1}$ | | |
| Maize | 2.5 | 5.0 | | | | |
| Maize | 2.2 | 5.0 | | | | |
| Maize | 2.7 | 4.9 | | | | |
| Mucuna relay + 25 kg P ha$^{-1}$ | 2.4 | 5.4 | 6.2 | 210 | 20 | 160 |
| Mucuna relay | 2.2 | 5.7 | 6.5 | 210 | 20 | 150 |
| Mucuna fallow | | | 6.2 | 190 | 20 | 130 |
| LSD$_{5\%}$ | ns | ns | ns | ns | ns | ns |

ns not significantly different at $P = 0.05$

[a] “Longe 1” maize variety

## Classifying farmers’ fields

The mean grain yield for the farmers’ practice (control) at Kasheshe/Nemba was 3.3 t ha$^{-1}$. This yield level was used to group the fields into high- and low-productivity groups.

Table 24: Maize[a] yield and mean values of selected soil properties for the two groups of fields at Kasheshe/Nemba

| | Group[b] | | | Critical value[c] |
|---|---|---|---|---|
| | I | II | Prob[d] | |
| Number of farmers | 9 | 9 | | |
| Maize yield | | | | |
| Grain (t ha$^{-1}$) | 4.2 | 1.9 | *** | |
| Stover (t ha$^{-1}$) | 6.7 | 2.9 | ** | |
| Soil properties | | | | |
| pH | 5.5 | 5.2 | * | 5.2 |
| OM (%) | 7.9 | 5.6 | *** | 3.0 |
| Extractable P (mg kg$^{-1}$) | 197 | 4.3 | *** | 5.0 |
| Extractable K (cmol$_c$ kg$^{-1}$) | 1.4 | 1.1 | ** | 0.4 |
| Extractable Ca (cmol$_c$ kg$^{-1}$) | 7.0 | 2.5 | *** | 0.9 |
| Sand (%) | 29 | 18 | *** | na |
| Silt (%) | 40 | 40 | ns | na |
| Clay (%) | 31 | 42 | ns | na |
| Bulk density (kg m$^{-3}$) | 1200 | 1230 | ns | na |

[a]“PANNAR 67 maize variety

[b]Group I = high productivity fields, Group II = low productivity fields

[c]Below these values levels are low/deficient (Foster 1971); na = not applicable

[d]level of significance for the difference between means of the same soil property

ns, *, **, *** indicate non-significant at P = 0.05 and P = 0.05, 0.01 and 0.001 levels, respectively

There was a significant difference ($P=0.001$) in the mean grain yield between the two groups of fields, which was attributed to differences in soil fertility. Group I fields were of higher fertility status and the means of all soil chemical properties with the exception of pH were significantly higher ($P < 0.05$) than for Group II fields. The extremely high levels of organic matter, and the high extractable P and Ca observed for Group I fields indicates that the fields are of high productivity. However, for Group II fields the mean of the soil properties with the exception of extractable P are average for Uganda soils, indicating that the fields are of moderate fertility.

### *Maize response to alternative treatments in the preceding season (2001A)*

The maize yields (t ha$^{-1}$) in response applied N and preceding mucuna treatments at Kasheshe/Nemba are given in Tables 25a and 25b, without and with the addition of P and K fertilizers, respectively. There was a significant increase (P=0.05) in maize yield in response to the application of inorganic-N fertilizer and to a preceding mucuna fallow or relay when compared to the farmer practice (control) for both fertility groups of fields. The maize response to the application of inorganic-N fertilizer and preceding a mucuna fallow or relay was similar. This implies that the two methods are effective N sources for the maize crop, confirming that green manure can entirely substitute inorganic-N fertilizer at the current average application rate in the low input agriculture at this site. Similar results were reported by Becker et al. (1995).

Table 25a: Maize[a] grain yield (t ha$^{-1}$) for the two groups of fields at Kasheshe/Nemba during 2001A season (without P and K fertilizers)

| Treatments | Grain yield | | | Stover yield | | |
|---|---|---|---|---|---|---|
| | ---------------------------------Group--------------------------- | | | | | |
| | I | II | Prob[b]. | I | II | Prob[b]. |
| Farmers’ practice (control) | 4.2 | 1.9 | *** | 6.7 | 2.8 | ** |
| 40 kg N ha$^{-1}$ | 5.6 | 2.8 | *** | 13.2 | 3.8 | *** |
| 80 kg N ha$^{-1}$ | 6.1 | 2.6 | *** | 14.1 | 3.4 | *** |
| Preceding mucuna-relay + 25 kg P ha$^{-1}$ | 6.1 | 3.1 | *** | 15.9 | 4.6 | *** |
| Preceding mucuna-relay | 5.7 | 2.5 | *** | 13.7 | 3.0 | *** |
| Preceding mucuna fallow | 5.9 | 2.7 | *** | 13.3 | 3.2 | *** |
| Preceding weedy fallow | 4.4 | 2.4 | *** | 11.5 | 4.1 | *** |
| Mean | 5.4 | 2.6 | | 12.6 | 3.6 | |
| $LSD_{5\%}$ | 0.8 | 0.6 | | 2.87 | 1.1 | |

[a]“PANNAR” maize variety
[b]level of significance for the difference between means of the same treatment between groups
**, *** significant at P = 0.01 and 0.001 respectively

Table 25B: Maize[a] grain yield (t ha$^{-1}$) for the two groups of fields at Kasheshe/Nemba during 2001A season (with P and K fertilizers)

| Treatments | Grain yield | | | Stover yield | | |
|---|---|---|---|---|---|---|
| | ----------------------------Group--------------------------------- | | | | | |
| | I | II | Prob[b]. | I | II | Prob[b]. |
| Farmers’ practice (control)[c] | 4.2 | 1.9 | *** | 6.7 | 2.9 | ** |
| 40 kg N ha$^{-1}$ | 5.9 | 3.4 | *** | 13.1 | 5.5 | *** |
| 80 kg N ha$^{-1}$ | 6.2 | 4.0 | *** | 15.7 | 6.3 | *** |
| Preceding mucuna relay + 25 kg P ha$^{-1}$ | 6.4 | 3.8 | *** | 16.4 | 5.4 | *** |
| Preceding mucuna relay | 5.9 | 3.7 | *** | 13.9 | 5.2 | *** |
| Preceding mucuna fallow | 6.2 | 4.0 | *** | 14.2 | 5.1 | *** |
| Preceding weedy fallow | 4.5 | 2.4 | *** | 12.8 | 3.1 | *** |
| Mean | 5.6 | 3.3 | | 13.3 | 4.8 | |
| $LSD_{5\%}$ | 0.8 | 1.1 | | 2.8 | 2.4 | |

[a]“PANNAR” maize variety
[b]level of significance for the difference between means of the same treatment between groups
**, *** significant at P = 0.01 and 0.001 respectively
[c]P and K fertilizers not applied under farmers’ practice

The mucuna-derived N was on average applied at a rate of 200 kg N ha$^{-1}$, and the results from the decomposition study (reported under Section 4.1.2) indicate that 154 kg N ha$^{-1}$ (77%) were released within 175 days and available for plant uptake. This is adequate to explain the observed increase in maize yield. Since approximately 86 kg N ha$^{-1}$ (43% of the N) was derived from BNF, the results confirm that BNF can contribute to the N requirements and sustain tropical agriculture at moderate levels of output under such favorable conditions (Giller et al. 1997).

Doubling the inorganic fertilizer rate from 40 to 80 kg N ha$^{-1}$did not result in a significant increase in maize yield for both groups of fields. This suggests that either 40 kg N ha$^{-1}$ was sufficient under the existing conditions, or another nutrient or environmental constraint is a limiting factor at higher N levels. The results rule out the possibility of P and/or K being a limiting factor for Group I fields, since the addition of P and K fertilizers to inorganic N did not result in a significant increase in maize yield (Appendix A3). However, a significant increase ($P < 0.05$) in maize grain yield in response to the application of P and K fertilizers to 80 kg N ha$^{-1}$ or to preceding mucuna fallow or relay of the Group II fields indicates that P and/or K are also limiting factors for these low-productivity fields (Appendix A4).

**Comparing two fertility groups of fields**

There was highly significant difference ($P = 0.001$) in maize yield between the two groups of fields with and without P and K fertilizers, which is largely attributed to differences in soil fertility. The strategies used to increase yields could not bridge the yield gap between the two groups of fields. This suggests that N, P and K were not the only factors causing the significant difference in yield between the two groups of fields. As in Kongta, there is again the possibility that the quantity of P and K applied was not enough to bring the two groups of fields to the same fertility levels. In addition, Group II fields might have suffered from serious erosion, hence losing most of the topsoil where the fertility is mainly found. So the farmers are most likely cultivating sub-soils. Also compaction (Table 24) may be a constraint for the heavier – textured soils of Group II.

**Combined grain yield of the two seasons (1-year period)**

The results in the previous section indicate a significant (P=0.05) increase in maize yield in response to the application of inorganic fertilizers and to a preceding mucuna fallow or relay. However, the use of mucuna in relay rotation reduces the associated maize yield, while as a fallow it results in the loss of a complete season. Considering the total maize yield over the two seasons can capture these effects. The combined maize yields for the 2000B and 2001A seasons in response to the different treatments are given in Table 26.

Table 26: Total (overall) grain production (t $ha^{-1}$) for the two seasons for the groups of fields at Kasheshe/Nemba (without and with P and K fertilizers)

| Treatments | - (P and K) | | | + (P and K)[a] | | |
|---|---|---|---|---|---|---|
| | ---------------------------------Group | | | ---------------------------- | | |
| | I | II | Prob[b]. | I | II | Prob[b]. |
| Farmers' practice (control)) | 6.4 | 3.6 | *** | | | |
| 40 kg N $ha^{-1}$ | 8.0 | 4.3 | *** | 8.4 | 4.9 | *** |
| 80 kg N $ha^{-1}$ | 8.6 | 4.4 | *** | 8.7 | 5.8 | *** |
| Preceding mucuna relay + 25 kg P $ha^{-1}$ | 8.4 | 5.0 | *** | 8.7 | 5.7 | *** |
| Preceding mucuna relay | 7.9 | 4.3 | *** | 8.0 | 5.5 | *** |
| Preceding mucuna fallow | 5.8 | 2.7 | *** | 6.2 | 4.0 | *** |
| Preceding weedy fallow | 4.4 | 2.4 | *** | 4.5 | 2.4 | *** |
| Mean | 7.1 | 3.8 | *** | 7.3 | 4.5 | *** |
| $LSD_{5\%}$ | 0.9 | 0.7 | | 0.8 | 1.3 | |

[a] P and K fertilizers not applied under farmers practice

[b] level of significance for the difference between means of the same treatment between the two groups

*, **, *** indicate significant at P = 0.05, 0.01, 0.001 levels, respectively

The results show that for high-productivity fields, application of 80 kg N $ha^{-1}$ resulted in the highest increase in maize grain yield of 2.2 t $ha^{-1}$ above the control. A preceding mucuna relay plus P increased yield by 2.0 t $ha^{-1}$, while application of 40 kg N $ha^{-1}$ or preceding mucuna relay resulted in an increase of 1.6 t $ha^{-1}$. The reduction in maize yield due to the mucuna fallow was 0.6 t $ha^{-1}$, though this not significantly different from the yield of the control for two seasons. Application of P and K fertilizers to 40 kg N $ha^{-1}$ and to preceding mucuna fallow resulted, on average, in an additional 0.4 t $ha^{-1}$ of grain. No additional yield benefits were gained in the case of 80 kg N $ha^{-1}$ and preceding mucuna relay.

For the low-productivity fields, the highest maize grain yield response of 1.4 t $ha^{-1}$ above the control was obtained with the preceding mucuna relay plus P, compared with an average of 0.8 t $ha^{-1}$ obtained with both rates of inorganic N fertilizers and preceding mucuna relay minus P treatment. The preceding mucuna fallow did not compensate for the yield loss when the field was under fallow, but resulted in an overall yield reduction of 0.9 t ha$^{-1}$ over the two seasons in the absence of P and K only. Application of P and K fertilizers resulted, on average, in an additional increase in the range of 0.4 - 1.4 t ha$^{-1}$ of grain for all treatments compared to the same treatments without P and K fertilizers.

Therefore, in terms of the overall increase in maize grain yield, the best results are obtained on high-productivity fields by applying inorganic-N fertilizers or by a preceding mucuna relay. Farmers with low-productivity fields should apply P and K fertilizers to 80 kg N ha$^{-1}$ and a preceding mucuna relay.

#### 4.2.1.3 Odwarat

**Soil characteristics**

The fields had sandy clay loam to sandy loam soils. The soils are generally of low fertility, with the majority of the fields having values of soil chemical properties below the critical low levels for Uganda soils according to Foster (1971). The fields are likely to give low crop yields since the majority have low soil pH, extractable P and organic matter, and these determine crop yields on the ferrallitic soils in Uganda (Foster 1978, 1980a,b). The results are in agreement with the productivity rating given to the soils of this area (Harrop 1970; Ssali 2000). The results from the analysis of selected soil properties are indicated in Table 27.

Table 27: The range and mean values of selected soil properties for the fields at Odwarat

| Soil parameter | Range | Mean | Low critical value[a] | Fields below the low critical value (%) |
|---|---|---|---|---|
| pH (1 soil:2.5 water) | 4.7 – 5.9 | 5.1 | 5.2 | 50 |
| OM (%) | 0.8 – 2.9 | 1.4 | 3.0 | 100 |
| Extractable P (mg kg$^{-1}$) | 1.9 – 7.2 | 3.9 | 5.0 | 70 |
| Extractable K (cmol$_c$ kg$^{-1}$) | 0.3 – 0.9 | 0.5 | 0.4 | 36 |
| Extractable Ca (cmol$_c$ kg$^{-1}$) | 0.2 – 1.5 | 0.5 | 0.9 | 86 |
| Sand (%) | 45 –79 | 70 | na | na |
| Silt (%) | 9 - 29 | 11 | na | na |
| Clay (%) | 8 - 26 | 19 | na | na |

[a]Below these values, levels are low/deficient (Foster 1971); na = not applicable

***Maize and mucuna yield in the first season (2000B)***

There was a significant decrease (P = 0.05) in maize yield for the intercrop compared to the sole maize, which is partly attributed to competition between the two crops in the relatively poor soils at this site. In addition, poor management of mucuna by farmers led to the smothering of the maize, with a subsequent reduction in maize yield. The maize, mucuna dry matter, N, P and K yields during 2000B season are given in Table 28.

Table 28: Maize, Mucuna dry matter, N, P and K yields at Odwarat during 2000B season

| Treatment | Maize | | Mucuna | | | |
|---|---|---|---|---|---|---|
| | Grain | Stover | Dry matter | N | P | K |
| | t ha$^{-1}$ | | t ha$^{-1}$ | kg ha$^{-1}$ | | |
| Maize | 1.7 | 2.8 | | | | |
| Maize | 1.8 | 3.4 | | | | |
| Maize | 1.7 | 2.6 | | | | |
| Mucuna relay + 25 kg P ha$^{-1}$ | 1.4 | 2.5 | 8.2 | 204 | 14 | 112 |
| Mucuna relay | 1.3 | 2.3 | 7.5 | 149 | 13 | 91 |
| Mucuna fallow | | | 7.7 | 155 | 13 | 88 |
| LSD$_{5\%}$ | 0.3 | 0.7 | ns | 16 | ns | 9 |

ns = not significantly different at P = 0.05

There was a significant difference (P=0.05) in N yield between the mucuna relay plus P and the relay without P. This is attributed to increased biological N fixation in response to P fertilizers. Increased BNF in response to P fertilizers was observed in a study carried out within the same agro-ecological zone at Kibale (reported under Section 4.1.1). Mucuna on average accumulated 170 kg N ha$^{-1}$, which is within the range (100 – 200 kg N) reported for green manure crops in the tropics by Giller et al. (1994). Based on $^{15}$N studies conducted at Kibale, it is estimated that 97 kg ha$^{-1}$ (57%) was derived from the atmosphere, which is a significant contribution to the N input to the system.

**Classifying farmers' fields**

The mean grain yield for the farmers' practice (control) for the Odwarat site was 1.0 t ha$^{-1}$. This yield was used to split the fields into high- and low-productivity groups. Group I consisted of slightly more productive fields than Group II. The mean maize yield and the selected values of soil properties for the two groups of fields are given in Table 29.

There was a significant difference (P=0.01) in the mean grain yield between the two groups of fields, which could probably be explained in part by field history. Approximately 86% of the Group II fields had been under continuous cultivation since 1998 (for over five consecutive seasons) compared to 43% for the Group I fields. In Uganda, the rotation generally recommended is three years of cropping followed by three years of rest (Foster 1976). None of the soil properties were significantly different between the two groups of fields.

Table 29: Maize yield (t $ha^{-1}$) and the mean values of selected soil properties for the two groups of fields

| | Group[a] | | | Critical values[b] |
|---|---|---|---|---|
| | I | II | Prob[c]. | |
| Number of farmers | 7 | 7 | | |
| Maize yield | | | | |
| Grain (t $ha^{-1}$) | 1.6 | 0.8 | ** | |
| Stover (t $ha^{-1}$) | 2.7 | 1.4 | ** | |
| Soil properties | | | | |
| pH | 5.2 | 5.0 | ns | 5.2 |
| OM (%) | 1.5 | 1.3 | ns | 3.0 |
| Extractable P (mg $kg^{-1}$) | 3.7 | 4.2 | ns | 5.0 |
| Extractable K ($cmol_c$ $kg^{-1}$) | 0.5 | 0.4 | ns | 0.4 |
| Extractable Ca ($cmol_c$ $kg^{-1}$) | 0.6 | 0.4 | ns | 0.9 |
| Sand (%) | 69 | 71 | ns | na |
| Silt (%) | 12 | 11 | ns | na |
| Clay (%) | 19 | 18 | ns | na |
| Bulk density (kg $m^{-3}$) | 1460 | 1490 | ns | na |

[a] Group I = slightly more productive fields; Group II = slightly less productive fields
[b] Below these values levels are low/deficient (Foster 1971)
[c] level of significance for the difference between means of the same chemical property between groups
ns, ** indicate non-significant at P = 0.05 and significant at P = 0.01respectively
na = not applicable

***Maize response to alternative treatments in the preceding season (2001A)***

The maize yields (t ha$^{-1}$) in response to applied N and preceding mucuna treatments at Odwarat are given in Tables 30a and 30b without and with P and K fertilizers, respectively.

Table 30a: Maize grain yield (t ha$^{-1}$) for the two groups of fields at Odwarat during 2001A season (without P and K fertilizers)

| Treatments | Grain yield | | | Stover yield | | |
|---|---|---|---|---|---|---|
| | | | Group | | | |
| | I | II | Prob$^{a}$. | I | II | Prob$^{a}$. |
| Farmers' practice (control) | 1.6 | 0.8 | ** | 2.7 | 1.4 | ** |
| 40 kg N ha$^{-1}$ | 2.0 | 1.7 | ns | 2.8 | 2.3 | ns |
| 80 kg N ha$^{-1}$ | 1.8 | 1.6 | ns | 2.3 | 2.1 | ns |
| Preceding mucuna relay + 25 kg P ha$^{-1}$ | 2.1 | 1.8 | ns | 2.9 | 2.5 | ns |
| Preceding mucuna relay | 1.7 | 1.7 | ns | 2.4 | 2.2 | ns |
| Preceding mucuna fallow | 1.9 | 1.6 | ns | 2.7 | 2.3 | ns |
| Preceding weedy fallow | 1.4 | 0.9 | ns | 2.5 | 1.6 | ns |
| Mean | 1.8 | 1.5 | * | 2.6 | 2.1 | ** |
| LSD$_{5\%}$ | ns | 0.6 | | ns | 0.8 | |

$^{a}$level of significance for the difference between means of the same treatment between groups

Table 30B: Maize grain yield (t ha$^{-1}$) for the two groups of fields at Odwarat during 2001A season (with P and K fertilizers)

| Treatments | Grain yield | | | Stover yield | | |
|---|---|---|---|---|---|---|
| | | | Group | | | |
| | I | II | Prob$^{a}$. | I | II | Prob$^{a}$. |
| Farmers' practice (control)$^{b}$ | 1.6 | 0.8 | ** | 2.7 | 1.4 | ** |
| 40 kg N ha$^{-1}$ | 2.2 | 1.9 | ns | 3.4 | 2.5 | ns |
| 80 kg N ha$^{-1}$ | 3.1 | 2.7 | ns | 3.9 | 3.0 | ns |
| Preceding mucuna-relay + 25 kg P ha$^{-1}$ | 3.0 | 2.0 | ** | 3.4 | 2.8 | ns |
| Preceding mucuna-relay | 2.4 | 2.0 | ns | 3.6 | 2.8 | ns |
| Preceding mucuna fallow | 2.4 | 1.9 | ns | 3.2 | 2.2 | ns |
| Preceding weedy fallow | 1.4 | 1.0 | ns | 2.5 | 1.6 | ns |
| Mean | 2.3 | 1.7 | * | 3.2 | 2.3 | * |
| LSD$_{5\%}$ | 0.9 | 0.7 | | ns | 0.9 | |

$^{a}$level of significance for the difference between means of the same treatment between groups
ns, *, **, not significantly different at P = 0.05 and significant at P = 0.05, 0.01 levels respectively
$^{b}$P and K fertilizers not applied to farmers' practice

If P and K fertilization was not part of the package, there was no significant increase (P=0.05) in maize yield in response to the application of inorganic N fertilizers, or to a preceding mucuna fallow or relay crop compared to the control for Group I fields. This implies that other factors than N were causing the generally low yield (1.8 t ha$^{-1}$). Indeed, a significant increase (P = 0.05) in maize grain yield was obtained in response to the application of P and K in combination with 80 kg N $ha^{-1}$, or a preceding mucuna fallow or relay (Appendix A5). This points to P and/or K as limiting factors at high levels of N. This is further confirmed by the significant increase ($P < 0.05$) in maize yield in response to the application of P and K fertilizers to 80 kg N $ha^{-1}$, and to a preceding mucuna relay plus P when compared to the same treatments without P and K.

However, for Group II fields there was a significant increase ($P=0.05$) in maize yield in response to the application of inorganic N fertilizers or to a preceding mucuna fallow or relay crop compared to the farmer practice; N was limiting maize yield on these fields. The lack of a significant difference ($P= 0.05$) in maize response between the alternative treatments indicates that inorganic N and a preceding mucuna crop are both effective N sources for the maize crop.

The N released during the decomposition of mucuna residues was apparently available for maize uptake, confirming that green manure can entirely substitute inorganic fertilizer N at the current average application rate in the low input agriculture at this site, as was observed at Kasheshe/Nemba. The mucuna–derived N was approximately 170 kg N $ha^{-1}$, and the results from the decomposition study carried out within the same agro-ecological zone (reported under Section 4.1.2), indicate that 165 kg N $ha^{-1}$ (97%) was released within in 175 days. Part of this taken up by the maize would be sufficient to result in a significant yield increase.

Doubling the inorganic fertilizer rate from 40 to 80 kg N $ha^{-1}$ did not result in a significant increase ($P=0.05$) in maize yield for the Group-II fields. Probably another nutrient or the environment was more limiting. The significant difference ($P = 0.05$) in maize yield observed between 40 and 80 kg N $ha^{-1}$ following the application of P and K fertilizers indicates that P and/or K were limiting at high levels of N (Appendix A6). This is confirmed by the significant difference ($P< 0.05$) in maize grain yield with 80 kg N $ha^{-1}$, with and without P and K fertilizers (1.6 vs. 2.7 t $ha^{-1}$).

The lack of response to the application of P and K fertilizers to the 40 kg N $ha^{-1}$ treatment or to preceding mucuna fallow or relay, indicates that P and/or K were not limiting under these situations. It should be noted that, though the mucuna-derived N was applied at a rate of 170 kg N $ha^{-1}$, with 165 kg N $ha^{-1}$ (97%) of it being eventually released, not all would have been timely available for uptake by maize. Moreover, some of the N is lost from the system.

There was no significant difference (P=0.05) between the weedy fallow at both levels of P and K, and the control for both groups of fields, implying that the one season weedy fallow was not an effective strategy for improving soil productivity. This was expected because the recommendation in Uganda is three years of cropping followed by a similar period (3 years) under fallow (Foster 1976).

### Comparing the two fertility groups of fields

In general, there was a significant difference (P = 0.05) in maize yield between the two groups of fields, with and without P and K fertilizers. The different strategies were not quite effective in increasing the productivity of Group II fields to that of Group I fields. However, the largest yield increase was obtained following the addition of N, meaning that N is the main limiting nutrient. The additional increase in response to the application of P and K fertilizers indicates that the two are also limiting maize production at the site. This suggests that the observed yield difference between the two groups of fields is indeed due to differences in soil fertility, even though the soil properties did not reflect this difference (Table 29). Apparently, the longer period of cultivation of the Group II fields leads to soil fertility decline that is not discerned with chemical extractions used in soil testing procedures. It should be noted that the maize yields at this site are generally low partly due to the low soil fertility and the abundance of the witch weed (*Striga spp.*) observed in maize fields.

### Combined grain yield of the two seasons (1-year period)

The combined maize yields for the 2000B and 2001A seasons in response to the different treatments at Odwarat are given in Table 31. On high-productivity fields, inorganic fertilizers or a preceding mucuna relay resulted in an increase of 0.5 t ha$^{-1}$ in maize grain, though not significantly different from the control. The reduction in maize yield due to the mucuna fallow was 0.8 t ha$^{-1}$ over two seasons. Application of P and K fertilizers to 40 and 80 kg N ha$^{-1}$ resulted in an additional 0.9 t ha$^{-1}$ of grain, and 1.2 t ha$^{-1}$, with the preceding mucuna relay.

For the low-productivity fields, an average increase of 1.3 t ha$^{-1}$ in grain yield was obtained with inorganic N fertilizers as well as with the preceding mucuna relay. The yield following a mucuna fallow compensated for the yield loss when the field was under fallow. Application of P and K fertilizers to 80 kg N $ha^{-1}$ resulted in an additional 0.7 t $ha^{-1}$of grain.

Table 31: Total (overall) grain production (t $ha^{-1}$) for the two seasons for the groups of fields at Odwarat (without and with P and K fertilizers)

| Treatments | - (P and K) | | | + (P and K)[a] | | |
|---|---|---|---|---|---|---|
| | Group | | | | | |
| | I | II | Prob[b]. | I | II | Prob[b]. |
| Farmers' practice (control) | 3.1 | 1.5 | ** | | | |
| 40 kg N $ha^{-1}$ | 3.7 | 3.0 | ns | 4.0 | 3.2 | ns |
| 80 kg N $ha^{-1}$ | 3.7 | 2.9 | ns | 4.2 | 3.6 | ns |
| Preceding mucuna relay + 25 kg P $ha^{-1}$ | 3.3 | 3.2 | ns | 4.5 | 3.5 | ns |
| Preceding mucuna relay | 3.2 | 2.6 | ns | 3.6 | 2.8 | ns |
| Preceding mucuna fallow | 2.2 | 1.4 | ns | 2.3 | 1.8 | ns |
| Preceding weedy fallow | 1.4 | 1.2 | ns | 1.2 | 0.8 | ns |
| Mean | 2.9 | 2.3 | ** | 3.3 | 2.5 | *** |
| $LSD_{5\%}$ | 1.0 | 1.1 | | 1.1 | 1.1 | |

[a] P and K fertilizers not applied under farmers practice

[b] level of significance for the difference between means of the same treatment between the two groups

*, **, *** indicate significant at P = 0.05, 0.01, 0.001 levels, respectively

Thus, in terms of increase in maize grain, the best approach for farmers with high-productivity fields is to apply P and K fertilizers to inorganic N and preceding mucuna relay. Farmers with low-productivity fields would produce more by applying 40 kg N $ha^{-1}$ or by using a preceding mucuna relay with P and or K fertilizers.

#### 4.2.1.4 Agonyo II

#### Soil characteristics

The results from the analysis of selected soil properties are given in Table 32. The fields had sandy clay loam soils, most of them having mean values of the soil chemical properties above the low critical values, indicating that the soils are of moderate fertility. The only exception was soil pH, with a considerable number of fields having values below the low critical level. The low soil pH will affect the productivity of these fields, since it is one of the factors determining root development and the availability of plant nutrients of Uganda soils (Foster 1978, 1980a,b).

Table 32: The range and mean values of selected soil properties at Agonyo II

| Soil parameter | Range | Mean | Low critical value[a] | Fields below the low critical value (%) |
|---|---|---|---|---|
| pH (1 soil:2.5 water) | 4.2 – 5.9 | 5.3 | 5.2 | 47 |
| OM (%) | 3.3 – 5.8 | 4.3 | 3.0 | 0 |
| Extractable P (mg $kg^{-1}$) | 3.7 – 30.5 | 11.3 | 5.0 | 24 |
| Extractable K ($cmol_c$ $kg^{-1}$) | 0.3 – 1.4 | 0.6 | 0.4 | 24 |
| Extractable Ca ($cmol_c$ $kg^{-1}$) | 0.2 – 3.1 | 1.8 | 0.9 | 6 |
| Sand (%) | 21 – 65 | 52 | na | na |
| Silt (%) | 7 – 37 | 21 | na | na |
| Clay (%) | 22 – 42 | 27 | na | na |

[a] Below these values, levels are low/deficient (Foster 1971); na = not applicable

### *Maize and mucuna yield in first season (2000B)*

The maize and mucuna dry matter, as well as N, P and K yields during 2000B season are given in Table 33. There was a significant reduction (P=0.05) in maize yield for the intercrop as compared to maize sole crop. This is partly attributed to the competition for resources between the two crops, and to poor management of mucuna by farmers.

Table 33: Maize, mucuna dry matter, N, P and K yield at Agonyo II during 2000B season

| Treatment | Maize | | Mucuna | | | |
|---|---|---|---|---|---|---|
| | Grain | Stover | Dry matter | N | P | K |
| | t $ha^{-1}$ | | t $ha^{-1}$ | kg $ha^{-1}$ | | |
| Maize | 3.0 | 4.3 | na | | | |
| Maize | 2.7 | 4.1 | na | | | |
| Maize | 3.0 | 4.4 | na | | | |
| Mucuna relay + 25 kg P $ha^{-1}$ | 2.2 | 3.5 | 6.5 | 195 | 14 | 95 |
| Mucuna relay | 2.2 | 3.7 | 6.4 | 179 | 13 | 93 |
| Mucuna fallow | na | na | 7.2 | 202 | 15 | 103 |
| $LSD_{5\%}$ | 0.4 | 0.8 | ns | ns | ns | ns |

na = not applicable

Farmers did not prevent mucuna (through frequent removal) from intertwining with the maize, which led to maize becoming smothered. However, there was no significant reduction (P = 0.05) in mucuna dry matter, N, P and K yield in the intercrops as compared to the fallow, indicating that mucuna was not affected by maize. Mucuna on average, accumulated 192 kg N $ha^{-1}$, with 109 kg N $ha^{-1}$ (57 %) derived from the atmosphere through BNF, which is a significant contribution to the N input into the system.

## Classifying farmers' fields

The mean grain yield for the farmers' practice in Agonyo II was 2.0 t $\text{ha}^{-1}$. This yield level was used to split the fields into high and low productivity groups. Group I consisted of more productive fields than Group II. The mean maize yield and the values of selected soil properties for the two groups of fields are given in Table 34.

There was a significant difference (P=0.001) in the mean grain yield between the two groups of fields, which is attributed to the difference in soil fertility. The mean soil pH of Group II fields was significantly lower (P = 0.05) than that of Group I fields and below the critical value for Uganda soils.

Table 34: Maize yield and mean values of selected soil properties for the two groups of fields

| | Group[a] | | | Critical values[b] |
|---|---|---|---|---|
| | I | II | Prob$^{3}$. | Low |
| Number of farmers | 7 | 10 | | |
| Maize yield | | | | |
| Grain (t $\text{ha}^{-1}$) | 2.3 | 1.6 | *** | |
| Stover (t $\text{ha}^{-1}$) | 4.5 | 3.2 | ** | |
| Soil properties | | | | |
| pH | 5.4 | 5.0 | * | 5.2 |
| OM (%) | 4.5 | 4.1 | ns | 3.0 |
| Extractable P (mg $\text{kg}^{-1}$) | 13.5 | 9.0 | ns | 5.0 |
| Extractable K ($\text{cmol}_c$ $\text{kg}^{-1}$) | 0.7 | 0.5 | ns | 0.4 |
| Extractable Ca ($\text{cmol}_c$ $\text{kg}^{-1}$) | 1.9 | 1.6 | ns | 0.9 |
| Sand (%) | 55 | 50 | ns | na |
| Silt (%) | 19 | 23 | ns | na |
| Clay (%) | 26 | 27 | ns | na |
| Bulk density (kg $\text{m}^{-3}$) | 1440 | 1440 | ns | na |

[a]Group I = high productivity fields; Group II = low productivity fields

[b]Below these values, levels are low/deficient (Foster 1971), na = not applicable

[c]level of significance for the difference between means of the same property between the groups

ns, *, **, *** indicate non-significant at P = 0.05 and significant at P = 0.05, 0.01 and 0.001 levels, respectively

### *Maize response to alternative treatments in the preceding season (2001A)*

The maize yield (t $\text{ha}^{-1}$) in response to applied N and preceding mucuna treatments at Agonyo II are given in Tables 35a and 35b without and with P and K fertilizers, respectively. There was a significant increase (P=0.05) in maize yield in response to the application of inorganic N fertilizer as well as to preceding mucuna relay as compared to the farmer practice (control) for Groups I fields. For Group II fields, a significant increase (P=0.05) in maize yield was obtained in response to the application of 80 kg N $\text{ha}^{-1}$ and to a preceding mucuna fallow or relay crop.

Table 35a: Maize grain yield (t ha$^{-1}$) for the two groups of fields at Agonyo II during 2001A season (without P and K fertilizers)

| Treatments | Grain yield | | | Stover yield | | |
|---|---|---|---|---|---|---|
| | | | Group | | | |
| | I | II | Prob[a]. | I | II | Prob[a]. |
| Farmers' practice (control) | 2.3 | 1.6 | * | 4.5 | 3.2 | * |
| 40 kg N ha$^{-1}$ | 3.2 | 2.1 | ** | 6.0 | 3.4 | ** |
| 80 kg N ha$^{-1}$ | 3.3 | 2.7 | * | 6.1 | 4.0 | ** |
| Preceding mucuna relay + 25 kg P ha$^{-1}$ | 2.9 | 2.5 | ns | 6.0 | 4.5 | * |
| Preceding mucuna relay | 2.8 | 2.8 | ns | 5.2 | 4.8 | ns |
| Preceding mucuna fallow | 2.6 | 2.8 | ns | 5.4 | 4.5 | ns |
| Preceding weedy fallow | 2.5 | 2.0 | ns | 4.5 | 3.8 | ns |
| Mean | 2.8 | 2.4 | ** | 5.4 | 4.0 | ** |
| $LSD_{5\%}$ | 0.6 | 0.6 | | 1.5 | 1.5 | |

[a]level of significance for the difference between means of the same treatment between groups
ns, *, **, not significantly different at P = 0.05 and significant at P = 0.05, 0.01 levels respectively

Table 35b: Maize grain yield (t ha$^{-1}$) for the two groups of fields at Agonyo II during 2001A season (with P and K fertilizers)

| Treatments | Grain yield | | | Stover yield | | |
|---|---|---|---|---|---|---|
| | | | Group | | | |
| | I | II | Prob[a]. | I | II | Prob[a]. |
| Farmers' practice (control)[b] | 2.3 | 1.6 | * | 4.5 | 3.2 | * |
| 40 kg N ha$^{-1}$ | 3.2 | 3.2 | ns | 6.0 | 4.8 | ns |
| 80 kg N ha$^{-1}$ | 3.4 | 3.3 | ns | 6.1 | 5.5 | ns |
| Preceding mucuna relay + 25 kg P ha$^{-1}$ | 3.5 | 3.5 | ns | 6.9 | 6.3 | ns |
| Preceding mucuna relay | 2.9 | 3.1 | ns | 6.0 | 5.4 | ns |
| Preceding mucuna fallow | 3.4 | 2.9 | ns | 6.3 | 4.4 | * |
| Preceding weedy fallow | 2.4 | 2.1 | ns | 5.1 | 3.3 | * |
| Mean | 3.0 | 2.8 | ns | 5.8 | 4.7 | ** |
| $LSD_{5\%}$ | 0.6 | 0.7 | | 1.5 | 1.7 | |

[a]level of significance for the difference between means of the same treatment between groups
ns, *, **, not significantly different at P = 0.05, and significant at P = 0.05, 0.01 levels, respectively
[b]P and K fertilizers not applied to farmers' practice

In general, there was no significant difference in maize response to inorganic fertilizers and to preceding mucuna, implying that the alternative strategies were effective in providing N for maize. The N released during the decomposition of mucuna residues was available for maize uptake. Thus, in this low-potential agro-ecological zone, green manure can entirely substitute inorganic fertilizer N at the current average application rate.

The mucuna–derived N was approximately 192 kg N ha$^{-1}$, with approximately 186 kg N ha$^{-1}$ released in 175 days (reported under Section 4.1.2). Some of this N was available for plant uptake, resulting to the observed significant increase in maize yield. Since approximately 109 kg N ha$^{-1}$ (55%) was supposedly derived from BNF (reported under Section 4.1.1), the results confirm that BNF can contribute to the N requirements and sustain smallholder agriculture at this site.

Doubling the inorganic fertilizer rate from 40 to 80 kg N $ha^{-1}$ resulted in a significant increase ($P < 0.05$) of maize yield for Group II fields only, indicating that the lower N rate was not sufficient to meet the N requirement by maize on these fields. The different response obtained for the two groups confirms difference in soil fertility between the groups, with soils of Group I fields being of better fertility status than the Group II fields. Again, this is not readily seen from the soil chemical properties listed in Table 34.

The significant increase ($P = 0.05$) in maize yield in response to the application of P and K fertilizers to the preceding mucuna relay or fallow treatments for Group I fields (Appendix A7); to inorganic N fertilizers, and to preceding mucuna relay plus P for Group II fields indicate that P and/or K are also limiting maize production (Appendix A8).

A one-season weedy fallow was not an effective strategy for increasing maize yield at this site. This is in agreement with the current recommendation of 3 years of cropping followed by 3 years under fallow (Foster 1976).

### Comparing the two fertility groups of fields

Significant differences ($P < 0.05$) in maize yield between the two groups of fields were observed only for the inorganic N treatments. This suggests that N was not the only limiting factor for Group II fields. A preceding mucuna fallow or relay implies that mucuna had the same effect under both groups of fields, possibly due to the additional benefits such as supply of P and K during mineralisation. There was no significant difference ($P = 0.05$) in maize yield between the two groups of fields following the application of P and K fertilizers to inorganic N treatments, indicating that P and/or K were also limiting factors. Therefore, the N replenishment strategies together with P and K fertilizers were effective in raising the productivity of Group II fields to the level of Group I fields, confirming differences in the soil fertility between the groups.

### Combined grain yield of the two seasons (1-year period)

The combined maize yield for the 2000B and 2001A seasons in response to the different treatments is given in Table 36. Inorganic fertilizers or a preceding mucuna relay plus P did not result in a significant overall increase (P=0.05) in maize grain yield compared to the control for high-productivity fields. However, the mucuna fallow resulted in a significant overall yield reduction of 3.6 t $ha^{-1}$ of maize grain. A similar yield loss was obtained during a preceding weedy fallow. Application of P and K fertilizers to inorganic N and preceding mucuna did not result in a significant increase in maize yield.

Table 36: Total (overall) grain production (t $ha^{-1}$) for the two seasons for the groups of fields at Agonyo II (without and with P and K fertilizers)

| Treatments | - (PK) | | | + (PK)[a] | | |
|---|---|---|---|---|---|---|
| | Group | | | | | |
| | I | II | Prob[b]. | I | II | Prob[b]. |
| Farmers' practice (control) | 5.9 | 3.7 | *** | | | |
| 40 kg N $ha^{-1}$ | 5.7 | 5.0 | ns | 6.1 | 5.1 | ** |
| 80 kg N $ha^{-1}$ | 6.0 | 5.5 | ns | 5.7 | 5.8 | ns |
| Preceding mucuna relay + 25 kg P $ha^{-1}$ | 5.7 | 4.4 | ** | 6.1 | 4.9 | ** |
| Preceding mucuna relay | 4.8 | 4.9 | ns | 5.0 | 4.7 | ns |
| Preceding mucuna fallow | 2.3 | 2.9 | ns | 2.9 | 3.2 | ns |
| Preceding weedy fallow | 2.4 | 2.2 | ns | 2.5 | 2.1 | ns |
| Mean | 4.7 | 4.1 | *** | 4.9 | 4.2 | *** |
| $LSD_{5\%}$ | 0.8 | 1.0 | | 0.9 | 1.0 | |

[a] P and K fertilizers not applied under farmers practice

[b] level of significance for the difference between means of the same treatment between the two groups

*, **, *** indicate significant at P = 0.05, 0.01, 0.001 levels, respectively

For the low-productivity fields, an average increase of 1.5 t $ha^{-1}$ in grain yield was obtained in response to the application of inorganic-N fertilizers and of 1.0 t $ha^{-1}$ to the preceding mucuna relay compared to the control. The preceding mucuna fallow response did not compensate for the yield loss when the field was under fallow. Application of P and K fertilizers to 80 kg N $ha^{-1}$ resulted in an additional 0.3 t $ha^{-1}$ of grain, and 0.5 t $ha^{-1}$ in the case of a preceding mucuna relay plus P.

In terms of the overall increase in maize grain, the best practice for farmers with high-productivity fields is to continue in the short run with their current practice. However, one should anticipate a gradual reduction in the productivity of these fields with continued cropping. For farmers with low-productivity fields, the best yields are gained with 80 kg N ha$^{-1}$or the use of a preceding mucuna relay. High-productivity fields might benefit from such practices in the long run as well.

#### 4.2.1.5 *Cross – environment agronomic analysis*

To determine the benefits from the mucuna strategy, it was necessary to grow mucuna either in relay or fallow during the 2000B season for use in the subsequent season. This resulted in a loss of a complete season crop in case of the fallow, and reductions in maize yield were observed in some locations for the relay. Therefore, it is necessary to evaluate the benefits of mucuna for two seasons so as to capture its effect on yield during the preceding season. The alternative to mucuna–accumulated N is to use inorganic N fertilizers. In the subsequent season, a maize crop was used to evaluate the effects of the mucuna–accumulated N as compared to inorganic fertilizer N. The total maize grain yield for the two seasons is presented in Table 37.

Table 37: Total maize grain yield (t ha$^{-1}$) for two seasons from the alternative strategies under both contrasting environmental potential and soil productivity

| **TREATMENTS** | **ENVIRONMENT POTENTIAL** | | | |
|---|---|---|---|---|
| | **Low** | **High** | | |
| Farmers' practice | 2.6 | 3.2 | **Low** | **SOIL PRODUCTIVITY** |
| 40 kg N ha$^{-1}$ | 4.0 | 4.4 | | |
| 80 kg N ha$^{-1}$ | 4.2 | 4.7 | | |
| Mucuna relay + P | 3.8 | 4.6 | | |
| Mucuna relay | 3.7 | 4.2 | | |
| Mucuna fallow | 2.2 | 2.4 | | |
| Weedy fallow | 1.7 | 2.0 | | |
| $LSD_{5\%}$ | 1.0 | 1.0 | | |
| Farmers' practice | 4.2 | 5.5 | **High** | |
| 40 kg N ha$^{-1}$ | 4.6 | 8.3 | | |
| 80 kg N ha$^{-1}$ | 4.8 | 8.1 | | |
| Mucuna relay + P | 4.5 | 6.8 | | |
| Mucuna relay | 4.8 | 7.1 | | |
| Mucuna fallow | 2.2 | 5.5 | | |
| Weedy fallow | 1.9 | 3.8 | | |
| $LSD_{5\%}$ | 1.4 | 1.9 | | |

On average, there was a significant (P=0.05) increase in maize grain yield on average of 1.3 t ha$^{-1}$ in response to the application of inorganic N fertilizers, as well as to a preceding mucuna relay for the low-productivity fields in both high- and low-potential environments. Significant (P=0.05) increases in maize yield, on average of 2.7

t ha$^{-1}$ and 1.5 t ha$^{-1}$, were obtained in response to application of inorganic N fertilizers and to the preceding mucuna relay, respectively, on high-productivity soils in high-potential areas. The results indicate that both inorganic fertilizers and mucuna green manure served as effective N sources for maize. There was no significant difference ($P=0.05$) in maize grain yield in response to a mucuna fallow compared to the control for the low-productivity fields in both high- and low-potential environments, and also for the high-productivity fields in high-potential environment. This indicates that the response to mucuna largely compensated for the yield loss during the season when the fields were under fallow.

In sharp contrast, the alternative N replenishment strategies did not result in a significant ($P=0.05$) increase in maize yield for the high-productivity fields in the low-potential environment. Moreover, the mucuna fallow resulted in a significant overall yield loss of 2.0 t ha$^{-1}$ compared to the control. This clearly is the most challenging environment for the design of sustainable production systems.

The results of the effect of application of P and K fertilizers in combination with the alternative N replenishment strategies on the overall maize grain production over the two seasons are indicated in Appendix A9. It is observed that application of P and K fertilizers resulted in, on average, an overall increase of 1.6 t ha $^{-1}$ and 1.2 t ha$^{-1}$ for the low-productivity fields in the low- and high-potential environments, respectively. However, the increase in maize yield was, on average, 2.6 t ha$^{-1}$ for the high-productivity fields in the high-potential environment, with no significant effect on similar fields in the low-potential environment.

#### 4.2.1.6 *Cross – environment economic analysis*

Most smallholder farmers are subsistence farmers', selling the surplus only after their food needs are met. The results in the previous sections show that the alternative strategies are effective in increasing maize production on contrasting soils in eastern Uganda. The increase in maize yield can lead to food security, the primary objective of the smallholder farmers. Since there are costs associated with the alternative strategies, and smallholder farmer's sell the surplus, it is important to subject the observed yield increment to economic analysis so as to determine the economic benefits associated with the alternative strategies on contrasting soils and in contrasting agro-ecological zones.

The costs taken into consideration for the farmers’ practice were those for the improved seeds, field preparation, and harvesting. A weedy fallow was included to determine its economic benefits in a situation where farmers have made the decision to rest a particular field for one season. The total variable costs for mucuna and weedy fallows are less than for the farmers’ practice due to the saving on seeds (mucuna seeds are cheaper than maize seeds) during the season when the fields were under fallow. In addition, the fields had fewer weeds due to suppression by mucuna, so a single ploughing was enough for planting maize compared to two for other treatments, which is an indirect saving for the farmer.

The “benefit to cost ratio” (B/C) is used as an indicator of the profitability of a given practice. A B/C value of one (1) is the break-even point for the farmers. The benefit to cost ratio below one (1) implies that the farmers are not recovering the costs. The benefit to cost ratio of the alternative strategies under contrasting environmental potential and contrasting soil productivity is given in Table 38.

Table 38: The “benefit to cost ratio”[a] (B/C) for the alternative strategies under contrasting agricultural potential and contrasting soil productivity

| **TREATMENTS** | **ENVIRONMENT POTENTIAL** | | | |
|---|---|---|---|---|
| | **Low** | **High** | | |
| Farmers’ practice | 0.79 | 0.73 | **Low** | **SOIL PRODUCTIVITY** |
| 40 kg N ha$^{-1}$ | 0.99 | 0.84 | | |
| 80 kg N ha$^{-1}$ | 0.91 | 0.82 | | |
| Mucuna relay + P | 0.89 | 0.87 | | |
| Mucuna relay | 1.19 | 1.02 | | |
| Mucuna fallow | 0.89 | 0.70 | | |
| Weedy fallow | 1.06 | 0.82 | | |
| LSD$_{5\%}$ | 0.25 | 0.28 | | |
| Farmers’ practice | 1.38 | 1.14 | **High** | |
| 40 kg N ha$^{-1}$ | 1.15 | 1.59 | | |
| 80 kg N ha$^{-1}$ | 1.04 | 1.36 | | |
| Mucuna relay + P | 1.04 | 1.20 | | |
| Mucuna relay | 1.29 | 1.64 | | |
| Mucuna fallow | 0.89 | 1.59 | | |
| Weedy fallow | 1.17 | 1.42 | | |
| LSD$_{5\%}$ | ns | 0.27 | | |

[a] The higher the value, the more profitable the strategy
B/C = 1 indicate that farmers are recovering costs
Values below 1 indicate farmers are not recovering costs

The gross field benefits, total variable costs and gross margins for the alternative N replenishment strategies are given in Appendices A10 and A11 for the high- and low-potential areas, respectively.

First of all, it is observed that on low-productivity soils farmers do not even recover their variable costs in maize and mucuna seeds, ploughing and labour. Thus, farmers with such fields easily fall into a spiral of increasing poverty. In contrast, farming on high-productivity soils still pays off for farmers in high- and low-potential areas.

### High-potential environment

It is observed that the alternative N replenishment strategies are profitable on high-productivity fields of the high-potential areas with large increases in yield in response to these strategies. Farmers more than recover the cost incurred in relation to the alternative strategies, it is only the 40 kg N ha$^{-1}$ and the preceding mucuna relay or fallow yield benefit to cost ratios which are significantly different (P= 0.05) from those of the farmers practice. The reduction in the "benefit to cost ratio" observed with the increase of N from 40 to 80 kg N ha$^{-1}$, and with the application of P fertilizers to mucuna relay is due to the extra cost incurred through the use of more fertilizers.

However, for the low-productivity fields it is only with the mucuna relay that farmers do recover the costs incurred. The values of the benefit to cost ratio for other N replenishment strategies are below one (1), implying that farmers do not recover the costs. Since farmers do not recover the costs incurred with their current practice, there is an incentive to shift to alternative mucuna-maize relay cropping on these fields.

### Low-potential environment

On high-productivity fields, farmers recover the costs related to the alternative N replenishment strategies reflected by the "benefit to cost ratios" of all the strategies above one (1), with the exception of mucuna fallow. However, there is no significant difference (P=0.05) in the benefit to cost ratio of the alternative strategies compared to the farmers' current practice. Thus, the farmers' current practice is as profitable as the alternative cropping strategies, but at lower production levels. The low benefit to cost ratios obtained with the different strategies is due to the generally low crop response on the more productive fields in the low-potential environments.

However, for the low-productivity fields, values of the benefit to cost ratios indicate that with a mucuna relay and with 40 kg N ha$^{-1}$ farmers can recover their cost. The mucuna relay is the only strategy that is significantly more profitable than the farmers' current practice.

**Fertilizer price**

The results from the previous section show that fertilizer application reduces the economic benefits due to high cost of fertilizers. An analysis was carried out to determine the effect of a reduction in fertilizer price of up to 90% on the profitability of their use across the agro-ecological zones. Two assumptions were made: the maize yield obtained is typical for the areas covered by the study, and the field price of maize remains at UgShs. 100 per kg.

In order to at least recover the extra cost of fertilizer use on low-productivity fields, prices would have to be reduced by 10, 30 and 40% for the 40, 80 kg N ha$^{-1}$ and the mucuna plus P relay in the low-potential areas (Appendix A12). In the high-productive areas, the corresponding price reductions needed are 90, 80 and 70%, respectively (Appendix A11). On high-productivity soils, the fertilizer levels tested here always led to full recovery of the investment, even at current prices.

To achieve a substantial reduction in fertilizer price will require government intervention, which is unlikely due to the structural adjustment policies currently being pursued by the Government. A viable alternative is to use a low cost/input technology such as mucuna relay for soil fertility improvement in order to support agricultural production in low-productivity fields. The results agree with Vlek (1990), who found that promoting fertilizers in areas where their use will not result in markedly increased land and labour productivity is a misdirection of scarce resources.

**Summary and conclusion**

The mean mucuna biomass (DM) production and N accumulation was 2.6 t ha$^{-1}$ (80 kg N ha $^{-1}$) at Kongta; 6.3 t ha$^{-1}$ (200 kg N ha$^{-1}$) at Kasheshe/Nemba; 7.9 t ha$^{-1}$ (170 kg N ha$^{-1}$) at Odwarat; and 6.6 t ha$^{-1}$ (190 kg N ha$^{-1}$) at Agonyo II. The corresponding quantity of N fixed was estimated 34, 86, 97 and 108 kg ha$^{-1}$, with a local value of US $ 26, 66, 74, and 83 at Kongta, Kasheshe/Nemba, Odwarat, and Agonyo II, respectively. In addition, mucuna accumulated P and K in the range 7-30 and 60-174 kg ha$^{-1}$, respectively, thus recycling these nutrients within the system.

Intercropping maize with mucuna in the relay reduced maize yield significantly ($P = 0.05$) in the low-potential areas, partly due to competition for resources, and to smothering of maize by mucuna, when farmers failed to manage the intercropped mucuna.

The mean yield of the farmers' practice (maize without input) was used to distinguish two types of fields at each site: low- and high-productivity. Significant ($P < 0.05$) differences in maize yield between the two groups of fields are due to differences in measured chemical soil properties at Kongta, Kasheshe/Nemba and Agonyo II. For Odwarat, the significant ($P < 0.05$) difference are due to the number of seasons the fields have been under cultivation, as a proxy for soil fertility differences not detectable by chemical methods.

The 2001a season data indicate that inorganic fertilizers and a preceding mucuna crop are effective sources of N on contrasting soils and in contrasting agro-ecological zones. Their use increased maize grain yield on high-productivity fields by 2.7 t ha$^{-1}$ (124% increase) at Kongta; 1.7 t ha$^{-1}$ (40% increase) at Kasheshe/Nemba; and 0.9 t ha$^{-1}$ (37% increase) at Agonyo II. On the low-productivity fields, the average increase was 1.1 t ha$^{-1}$ (102% increase) at Kongta; 0.9 t ha$^{-1}$ (46% increase) at Kasheshe/Nemba; 0.9 t ha$^{-1}$ (125% increase) at Odwarat; and 1.1 t ha$^{-1}$ (94% increase) at Agonyo II.

In general, application of P and K fertilizers resulted in a significant yield increase in the range 1.3 – 1.9 t ha$^{-1}$ (94 – 178%) for low-productivity fields across the agro-ecological zones (with the exception of Kongta site). The increase was in the range 1.1 – 1.3 t ha$^{-1}$ (48 – 80%) for high-productivity fields in the low-potential agro-ecological zones. However, comparing specific treatments with and without P and K fertilizers, significant yield increases in the range 0.9 – 1.6 t ha$^{-1}$ were obtained with 80 kg N ha$^{-1}$ and with a preceding mucuna, indicating that P and/or K become limiting at higher N rates across the agro-ecological zones.

Unlike at the Agonyo II and Odwarat sites, the N replenishment strategies, even with the application of P and K fertilizers, did not bridge the yield gaps between high- and low-productivity fields at Kasheshe/Nemba and Kongta. Apparently these nutrients were not the only limiting factors for the low-productivity fields. In addition to high nutrient depletion, loss of topsoil through erosion and soil compaction might have contributed to the low productivity of these soils.

The grain yield summed over two seasons also confirmed that the N replenishment strategies were effective in supplying N to the maize plant. The highest yield increment of 2.7 t ha $^{-1}$ was obtained with the application of inorganic fertilizers on high-productivity fields in high-potential areas, compared to 1.5 t ha $^{-1}$ obtained with a preceding mucuna relay. However, the average increase in grain yield in response to application of inorganic N fertilizers and to preceding mucuna relay was 1.3 t ha $^{-1}$ for the low-productivity fields in both the high- and low-productivity area. The higher yields obtained in response to inorganic fertilizers for the high-productivity soils in high-potential areas prove that these strategies are most effective in these environments.

All N-replenishment strategies are profitable on the high-productivity fields in high-potential areas as observed from high "benefit to cost ratio" due to a substantial yield response. The 40 kg N ha $^{-1}$ is more profitable compared to 80 kg N ha $^{-1}$. The mucuna relay is economically viable on low- and high-productivity fields.

In low-potential areas and on low-productivity fields, mucuna relay is the only profitable system. Farmers do not recover their costs with other strategies, not even with their current practice. On the other hand, on high-productivity fields, farmers do recover the costs (with the exception of the mucuna fallow) and all the strategies are as profitable as the farmers’ current practice. However, considering the long-term effects on both food security and system sustainability, mucuna that adds N through BNF might be more desirable in the long run.

### 4.2.2 Rice system

#### 4.2.2.1 Nakisenye

**Soil characteristics**

The results of the analysis for selected soil properties are given in Table 39. The fields had clay soils, with the majority (93%) having a pH below the low critical value for Uganda soils (Foster 1971). The mean values of other soil properties indicate that the soils are suitable for upland crops (the critical values were determined for such crops). However, for rice cultivation the situation may be different since the chemistry of a soil changes under submerged conditions; the soil pH changes towards neutrality, thus influencing nutrient availability. The high organic-matter levels are due to the location of the fields in low-lying areas, where anaerobic conditions exist during certain times of the year. Organic matter decomposition is slow under anaerobiosis. Moreover, depositions of sediments eroded from upland areas are often rich in organic matter.

Table 39: The range and mean values of selected soil properties at Nakisenye

| Soil parameter | Range | Mean | Low critical value[a] | Fields below the low critical value (%) |
|---|---|---|---|---|
| pH (1 soil:2.5 water) | 4.7 – 5.8 | 5.1 | 5.2 | 93 |
| OM (%) | 5.0 – 15.0 | 12.6 | 3.0 | 0 |
| Extractable P (mg $kg^{-1}$) | 29 – 52 | 45.1 | 5.0 | 0 |
| Extractable K ($cmol_c$ $kg^{-1}$) | 0.7 – 1.6 | 1.1 | 0.4 | 0 |
| Extractable Ca ($cmol_c$ $kg^{-1}$) | 2.2 – 5.0 | 4.0 | 0.9 | 0 |
| Sand (%) | 23 – 40 | 29 | na | na |
| Silt (%) | 19 – 35 | 23 | na | na |
| Clay (%) | 24 – 50 | 48 | na | na |

[a]Below these values, levels are low/deficient (Foster 1971); na = not applicable
na = not applicable

***Maize and mucuna yield in the first season (2000B)***

The maize, mucuna dry matter, N, P and K yield during 2000B season are given in Table 40. There was no significant difference (P=0.05) in maize yield between the intercrop and the control, implying that mucuna did not affect the maize. This is partly attributed to the good management of mucuna by the farmers, who prevented it from smothering the maize by cutting off the vines and removing them from the maize. However, there was a significant reduction in mucuna biomass production in the intercrop compared to the sole crop, due in part to the frequent cutting of mucuna vines. On average, mucuna accumulated 205 kg N $ha^{-1}$, which is within the range reported for green manures in the tropical lowland rice systems (Buresh and De Datta 1991; Singh et al. 1991; George et al. 1994; Ladha et al. 1996).

Table 40: Maize, mucuna dry matter, N, P and K yield at Nakisenye during 2000B season

| Treatment | Maize | | Mucuna | | | |
|---|---|---|---|---|---|---|
| | Grain | Stover | Dry matter | N | P | K |
| | t ha$^{-1}$ | | t ha$^{-1}$ | kg ha$^{-1}$ | | |
| Maize | 3.1 | 4.7 | | | | |
| Maize | 3.5 | 5.0 | | | | |
| Mucuna relay | 3.4 | 5.5 | 5.8 | 187 | 12 | 84 |
| Mucuna relay + 25 kg P ha$^{-1}$ | 3.5 | 5.2 | 6.2 | 197 | 12 | 86 |
| Mucuna fallow | na | na | 7.6 | 230 | 14 | 102 |
| LSD$_{5\%}$ | ns | ns | 1.4 | ns | ns | ns |

ns = not significantly different at P = 0.05; na = not applicable

***Rice yield in the subsequent season (2001A)***

The rice yield (t ha$^{-1}$) in response to the different treatments at Nakisenye during 2001a season is shown in Table 41. There was a significant increase (P=0.05) in rice yield in response to the application of inorganic N fertilizers and to preceding mucuna fallow or relay when compared to the control. Apparently, N was limiting rice production at the site. Several investigators (Becker et al. 1990; Ladha et al. 1996; Becker and Johnson 1998) reported an increase in rice yield in response to preceding green manures.

Table 41: Rice yield (t ha$^{-1}$) at Nakisenye during 2001a season (No. of farmers = 13)

| Treatment | Grain | Straw |
|---|---|---|
| Control | 1.5 | 10.8 |
| 60 kg N ha$^{-1}$ | 2.0 | 11.7 |
| NPK[a] | 2.3 | 15.5 |
| Preceding mucuna relay | 2.3 | 13.7 |
| Preceding mucuna relay + PK[b] | 2.1 | 16.9 |
| Preceding mucuna fallow | 2.2 | 15.4 |
| Preceding a weedy fallow | 1.7 | 14.9 |
| Mean | 2.0 | 14.1 |
| LSD$_{5\%}$ | 0.4 | 5.1 |

[a] NPK = (60 kg N + 20 kg P + 25 kg K) ha$^{-1}$
[b] PK = (20 kg P + 25 kg K) ha$^{-1}$

The yield response to the application of inorganic N fertilizer and preceding mucuna fallow or relay was of a similar magnitude, indicating that both methods served as effective N sources for the rice crop. The efficiency of utilisation of mucuna-derived N by the rice crop may be low due to the excessive amounts of N that are added. George et al. (1998) reported that up to 32% of the N in the green manure is lost due to the excessive amounts of N that are often added.

The lack of a significant difference (P = 0.05) between the NPK and N, only treatments implies that P and K were not limiting rice production at these low yield levels. The same explains the lack of a significant difference (P = 0.05) in rice grain yield between the treatments with preceding mucuna relay with and without P and K fertilizers.

There was a significant increase (P = 0.05) in rice yield in response to preceding mucuna fallow as compared to the weedy fallow, due to the N input into the system by mucuna. This further demonstrates the superiority of leguminous short-term fallows to weedy fallows in soil fertility improvement. There was no significant difference (P = 0.05) in rice grain yield between the weedy fallow and the control, indicating that a single season weedy fallow is not adequate as a soil fertility replenishment strategy.

#### 4.2.2.2 Doho rice scheme

**Soil characteristics**

The results of the analysis for selected soil properties are shown in Table 42. The fields had clay soils, with the majority (47%) having a pH below the low critical value for Uganda soils (Foster 1971); the mean values of other soil properties indicated an above average soil fertility. However, the defined critical values are most likely not applicable under this situation because rice is grown under flooded conditions and the chemistry of the soil changes greatly under submerged conditions. The observed high organic-matter levels are due to the fields' being submerged almost all year around, which retards organic matter decomposition. In addition, the area receives sediments of soil eroded from the Mt. Elgon area, which are rich in organic matter and nutrients.

Table 42: The range and mean values of selected soil properties at Doho rice scheme

| Soil parameter | Range | Mean | Low critical value[a] | Fields below the low critical value (%) |
|---|---|---|---|---|
| pH (1 soil:2.5 water) | 4.6 – 5.2 | 4.8 | 5.2 | 47 |
| OM (%) | 5.1 – 18.2 | 11.6 | 3.0 | 0 |
| Extractable P (mg kg$^{-1}$) | 8.4 – 63.7 | 26.9 | 5.0 | 24 |
| Extractable K (cmol$_c$ kg$^{-1}$) | 0.6 – 1.4 | 0.9 | 0.4 | 24 |
| Extractable Ca (cmol$_c$ kg$^{-1}$) | 4.6 – 7.0 | 5.9 | 0.9 | 6 |
| Sand (%) | 26 - 40 | 32 | na | na |
| Silt (%) | 7 – 33 | 23 | na | na |
| Clay (%) | 23 - 53 | 45 | na | na |

[a]Below these values levels are low/deficient (Foster 1971); na = not applicable

## Azolla biomass

The quantity of *Azolla* incorporated at the beginning of the 2000B and 2001A seasons was 1.47 and 1.27 t ha$^{-1}$, respectively, with an average total N content of 2.9%. It is estimated that 3.8 and 4.4 t ha$^{-1}$ was incorporated into the soil from the three crops of *Azolla*, contributing 110 - 128 kg N ha$^{-1}$, respectively (on the assumption that the total N content of *Azolla* did not vary at each incorporation, and that similar quantities of *Azolla* were incorporated each time). The quantity of N accumulated by *Azolla* in the rice intercrop is within the range reported by Kikuchi et al. (1984), 80% of which is presumably derived from biological N fixation (Watanabe 1982; Eskew 1987; Watanabe et al. 1991).

## Rice yield

The rice yield (t ha$^{-1}$) in response to the different treatments at the Doho rice scheme is shown in Table 43. There was a significant increase (P=0.05) in rice yield in response to the different strategies compared to the control, indicating the effectiveness of the different strategies in increasing rice production. The rice yield in response to the application of 60 kg N ha$^{-1}$ was similar to that of *Azolla* incorporation. Thus, *Azolla* was as effective as the applied inorganic N fertilizers. The increase in rice yield following the incorporation of *Azolla* is in agreement with the results reported in Asia (Watanabe 1982; Lumpkin and Plucknett 1982).

Table 43: Rice yield (t ha$^{-1}$) at Doho rice scheme during 2000B and 2001A seasons (No.of farmers =14)

| Treatment | Season | | | Season | | |
|---|---|---|---|---|---|---|
| | 2000B | 2001A | Total | 2000B | 2001A | Total |
| | | Grain | | | Straw | |
| Farmers' practice (control) | 2.2 | 1.5 | 3.7 | 6.7 | 7.0 | 13.7 |
| NPK[1] | 3.4 | 2.8 | 6.2 | 10.3 | 9.6 | 19.9 |
| Azolla | 2.7 | 2.2 | 4.9 | 8.1 | 6.4 | 14.5 |
| Azolla + NPK[a] | 3.0 | 2.5 | 5.5 | 9.5 | 7.8 | 17.3 |
| 60 kg N ha$^{-1}$ | 2.9 | 2.4 | 5.3 | 8.7 | 8.4 | 17.1 |
| Mean | 2.9 | 2.3 | 5.2 | 9.2 | 7.8 | 16.5 |
| LSD$_{5\%}$ | 0.4 | 0.4 | 0.7 | 2.3 | 2.3 | 3.3 |

[a] NPK = (60 kg N + 20 kg P + 25 kg K) ha$^{-1}$

The overall rice production over two seasons indicates a significant increase (P = 0.05) in rice yield in response to the application of N, P and K compared to N only, indicating that P and K were also limiting rice production at this site. However, the major increase was in response to N, implying it is the major limiting factor.

The lack of a significant difference ($P = 0.05$) in rice yield between *Azolla* plus N, P, K and N, P, K only, suggests that *Azolla* might not have contributed a significant amount of N to the system through biological N fixation. This would be due to the availability of inorganic N on which *Azolla* relied to meet its N requirements, hence competing with the rice crop. It is well established that soluble N inhibits biological N fixation (Herridge et al. 1990; Herridge and Danso 1995; Giller and Cadisch 1995).

### *Economic analysis*

**Nakisenye**

The farming calendar at Nakisenye consists of growing rice during the long rains when water is sufficient for rice cultivation, and an upland crop during the short rains because of insufficient water. Therefore, the economic analysis at Nakisenye included a short rains (2000B season) maize crop and a long rains (2001A season) rice crop. The partial budget for Nakisenye is given in Table 44.

Table 44: The partial budget for Nakisenye

| Treatment | Gross field benefit | Total variable costs | "Benefit to cost ratio"[a] |
|---|---|---|---|
| | ------,000 Uganda shillings/ha[b]--- | | |
| Farmers' practice (maize – rice) | 936 | 591 | 1.58 |
| 60 kg N $ha^{-1}$ | 1233 | 757 | 1.63 |
| NPK[c] | 1328 | 893 | 1.49 |
| Mucuna relay + PK[d] | 1266 | 911 | 1.39 |
| Mucuna relay | 1340 | 628 | 2.13 |
| Mucuna fallow | 977 | 561 | 1.74 |
| Weedy fallow | 783 | 476 | 1.65 |

[a] "Benefit to cost ratio" (B/C) = (Gross field benefit/total variable costs)
B/C = 1, implies that on average farmers recover the investment in the total variable costs
[b] Conversion rate of 1750 Uganda shillings per US dollar
[c] NPK = (60 kg N + 20 kg P + 25 kg K) kg $ha^{-1}$
[d] PK = (25 kg P + 25 kg K) $ha^{-1}$

High economic returns were obtained with all of the alternative strategies. Since rice is basically for the local market, producer prices do not fluctuate much. The high returns obtained even with the current farmers' practice explains, the extensive clearing by farmers for rice cultivation taking place in the swamps in eastern Uganda.

Using a mucuna relay gives the highest “benefit to cost ratio”. Even with the complete season crop lost by farmers when fields are under mucuna fallow, the increase in yield during the subsequent season compensated for this loss. The addition of P and K fertilizers to mucuna relay reduced the “benefit to cost ratio”, due to the high cost of the fertilizers, as the increase in yield is not proportional to the extra costs incurred.

Application of 60 kg N $ha^{-1}$ is as profitable as the farmers’ current practice, due to the high cost of the inorganic fertilizers. The addition of P and K fertilizers reduces the “benefit to cost ratio”, and yet there was no significant difference in yield between the N and NPK treatments. Therefore, for current yield levels, N, P, and K fertilizers are not economical and there is little incentive for farmers to adopt fertilizers. But mucuna will more than pay off.

### Doho rice scheme

The results of the economic analysis show that farmers break even with their current practice of growing rice each season without applying any source of nutrients (Table 45). It is observed that inorganic fertilizers or *Azolla* are more profitable than the current farmers’ practice, due to the significant increase in rice grain yield through the use of these strategies. The benefit to cost ratio from N, P, and K fertilizers is similar to that of N fertilizer alone, indicating that additional increase in grain yield in response to the application of P and K covered the extra cost of P and K fertilizers. However, application of N, P, and K fertilizers together with *Azolla* reduced the benefit to cost ratio compared to either strategy used alone. This is due to the extra costs incurred, which were not compensated with a proportional increase in grain yield.

Table 45: Partial budget for Doho rice scheme

| Treatment | Gross field benefit | Total variable costs | “Benefit to Cost ratio”[a] |
|---|---|---|---|
| -----, 000 Uganda shilling[b]/ha-------- | | | |
| Farmer practice (rice – rice) | 1539 | 1314 | 1.27 |
| 60 kg N/ha | 2385 | 1697 | 1.41 |
| NPK[c] | 2790 | 1999 | 1.40 |
| Azolla + NPK[c] | 2475 | 1935 | 1.28 |
| Azolla | 2205 | 1492 | 1.48 |

[a] ”Benefit to cost ratio” = (Gross field benefit/total variable costs)

[b] Conversion rate of 1750 Uganda shillings per US dollar

[c] NPK = (60 kg N + 20 kg P + 25 kg K) kg $ha^{-1}$

## Fertilizer cost

In Nakisenye, farmers were producing more rice and made as much money when they applied N as when they did not. However, in the case of N, P, and K fertilizers, their prices would have to come down by 25% for their use to be more profitable than the farmers' practice. In the case of combining mucuna relay with P and K, a reduction of more than 50% would be needed to profit from a shift to fertilizer use. In Doho, fertilizer use payed off in any of the systems tested. The trend is similar to the maize system. However, a reduction in fertilizer price more quickly increases the benefit to cost ratio in the rice system than in the maize system.

## Summary and conclusion

The Nakisenye site, and the Doho rice scheme have contrasting rice production systems due to differences in water availability. Irrigation makes it possible for the farmers in Doho to grow rice all year around, compared to one crop during the long rains at Nakisenye. *Azolla* was evaluated as a green manure for the Doho rice scheme, where it is abundant and farmers are not aware of its potential. Mucuna was used at Nakisenye, because farmers either leave their fields under fallow or grow an upland crop during the short rains.

Mucuna on average produced 6.6 t ha$^{-1}$ of dry matter and accumulated 205 kg N ha$^{-1}$, of which 117 kg N ha$^{-1}$ is estimated to be derived from BNF. In addition, mucuna accumulated 12.7 kg P ha$^{-1}$ and 91 kg K ha$^{-1}$. The 4.1 t ha$^{-1}$ *Azolla* dry matter contained an average of 119 kg N ha$^{-1}$ (90 kg N ha$^{-1}$ from BNF).

Inorganic fertilizers and green manures (mucuna and *Azolla*) are effective strategies for increasing rice yields for rice poor farmers in eastern Uganda. Application of inorganic fertilizers and preceding mucuna increased yield, on average, by 0.75 t ha$^{-1}$ at Nakisenye. Considering the rice production for two seasons at Doho, the use of *Azolla* or the application of inorganic N fertilizers resulted, on average, in an increase of 1.4 t ha$^{-1}$ of grain, and an additional 0.9 t ha$^{-1}$ was obtained with the application of PK fertilizers. The common practice of removing *Azolla* from the rice fields at the Doho rice scheme is a waste of a valuable source of N.

Comparing rice and maize systems, the economic analysis indicates that rice production is far more profitable than maize due to the high price of rice. Rice has become an important food crop with a high local demand in Uganda. Being a landlocked country (Uganda), the transport cost of imported rice is high, and locally produced rice is competitive.

### 4.2.3 Farmers’ evaluation of mucuna, *Azolla* and inorganic fertilizers

Farmers being the end users of the proposed strategies, it was thought important for data to be collected to gain information on their perception/evaluation of the alternative strategies. This was achieved through interviews with all participants using an open-ended questionnaire. The farmers were individually interviewed and their responses/ideas are presented in the following sections.

#### 4.2.3.1 Mucuna

The results of the survey assessing farmers' evaluation of mucuna use in the maize and rice systems are given in Table 46. In general, a large number of farmers appreciated the value of mucuna in improving soil productivity and crop yields. Farmers also recognised other benefits including weed suppression and ease of field preparation or ploughing for the subsequent season. Both result in a reduction in labour requirements, which reduces costs and enables farmers to prepare their fields early in the season, assuring timely planting.

Table 46: The number of farmers mentioning a particular observation regarding mucuna expressed as a percentage (%) of the total number of farmers who participated in the trials at different sites

| Farmers' perceptions | Site | | | |
|---|---|---|---|---|
| | Kasheshe/Nemba (20)[a] | Odwarat (20) | Agonyo II (20) | Nakisenye (20) |
| **Benefits** | | | | |
| High/good crop yields | 100 | 100 | 85 | 100 |
| Improved soil fertility | 85 | 70 | 65 | 80 |
| Weed suppression | 70 | 80 | 95 | 100 |
| Conserves moisture | 29 | 10 | 65 | 0 |
| Keeps the soil cool | 50 | 10 | 25 | 10 |
| Makes ploughing easier | 50 | 10 | 25 | 10 |
| Easy production of seeds | 15 | 0 | 0 | 0 |
| Fodder for livestock | 40 | 10 | 50 | 40 |
| **Problems** | | | | |
| Smothering plants in an intercrop | 80 | 70 | 80 | 70 |
| Harbours pest (rats) | 0 | 10 | 25 | 30 |
| Seeds are not edible | 0 | 10 | 0 | 0 |
| **Suggested solutions to above problems** | | | | |
| Manual removal from crop | 50 | 50 | 55 | 30 |
| Use it in sole crop | 35 | 20 | 35 | 50 |
| **Best use of mucuna in the system** | | | | |
| Intercrop | 50 | 10 | 0 | 40 |
| Fallow | 50 | 60 | 85 | 70 |

[a] Number of farmers in parenthesis

Farmers appreciated the value of mucuna in conserving soil moisture and keeping the soil cool through the mulching effect. Farmers in eastern Uganda and Honduras made similar observations as reported by Fischler and Wortmann (1999), and Buckles and Triomphe (1999).

#### 4.2.3.2 Inorganic fertilizers in maize system

The results of the farmers' evaluation of the use of inorganic fertilizers in the maize system are given in Table 47. A large number of farmers appreciated the value of inorganic fertilizers in increasing crop yields, indicating that soil fertility is a problem across the sites and that the fertilizers were effective, which agrees with the yield response obtained. The problems mentioned by the farmers, e.g., high cost, are commonly reported as limiting the use of fertilizers in sub-Saharan Africa (Vlek 1990; Sanchez 2002). The economic analysis of our experiments arrives at the same conclusions.

Table 47: The number of farmers mentioning a particular observation regarding inorganic fertilizers expressed as a percentage (%) of the total number of farmers who participated in the trials at different sites

| Farmers' perceptions | Site | | | |
|---|---|---|---|---|
| | Kasheshe/Nemba (20)[a] | Odwarat (20) | Agonyo II (20) | Nakisenye (20) |
| **Benefits** | | | | |
| High/good crop yields | 85 | 60 | 95 | 80 |
| Improves soil fertility | 0 | 20 | 15 | 40 |
| Crops grow well | 50 | 10 | 25 | 0 |
| **Problems** | | | | |
| Expensive (high cost) | 70 | 10 | 85 | 40 |
| Encourages excessive weed growth | 0 | 20 | 45 | 10 |
| Not available in the village | 0 | 50 | 55 | 60 |
| Lack of knowledge on fertilizer use | 0 | 20 | 0 | 0 |
| **Suggested solutions to above problems** | | | | |
| Use Mucuna | 35 | 0 | 15 | 0 |
| Use animal manure | 15 | 0 | 0 | 0 |

[a] Number of farmers in parenthesis

The majority of the farmers in high-potential areas mentioned that fertilizers are available in the area but that the price (high cost) is their major problem. The relatively low percentage of farmers mentioning high costs at the other two sites and none at Odwarat is due to the fact that farmers at these sites have no experience with the use of fertilizers. Because of low use, dealers cannot invest in taking fertilizers to these areas. That is the reason why the majority of farmers mentioned non-availability in these low-potential areas as a major problem of fertilizer use. However, the underlying causes are the low returns to fertilizer use in these areas as discussed earlier.

#### 4.2.3.3 *Azolla*

The results of the farmers' evaluation of *Azolla* use in the rice system are given in Table 48. All the farmers appreciated the value of *Azolla* in increasing rice yields, agreeing that it is an effective N source. Thus, it can address one of the factors limiting rice production in the Doho rice scheme.

Some of the problems mentioned by farmers arise from poor regulation/control of irrigation water. This results in the dislodging of newly transplanted rice by a dense mass of *Azolla* floating on the surface of the floodwater. In addition, the dense mass can also shade the young rice plants from sunlight, reducing their photosynthetic activities, thus affecting growth and subsequent yield. Control of irrigation water and incorporating *Azolla* are potential solutions to the problems as suggested by the farmers. The problem of *Azolla* harboring insects/pests is due to attack by a large number of insect larvae, which might not necessarily be pests for the rice crop. Boddey et al. (1997) and Giller (2001) reported that damage by insects is one of the most important factors leading to poor performance of *Azolla*. The insects/pests are normally controlled through spraying.

Table 48: The number of farmers mentioning a particular observation regarding *Azolla* expressed as a percentage (%) of the total number of farmers who participated in the trials at Doho irrigation scheme (No. of farmers = 14)

| Farmers' perceptions | Percentage (%) |
|---|---|
| **Benefits** | |
| High/good crop yields | 100 |
| Crops grow fast | 43 |
| | |
| **Problems** | |
| Dislodges newly transplanted rice seedlings | 43 |
| Shades rice plants from direct sunlight | 71 |
| Reduces number of tillers | 21 |
| Harbours pests/insects | 8 |
| | |
| **Suggested solutions to above problems** | |
| Regulating water flow | 57 |
| Incorporating into the soil | 71 |
| Removing it from the field | 16 |

#### 4.2.3.4 Farmers' evaluation of inorganic fertilizers in rice system

The results of the farmers' evaluation of the use of inorganic fertilizers in the rice system are given in Table 49. A large number of farmers appreciated the value of inorganic fertilizers in increasing rice yields, indicating that soil fertility is a problem in the Doho rice scheme and the fertilizers were effective, which agrees with the yield response obtained. The problems mentioned by farmers e.g. high price (expensive), lack of money, are usual ones, which limits the use of fertilizers in sub-Saharan Africa (Vlek 1990; Sanchez 2002). The fact that 57% of the farmers mentioned cost as a problem indicates that farmers at the scheme have experience with fertilizer use.

Table 49: The number of farmers mentioning a particular observation regarding inorganic fertilizers expressed as a percentage (%) of the total number of farmers who participated in the trials at Doho irrigation scheme (Number of farmers = 14 farmers)

| Farmers' perceptions | Percentage (%) |
|---|---|
| **Benefits** | |
| High/good crop yields | 64 |
| Plants mature early | 16 |
| Encourages large number of tillers | 16 |
| | |
| **Problems** | |
| Expensive | 87 |
| Encourages excessive vegetative growth | 21 |
| Lack of money | 30 |
| | |
| **Suggested solutions to above problems** | |
| Use low rates of fertilizers | 35 |
| Use *Azolla* | 16 |

**Summary and conclusion**

The farmers' favourable evaluation of the inorganic fertilizers, mucuna and *Azolla* confirm that they are effective in increasing crop yields, and present potential resources for addressing the problem of low crop yields. The recognition of the potential of mucuna in weed suppression and it being fodder for livestock shows that its use, though primarily as a source of N, can solve other constraints faced by farmers. Farmers prefer multi-purpose options because of the diversity of their needs. Farmers' appreciation of *Azolla* might lead to its use as a source of N for rice rather it being treated as an obnoxious weed in the rice system.

# 5 GENERAL DISCUSSION AND CONCLUSIONS

Mucuna produces large amounts of dry matter and accumulates N, P and K in contrasting soils and in contrasting agro-ecological zones of Uganda. The dry matter production varied from 2.6 to 11.6 t $ha^{-1}$ and the N accumulation from 80 to 350 kg N $ha^{-1}$, with 34 to 158 kg N $ha^{-1}$ derived from the atmosphere through BNF. The N from the atmosphere is a significant contribution to the N input into the low external input agriculture common for the smallholder farmers in Uganda. Mucuna can be used in the farming system either as a short-term fallow or in relay rotation with cereals. Its use in relay rotation enables farmers to have a maize crop harvest, which is important to the smallholder farmers. However, a maize/mucuna relay requires proper management to prevent the smothering of the maize by mucuna.

The mucuna–derived N is in an organic form, becoming available to the plants through a mineralization process. This is influenced by the quality (total N, C/N, lignin, polyphenol) of the organic material, soil micro- and meso-fauna, and climate. Between 78 to 270 kg N $ha^{-1}$ of the mucuna–derived N was released, at a rate of 0.065 – 0.130 per week, over 25 weeks. Unfortunately, this release is not necessarily in synchrony with plant demand, resulting in some N being lost from the system. The average N recovery of 93% at Bulegeni ARDC is due to the large amount of maize dry matter (21 t $ha^{-1}$) produced at the site, which indirectly meant high N demand. This compares with 61% at Kibale TVC, where 4.2 t $ha^{-1}$ of grain was produced. In addition, leaching of N might not have been significant in the clay soils at Bulegeni ARDC compared to the sandy clay loams at Kibale TVC.

The maize yield results show that the soils in eastern Uganda are unable to supply sufficient N for the needs of maize. Inorganic fertilizers and mucuna are effective N-supply sources for contrasting soils and in contrasting agro-ecological zones as observed from the significant ($P = 0.05$) yield increase. The increase above the control for more productive fields was 2.7, 1.7, 0.3 and 0.9 t $ha^{-1}$ at Kongta, Kasheshe/Nemba, Odwarat, and Agonyo II, respectively. For less productive fields, the increase was 1.1, 0.9, 0.9 and 1.1 t $ha^{-1}$ at Kongta, Kasheshe/Nemba, Odwarat and Agonyo II, respectively.

The use of mucuna in relay rotation reduces the associated maize yield, while as fallow it results in the loss of a complete season crop. Considering the maize yield over two seasons captured these effects. The results show that the strategies investigated performed better in high-potential agro-ecological zones.

For more productive fields, in high-potential agro-ecological zones, application of inorganic N fertilizers resulted in the greatest overall increase in grain yield of 3.4 t $ha^{-1}$ at Kongta and 1.9 t $ha^{-1}$ at Kasheshe/Nemba. A preceding mucuna relay increased yield by 2.1 t $ha^{-1}$ at Kongta and 1.8 t $ha^{-1}$ at Kasheshe/Nemba. The mucuna fallow resulted in a yield increase of 0.6 t $ha^{-1}$ at Kongta, in contrast to an overall yield reduction of 0.6 t $ha^{-1}$ at Kasheshe/Nemba. Application of P and K fertilizers to 80 kg N $ha^{-1}$ resulted in an additional 1.5 t $ha^{-1}$at Kongta, with no significant effect on inorganic N fertilizers at Kasheshe/Nemba, but resulted in additional 0.4 t $ha^{-1}$ with the mucuna fallow.

In low-potential agro-ecological zones, inorganic N fertilizers resulted in an average increase of 0.6 t $ha^{-1}$ at Odwarat, and a non-significant effect at Agonyo II. A preceding mucuna relay resulted in a non-significant effect at Odwarat, compared to an overall yield reduction of 1.1 t $ha^{-1}$ at Agonyo II. Application of P and K fertilizers to inorganic N and to preceding mucuna relay resulted, on average, in an additional 1.1 t $ha^{-1}$ of grain compared to a non-significant effect at Agonyo II. The mucuna fallow resulted in an overall yield reduction of 0.9 t $ha^{-1}$ at Odwarat, and 3.6 t $ha^{-1}$ at Agonyo II.

For the less productive fields, application of 80 kg N $ha^{-1}$ resulted in an overall yield increment of 2.7 t $ha^{-1}$, compared to 2.0 t $ha^{-1}$ obtained with 40 kg N $ha^{-1}$, and 1.6 t $ha^{-1}$ with a preceding mucuna relay at Kongta. Preceding mucuna relay plus P increased yield by 1.4 t $ha^{-1}$ compared to an average of 0.8 t $ha^{-1}$ obtained with inorganic N fertilizers and preceding mucuna relay at Kasheshe/Nemba. The overall increase in yield with inorganic N fertilizers was, on average, 1.3 t $ha^{-1}$ at Odwarat, and 1.5 t $ha^{-1}$ at Agonyo II. Preceding mucuna relay resulted in an overall yield increase of 1.3 t $ha^{-1}$ at Odwarat and 1.0 t $ha^{-1}$ at Agonyo II.

The maize response to P and K fertilizers is proof that these nutrients are also limiting maize production in eastern Uganda, particularly once the N deficiency has been corrected. Significant ($P = 0.05$) yield increases were obtained with P and K across most treatments at the low potential sites. Grain yield with 80 kg N $ha^{-1}$ with and without P and K fertilizers differed, on average, by 1.6 t $ha^{-1}$ for high-productivity fields at Kongta, 1.3 t ha$^{-1}$ for low-productivity fields at Kasheshe/Nemba, 1.0 t ha$^{-1}$ for both groups of fields at Odwarat, 0.9 and 0.7 t ha$^{-1}$ for high- and low-productivity fields at Agonyo II, respectively.

The alternative strategies tested to augment production bridged the yield gap between high- and low-productivity fields at the low-potential areas but not at the high-potential agro-ecological zones. This suggests that N, P, and K were not the only factors limiting maize production in the low-productivity fields in high-potential agro-ecological zones. Intensive cultivation might have led to high nutrient depletion to an extent that the quantities of applied nutrients were not sufficient to increase maize yield to the level of high-productivity fields. Also, secondary or micro-nutrients may have been deficient. Alternatively, poor soil management by farmers might have led to soil loss through erosion, which meant that farmers of Group II fields cultivated more acid sub-soil with less favourable soil physical characteristics.

The rice yield results show that the soils in eastern Uganda are unable to supply sufficient N for the needs of rice. Inorganic fertilizers, mucuna, and *Azolla* are effective N-supply strategies for rice as observed from the significant ($P = 0.05$) yield increase. The increase above the control was, on average, 0.7 t ha$^{-1}$ of grain at Nakisenye. Considering the rice yield over the two seasons at the Doho rice scheme, the increase above the control was, on average, 1.4 t ha$^{-1}$ for the inorganic N and *Azolla* treatments; application of P and K fertilizers resulted in an additional 0.9 t ha$^{-1}$ of grain. The lack of significant differences in yield response to inorganic N and mucuna or *Azolla* shows the potential of green manure in replacing chemical fertilizers.

The farmers' favourable evaluation of the inorganic fertilizers, mucuna, and *Azolla* indicates that they are attractive as means of increasing crop yields, and represent potential resources for addressing the problem of low crop yields. The recognition of mucuna's potential in weed suppression and its being used as fodder shows that the mucuna, though evaluated as a source of N, can solve other constraints faced by farmers. Farmers' appreciation of *Azolla* might result in its use as a source of N for rice rather than treat its being treated as an obnoxious weed in the rice system.

The economic analysis shows that N replenishment strategies (inorganic fertilizers, mucuna relay or fallow) are more profitable on high-productivity fields in high-potential agro-ecological zones due to better yield responses. The 40 kg N ha$^{-1}$ is more profitable than 80 kg N $ha^{-1}$. In these environments, the mucuna relay is economically viable on low- and high-productivity fields. In low-potential agro-ecological zones, mucuna relay is the only profitable strategy on low-productivity fields only. Farmers do not recover the costs with other strategies, including with their current practice. The adoption of inorganic fertilizers and mucuna relay plus P would reduce the profitability of high-productivity fields. In a situation where the alternative N replenishment strategies and the farmers' current practice have the same economic benefits, mucuna that adds N through BNF might provide the more sustainable system. Yet, it might be difficult for farmers to make the decision in favour of sustainability if their main concern, i.e. to have enough food to take them up to the next harvest, is not met in the process.

In order to at least recover the extra cost of fertilizer use on low-productivity fields, prices would have to reduce by 10, 30 and 40% for the 40, 80 kg N $ha^{-1}$ and the mucuna plus P relay, respectively, in the low-potential areas. In the high-productive areas, the corresponding price reductions needed are 90, 80 and 60%, respectively. The reduction in fertilizer price definitely requires government intervention, which might not be possible due to the structural adjustment policies being followed by the Government.

The use of *Azolla* and mucuna is profitable in rice farming. In Nakisenye, farmers were producing more rice and made as much money when they applied N as when they did not. Application of P and K fertilizers reduces the profitability of N replenishment due to the high cost of fertilizers. The economic analysis indicates that the farmers' current practice of growing rice is profitable and it may be the main reason why farmers are encroaching on wetland for rice cultivation.

However, in the case of N, P, and K, fertilizer prices would have to come down by 25% for their use to be more profitable than the farmers' current practice. When combining mucuna relay with P and K, a reduction of more than 50% would be needed to profit from a shift to fertilizer use. In Doho, fertilizer use pays off in any of the systems tested.

## Conclusions

1. Mucuna accumulates a large amount of biomass and N, the quantities being mainly affected by altitude. A significant fraction of this N (43-57%) comes from BNF, which is of great importance in the low external input agriculture of the smallholder farmers in eastern Uganda. Since N is limiting cereal production in eastern Uganda, exploitation of BNF systems through the use of green manure will lead to increased food security in the region.
2. Mucuna, *Azolla*, and inorganic N fertilizers are all effective N sources and their use results in significant increases in maize and rice yields on contrasting soils and in contrasting agro-ecological zones
3. The essential message of this extensive field study is that any strategy to augment soil productivity is effective and profitable on the better soil of the better-endowed agro-ecological zones. In contrast, the more labor- and less capital-intensive strategies, based on green manuring, have a better chance of bringing benefits to the farmers if either the soil or the agro-ecological zone is of marginal quality. If both are problematic, the options for the farmer are restricted to use of green manure in relay.
4. The price of a crop affects the profitability of the alternative strategies. The higher the price, the more profitable the strategies become. Rice production systems are, therefore, more profitable than maize systems and can readily integrate fertilizer practices. Reductions in fertilizer price is required if farmers are to at least recover the extra cost of fertilizer use on low-productivity fields across the agro-ecological zones.

Although the benefits of the strategies were evaluated for one season and the residual effects were not determined, the results show that in the current situation of farmers with limited resources, it is better to invest in soil fertility replenishment in areas with more productive soils because of more economic benefits. This agrees with Vlek (1990), who found that promoting fertilizers in areas where their use will not result in markedly increased land and labour productivity is a misdirection of scarce resources. The discussed low cost/input technologies such as mucuna in relay or fallow can improve soil fertility to support agricultural production in less productive areas to ensure food security.

**Recommendations for future research**

1. More research is required on the most cost-effective way of raising the productivity of depleted fields in high-potential agro-ecological zones.
2. Research is required on alternative green manure sources in the farming systems, since the chances of farmer adoption increases with multi-purpose plants.
3. Since rice is more profitable than maize, and farmers are encroaching on wetlands for rice cultivation, more work is required to increase the average rice yield from the current 1.7 t $ha^{-1}$, and also to ensure sustainable use of wetlands.

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# 7 APPENDICES

Appendix A1: Maize yield (t ha$^{-1}$) for Group I (high-productivity) fields at Kongta during 2001A season

| Treatments | Grain yield | | | Stover yield | | |
|---|---|---|---|---|---|---|
| | - (PK) | + (PK) | Prob$^{a}$. | - (PK) | + (PK) | Prob$^{a}$ |
| Farmers' practice (control) | 2.2 | | | 5.1 | | |
| 40 kg N ha$^{-1}$ | 6.0 | 5.9 | ns | 12.5 | 15.1 | ns |
| 80 kg N ha$^{-1}$ | 5.1 | 6.7 | * | 9.7 | 13.8 | ns |
| Preceding mucuna relay + 25 kg P ha$^{-1}$ | 4.2 | 3.9 | ns | 8.9 | 10.4 | ns |
| Preceding mucuna relay | 4.4 | 4.9 | ns | 10.6 | 13.5 | ns |
| Preceding mucuna fallow | 5.2 | 4.5 | ns | 10.4 | 13.1 | ns |
| Preceding weedy | 3.1 | 3.4 | ns | 7.0 | 7.8 | ns |
| Mean | 4.3 | 4.5 | ns | 9.2 | 11.3 | * |
| LSD$_{5\%}$ | 1.5 | 1.4 | | 4.3 | 5.2 | |

$^{a}$level of significance for the difference between means of the same treatment with & without P and K fertilizers

ns, *, non-significant at P = 0.05 and significant at P = 0.05 levels, respectively

Appendix A2: Maize yield (t ha$^{-1}$) at Kongta for Group II (low-productivity) fields

| Treatments | Grain yield | | | Stover yield | | |
|---|---|---|---|---|---|---|
| | - (PK) | + (PK) | Prob$^{a}$. | - (PK) | + (PK) | Prob$^{a}$ |
| Farmers' practice (control) | 1.1 | | | 4.6 | | |
| 40 kg N ha$^{-1}$ | 2.3 | 2.6 | ns | 6.5 | 7.4 | ns |
| 80 kg N ha$^{-1}$ | 2.9 | 3.3 | ns | 5.8 | 6.9 | ns |
| Preceding mucuna relay + 25 kg P ha$^{-1}$ | 2.2 | 2.4 | ns | 6.0 | 7.4 | ns |
| Preceding mucuna relay | 2.1 | 2.2 | ns | 5.5 | 6.4 | ns |
| Preceding mucuna fallow | 2.0 | 2.9 | * | 4.9 | 5.9 | ns |
| Preceding weedy | 1.5 | 1.4 | ns | 3.7 | 4.7 | ns |
| Mean | 2.0 | 2.3 | ns | 5.3 | 6.2 | ns |
| LSD$_{5\%}$ | 0.9 | 0.7 | | 2.6 | 2.3 | |

$^{a}$level of significance for the difference between means of the same treatment with and without P and K fertilizers

ns, *, non-significant at P = 0.05 and significant at P = 0.05 levels, respectively

Appendix A3: Maize yield (t ha$^{-1}$) for Group I (high-productivity) fields at Kasheshe/Nemba during 2001A season

| Treatments | Grain yield | | | Stover yield | | |
|---|---|---|---|---|---|---|
| | - (PK) | + (PK) | Prob$^{a}$. | - (PK) | + (PK) | Prob$^{a}$. |
| Farmers' practice (control) | 4.2 | | | 6.7 | | |
| 40 kg N ha$^{-1}$ | 5.6 | 5.9 | ns | 13.2 | 13.1 | ns |
| 80 kg N ha$^{-1}$ | 6.1 | 6.2 | ns | 14.1 | 15.7 | ns |
| Preceding mucuna relay + 25 kg P ha$^{-1}$ | 6.1 | 6.4 | ns | 15.9 | 16.4 | ns |
| Preceding mucuna relay | 5.7 | 5.9 | ns | 13.7 | 13.9 | ns |
| Preceding mucuna fallow | 5.9 | 6.2 | ns | 13.3 | 14.2 | ns |
| Preceding weedy | 4.4 | 4.5 | ns | 11.5 | 12.8 | ns |
| Mean | 5.4 | 5.6 | ns | 12.6 | 13.3 | ns |
| LSD$_{5\%}$ | 0.8 | 0.8 | | 2.9 | 2.8 | |

$^{a}$level of significance for the difference between means of the same treatment with & without P and K fertilizers

ns, *, **; not significantly different at P = 0.05; significant at 0.05 and 0.01 levels, respectively

Appendix A4: Maize grain yield (t $ha^{-1}$) for Group II (low-productivity) fields at Kasheshe/Nemba during 2001A season

| Treatments | Grain yield | | | Stover yield | | |
|---|---|---|---|---|---|---|
| | - (PK) | + (PK) | Prob[a]. | - (PK) | + (PK) | Prob[a]. |
| Farmers' practice (control) | 1.9 | | | 2.9 | | |
| 40 kg $ha^{-1}$ | 2.8 | 3.4 | ns | 3.8 | 5.5 | ns |
| 80 kg N $ha^{-1}$ | 2.6 | 4.0 | ** | 3.4 | 6.3 | * |
| Preceding mucuna relay + 25 kg P $ha^{-1}$ | 3.1 | 3.8 | ns | 4.6 | 5.4 | ns |
| Preceding mucuna relay | 2.5 | 3.7 | ** | 3.0 | 5.2 | * |
| Preceding mucuna fallow | 2.7 | 4.0 | ** | 3.2 | 5.1 | * |
| Preceding weedy | 2.4 | 2.4 | ns | 4.1 | 3.1 | ns |
| | | | | | | |
| Mean | 2.6 | 3.3 | * | 3.6 | 4.7 | * |
| $LSD_{5\%}$ | 0.6 | 1.1 | | 1.1 | 2.4 | |

[a] level of significance for the difference between means of the same treatment with & without P and K fertilizers

ns, *, **; not significantly different at P = 0.05; significant at 0.05 and 0.01 levels, respectively

Appendix A5: Maize yield (t $ha^{-1}$) for Group I (high-productivity) fields at Odwarat during 2001A season

| Treatments | Grain yield | | | Stover yield | | |
|---|---|---|---|---|---|---|
| | - (PK) | + (PK) | Prob[a]. | - (PK) | + (PK) | Prob[a]. |
| Farmers' practice (control) | 1.6 | | | 2.7 | | |
| 40 kg N $ha^{-1}$ | 2.0 | 2.2 | ns | 2.8 | 3.4 | ns |
| 80 kg N $ha^{-1}$ | 1.8 | 3.1 | ** | 2.3 | 3.9 | * |
| Preceding mucuna relay + 25 kg P $ha^{-1}$ | 2.1 | 3.0 | * | 2.9 | 3.4 | ns |
| Preceding mucuna relay | 1.7 | 2.4 | ns | 2.4 | 3.6 | * |
| Preceding mucuna fallow | 1.9 | 2.4 | ns | 2.7 | 3.2 | ns |
| Preceding weedy | 1.4 | 1.4 | ns | 2.5 | 2.5 | ns |
| | | | | | | |
| Mean | 1.8 | 2.3 | * | 2.6 | 3.2 | * |
| $LSD_{5\%}$ | ns | 0.8 | | ns | ns | |

[a] level of significance for the difference between means of the same treatment with and without P and K fertilizers

ns, *, **, not significantly different at P = 0.05 and significant at P = 0.05, 0.01 levels, respectively

Appendix A6: Maize grain yield (t $ha^{-1}$) for Group II (low-productivity) fields at Odwarat during 2001A season

| Treatments | Grain yield | | | Stover yield | | |
|---|---|---|---|---|---|---|
| | - (PK) | + (PK) | Prob[a]. | - (PK) | + (PK) | Prob[a]. |
| Farmers' practice (control) | 0.8 | | | 1.4 | | |
| 40 kg N $ha^{-1}$ | 1.7 | 1.9 | ns | 2.3 | 2.5 | ns |
| 80 kg N $ha^{-1}$ | 1.6 | 2.7 | ** | 2.1 | 3.0 | * |
| Preceding mucuna relay + 25 kg P $ha^{-1}$ | 1.8 | 2.0 | ns | 2.5 | 2.8 | ns |
| Preceding mucuna relay | 1.7 | 2.0 | ns | 2.2 | 2.8 | * |
| Preceding mucuna fallow | 1.6 | 1.9 | ns | 2.3 | 2.2 | ns |
| Preceding weedy | 0.9 | 1.09 | ns | 1.6 | 1.6 | ns |
| | | | | | | |
| Mean | 1.5 | 1.7 | * | 2.1 | 2.3 | * |
| $LSD_{5\%}$ | 0.6 | 0.7 | | 0.8 | 0.9 | |

[a] level of significance for the difference between means of the same treatment with and without P and K fertilizers

ns, *, **, not significantly different at P = 0.05 and significant at P = 0.05, 0.01 levels, respectively

Appendix A7: Maize yield (t ha$^{-1}$) for Group I (high-productivity) fields at Agonyo II during 2001A season

| Treatments | Grain yield | | | Stover yield | | |
|---|---|---|---|---|---|---|
| | - (PK) | + (PK) | Prob[a]. | - (PK) | + (PK) | Prob[a]. |
| Farmers' practice (control) | 2.3 | | | 4.5 | | |
| 40 kg N ha$^{-1}$ | 3.2 | 3.2 | ns | 6.0 | 6.0 | ns |
| 80 kg Nha$^{-1}$ | 3.3 | 3.4 | ns | 6.1 | 6.1 | ns |
| Preceding mucuna relay + 25 kg P ha$^{-1}$ | 2.9 | 3.5 | * | 6.0 | 6.9 | ns |
| Preceding mucuna relay | 2.8 | 2.9 | ns | 5.2 | 6.0 | ns |
| Preceding mucuna fallow | 2.6 | 3.4 | * | 5.4 | 6.3 | ns |
| Preceding weedy | 2.5 | 2.4 | ns | 4.5 | 5.1 | ns |
| Mean | 2. 8 | 3.0 | * | 5.4 | 5.8 | ns |
| LSD$_{5\%}$ | 0.6 | 0.6 | | 1.5 | 1.5 | |

[a]level of significance for the difference between means of the same treatment with and without P and K fertilizers

ns, *, not significantly different and significant at P = 0.05 level, respectively

Appendix A8: Maize yield (t ha$^{-1}$) for Group II (low-productivity) fields at Agonyo II during 2001A season

| Treatments | Grain yield | | | Stover yield | | |
|---|---|---|---|---|---|---|
| | - (PK) | + (PK) | Prob[a]. | - (PK) | + (PK) | Prob[a]. |
| Farmers' practice (control) | 1.6 | | | 3.2 | | |
| 40 kg N ha$^{-1}$ | 2.1 | 3.2 | ** | 3.4 | 4.8 | ns |
| 80 kg N ha$^{-1}$ | 2.7 | 3.3 | * | 4.0 | 5.5 | * |
| Preceding mucuna relay + 25 kg P ha$^{-1}$ | 2.5 | 3.5 | ** | 4.5 | 6.3 | * |
| Preceding mucuna relay | 2.8 | 3.1 | ns | 4.8 | 5.4 | ns |
| Preceding mucuna fallow | 2.8 | 2.9 | ns | 4.5 | 4.4 | ns |
| Preceding weedy | 2.0 | 2.1 | ns | 3.8 | 3.3 | ns |
| Mean | 2.4 | 2.8 | * | 4.0 | 4.7 | * |
| LSD$_{5\%}$ | 0.6 | 0.7 | | 1.4 | 1.7 | |

[a]level of significance for the difference between means of the same treatment with and without P and K fertilizers

ns, *, **, not significantly different at P = 0.05 and significant at P = 0.05, 0.01 levels, respectively

Appendix A 9: Total maize grain yield (t ha$^{-1}$) for two seasons from the alternative strategies under both contrasting environmental potential and soil productivity with application of P and K fertilizers

| TREATMENTS | ENVIRONMENT POTENTIAL | | | |
|---|---|---|---|---|
| | Low | High | | |
| Farmers' practice | 2.6 | 3.2 | Low | SOIL PRODUCTIVITY |
| 40 kg N ha$^{-1}$ | 4.2 | 4.7 | | |
| 80 kg N ha$^{-1}$ | 4.7 | 5.4 | | |
| Mucuna relay + P | 4.2 | 5.0 | | |
| Mucuna relay | 3.8 | 4.8 | | |
| Mucuna fallow | 2.5 | 3.5 | | |
| Weedy fallow | 1.5 | 1.9 | | |
| LSD$_{5\%}$ | 0.7 | 0.7 | | |
| Farmers' practice | 4.5 | 5.5 | High | |
| 40 kg N ha$^{-1}$ | 5.1 | 8.4 | | |
| 80 kg N ha$^{-1}$ | 5.0 | 8.9 | | |
| Mucuna relay + P | 5.3 | 7.4 | | |
| Mucuna relay | 4.3 | 7.5 | | |
| Mucuna fallow | 2.6 | 5.4 | | |
| Weedy fallow | 1.9 | 4.0 | | |
| LSD$_{5\%}$ | 1.2 | 1.8 | | |

Appendix A10: Partial budget for Kongta and Kasheshe/Nemba (high-potential agro-ecological zone)

| Treatment | Gross field benefit | Total variable costs | Gross margin[a] | Benefit to cost ratio[b] |
|---|---|---|---|---|
| | -----------; 000 Uganda shillings[c]/ha----------- | | | |
| Group I fields | | | | |
| Farmers' practice | 451 | 396 | 55 | 1.14 |
| 40 kg N ha$^{-1}$ | 740 | 465 | 275 | 1.59 |
| 80 kg N ha$^{-1}$ | 704 | 518 | 186 | 1.36 |
| Mucuna relay + 25 kg P ha$^{-1}$ | 570 | 477 | 93 | 1.20 |
| Mucuna relay | 610 | 372 | 238 | 1.64 |
| Mucuna fallow | 487 | 307 | 180 | 1.59 |
| Weedy fallow | 310 | 218 | 92 | 1.42 |
| Group II fields | | | | |
| Farmers' practice | 288 | 396 | -108 | 0.73 |
| 40 kg N ha$^{-1}$ | 394 | 465 | -71 | 0.85 |
| 80 kg N ha$^{-1}$ | 425 | 518 | -93 | 0.82 |
| Mucuna relay + 25 kg P ha$^{-1}$ | 415 | 477 | -62 | 0.87 |
| Mucuna relay | 381 | 372 | 9 | 1.02 |
| Mucuna fallow | 214 | 307 | -93 | 0.70 |
| Weedy fallow | 178 | 218 | -40 | 0.82 |

[a] Gross margin = Gross field benefit – total variable costs

[b] "Benefit to cost ratio" (B/C) = (Gross field benefit/total variable costs)

B/C = 1, implies that on average farmers recover the investment in the total variable costs

[c] Conversion rate of 1750 Uganda shillings per US dollar

## Appendix A11: Partial budget for Odwarat and Agonyo II (low-potential agro-ecological zone)

| Treatment | Gross field benefit | Total variable costs | Gross margin[a] | Benefit to cost ratio[b] |
|---|---|---|---|---|
| | ------------; 000 Uganda shillings[c]/ha--------- | | | |
| Group I fields | | | | |
| Farmers' practice | 407 | 294 | 113 | 1.38 |
| 40 kg N ha$^{-1}$ | 416 | 363 | 53 | 1.15 |
| 80 kg N ha$^{-1}$ | 433 | 416 | 17 | 1.04 |
| Mucuna relay + 25 kg P ha$^{-1}$ | 404 | 386 | 18 | 1.05 |
| Mucuna relay | 362 | 281 | 81 | 1.29 |
| Mucuna fallow | 196 | 221 | -25 | 0.89 |
| Weedy fallow | 172 | 147 | 25 | 1.20 |
| Group II fields | | | | |
| Farmers' practice | 231 | 294 | -63 | 0.79 |
| 40 kg N ha$^{-1}$ | 358 | 363 | -5 | 0.99 |
| 80 kg N ha$^{-1}$ | 377 | 416 | -39 | 0.91 |
| Mucuna relay + 25 kg P ha$^{-1}$ | 342 | 386 | -44 | 0.89 |
| Mucuna relay | 335 | 281 | 54 | 1.19 |
| Mucuna fallow | 197 | 221 | -21 | 0.89 |
| Weedy fallow | 155 | 147 | 8 | 1.05 |

[a] Gross margin = Gross field benefit – total variable costs

[b] "Benefit to cost ratio" (B/C) = (Gross field benefit/total variable costs)

B/C = 1, implies that on average farmers recover the investment in the total variable costs

[c] Conversion rate of 1750 Uganda shillings per US dollar

## Appendix A12: The "benefit to cost ratio" (B/C)[a] for the inorganic fertilizer-based strategies at different fertilizer prices

| **TREATMENTS** | **ENVIRONMENT POTENTIAL** | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **Low** | | | | | **High** | | | | | | |
| | Reduction in fertilizer price (%) | | | | | | | | | | | |
| | 0* | 10 | 20 | 30 | 40 | 0* | 60 | 70 | 80 | 90 | | |
| Farmers' practice | 0.79 | | | | | 0.73 | | | | | **Low** | **SOIL PRODUCTIVITY** |
| 40 kg N ha$^{-1}$ | 0.99 | 1.00 | 1.02 | 1.03 | 1.08 | 0.84 | 0.91 | 0.92 | 0.93 | 0.95 | | |
| 80 kg N ha$^{-1}$ | 0.91 | 0.93 | 0.96 | 0.98 | 1.07 | 0.82 | 0.94 | 0.96 | 0.98 | 1.01 | | |
| Mucuna relay + P | 0.89 | 0.91 | 0.93 | 0.96 | 0.98 | 0.87 | 0.98 | 1.00 | 1.03 | 1.05 | | |
| Mucuna relay | 1.19 | | | | | 1.02 | | | | | | |
| Mucuna fallow | 0.89 | | | | | 0.70 | | | | | | |
| Weedy fallow | 1.06 | | | | | 0.82 | | | | | | |
| Farmers' practice | 1.38 | | | | | 1.14 | | | | | **High** | |
| 40 kg N ha$^{-1}$ | 1.15 | 1.15 | 1.18 | 1.20 | 1.26 | 1.59 | | | | | | |
| 80 kg N ha$^{-1}$ | 1.04 | 1.04 | 1.10 | 1.13 | 1.23 | 1.36 | | | | | | |
| Mucuna relay + P | 1.04 | 1.05 | 1.10 | 1.13 | 1.16 | 1.20 | | | | | | |
| Mucuna relay | 1.29 | | | | | 1.64 | | | | | | |
| Mucuna fallow | 0.89 | | | | | 1.59 | | | | | | |
| Weedy fallow | 1.17 | | | | | 1.42 | | | | | | |

[a] B/C = 1, implies that on average farmers recovers the total variable costs

*B/C at current fertilizer price

## ACKNOWLEDGEMENTS

I would like to express my sincere appreciation to the following individuals and organisations for the guidance and support, which has made the completion of this work possible.

First and foremost my sincerest appreciation goes to Prof. Dr. Paul L. G. Vlek, my first supervisor, for providing me with the opportunity to pursue the studies, for his expert advice, support, constructive criticism and scientific guidance during the writing of this thesis.

My thanks go to Prof. Dr. Goldbach H, my second supervisor, for valuable suggestions and comments.

Special thanks to Dr. Ssali H, my supervisor in Uganda, for recommending me for the doctoral study, for his encouragement, the interest shown in the studies, for sacrificing time out of his busy schedule to visit the field trials, for constructive criticism during the field visits, and for reading the draft.

I would like to thank the Director of KARI for recommending me to pursue the Ph.D study and the Director General, NARO, for granting me the study leave.

I am grateful to the farmers for participating in the study with such enthusiasm and the field assistants for the wonderful work done.

Special thanks go to Dr. Nkonya E, Co-ordinator of the Project "Policies for improved land management in Uganda" for the logistical support.

My sincerest appreciation goes to Ms. Nansamba A, my Research Assistant, for the wonderful work in the field, during data entry phase, and the prompt response to the numerous emails requesting clarification and information, and for sacrificing festivity days to make sure that the work was completed on time.

I would also like to thank Ms. Ropprecht D and Mr. Lugolobi A for the $^{15}N$ analysis. I wish to thank Ms. Sina Bremer for translating the abstract and summary into German and Dr. Martius C, for proof reading the translated texts. Special thanks go to my colleagues Dr. Semalulu O and Dr. Byalebeka J for the useful discussions, and the encouragement during the fieldwork.

Special thanks go Mr. Kalule, Mr. Ssonko G, Mr. Katende and Ms. Nambi M, for the wonderful support during the fieldwork, and to the drivers Mr. Serumaga P and Mr. Olweny G, for being so careful that we completed the fieldwork in one piece. The "Epege" and the cold nights spent in the vehicle along the slippery roads to Kongta are a living memory. Thanks for enduring.

I thank the Zentrum für Entwicklungsforschung (ZEF) of the university of Bonn for hosting me throughout the period of this study. I am grateful for the financial support from DAAD, BMZ and CGIAR, which made this work possible. I am grateful to the IAEA for providing under UGA/05/020, the $^{15}N$ labelled fertilizers used in the study.

Special thanks go to my colleagues Mr. Asante F, Mr. Woelcke J, Ms. Gi-Soon, Ms. Sawhney P, Ms. Lohlein D, Mr. Hafeez M and Ms. Brunner A., for the company and support throughout my stay at ZEF. Many other friends and individuals, who helped me throughout my studies, though not mentioned here, are not forgotten. I sincerely thank you for the role you played to ensure that my studies were successful.

My sincere gratitude goes to my family for the support, and prayers during the duration of the study. Special thanks go to my mother–Gladys, grandmother-Eseri, my brother Dr. Kiwanuka, Sisters Kyazike, Nansubuga, and Catherine for the encouragement.

Most important, I thank my wife Maureen, and children- Mukasa, Tusubira Kulabako J, Kapalaga JM and Kaya JK, for their understanding that less time was spent with them because the work had to be completed. Special thanks go to Joan and Joel for joining dad in the fieldwork so that it was completed quickly so dad could come home. The question you asked frequently "dad when are you finishing studies and coming back to Uganda?" had a lot of hidden meaning and kept me going.

Finally, to my ancestors and to the Almighty God for giving me the strength to get this work accomplished.

***To my parents for the great decision they made to send us to school, and to my wife Maureen, and children – Mukasa P, Tusubira JK, Kapalaga JM and Kaya JK.***