NITROGEN BUDGETS IN LEGUME BASED CROPPING SYSTEMS IN NORTHERN MALAWI

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ABSTRACT

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Smallholder farmers in sub Saharan Africa (SSA) operate in a risky environment characterized by low soil fertility, unpredictable weather and markets. Identification of technologies that optimize crop yields in a variable climate, while building soil fertility, can contribute to sustainable cropping systems. Participatory on-farm trials were conducted in Ekwendeni of northern Malawi to evaluate performance and yield of legume diversified cropping systems. Prior to implementation of trials, household and farm field surveys were conducted to characterize cropping systems and soils. Soil fertility among farms was highly variable and largely coarse textured with very low organic matter (12±3.7 g kg^{-1}). There was no evidence of cropping systems effect on nutrient levels except for inorganic P which was lower in legume diversified fields than in maize fields. A survey showed that farmers valued a wide range of legume traits that included food, yield, maturity period, post harvest handling, soil fertility, market potential and pest resistance.

On-farm trials evaluated maize-based cropping with a range of legume growth types and planting arrangements (groundnut representing an annual grain legume and pigeonpea representing a semi-perennial grain legume, planted as sole and intercrop systems rotated with maize). The trials were conducted over two years and showed that interspecific competition, inorganic P and plant density markedly influenced crop growth and biological nitrogen fixation (BNF). The type of species present in the intercrop – legume or cereal - did not alter the BNF

response. On area basis, there was no evidence of higher N fixation rate by groundnut-pigeonpea intercrop (GNPP) “doubled-up legumes” compared to sole stands of either species. Overall performance of intercrops vs sole crops was superior in terms of grain yield produced in the first year of the rotation, as indicated by calculation of a land equivalent ratio (LER). The LERs were 1.50 and 1.56 for GNPP and MZPP compared to sole crops, indicating that intercropped species were more efficient at utilizing resources than sole stands.

Performance over the two years of the cropping system was evaluated in 2008/2009. Maize was planted on fields previously planted to sole or intercropped legumes. Indicators of N status (chlorophyll and biomass) showed that maize growth in year two was influenced by cropping system. In contrast, soil inorganic N did not show a response to cropping system. A previous crop of sole or intercropped legumes increased maize grain yields by 21-62% compared to a previous crop of maize. Integrated soil fertility management (ISFM) was also evaluated, comparing all cropping systems with the addition of 24 kg N ha^{-1} inorganic fertilizer to a continuous maize N-rate study (0, 24 and 92 kg of N ha^{-1} fertilizer). This allowed estimation of a N-fertilizer equivalency for ISFM maize in year two, which varied from 18 to 55 kg of N ha^{-1}. Overall, legume presence increased maize yield by 69-200% compared to sole crop, unfertilized maize.

A farmer preference survey showed a preference for GNPP/maize rotation even though this system did not optimize yield, followed by pigeonpea/maize rotation, and lastly MZPP/maize systems. Farmers’ choices were based on cropping systems that provide multiple benefits.

DEDICATION

This dissertation is dedicated to my dear parents, Godfrey and Mickness Mhango; and my sisters and brothers for their love and moral support in my whole academic career. Also in memory of my late brothers, Ammon and Chimwemwe.

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PREFACE

Chapter one has been written according to guidelines for publication in the journal of *Agriculture, Ecosystems and the Environment.* Chapters two and three have been written according to guidelines for publication in the journal of *Plant and Soil*.

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KEY TO ABBREVIATIONS

BNF: Biological nitrogen fixation

C:N: Carbon to nitrogen ratio

CEC: Cation exchange capacity

GN: Groundnut

GNPP: Groundnut intercropped with pigeonpea

Ha: Hectare

Kg: Kilogram

MZ: Maize

MZPP: Maize intercropped with pigeonpea

N: Nitrogen

POM: Particulate organic matter

PP: Pigeonpea

SSA: Sub Saharan Africa

SFHC: Soils, Food and Healthy Communities

WAP: Weeks after planting

CHAPTER ONE

CHARACTERIZATION OF HOUSEHOLDS, SOILS AND CROPPING SYSTEMS

ABSTRACT

Smallholder farmers face a rapidly changing environment in sub-Saharan Africa (SSA). A degraded soil resource base, climate change and a variable market environment are some of the challenges, and opportunities, faced by farmers. Knowledge of this farming systems environment is limited, and few studies take into account farmer decision making and changes in adaptive capacity over time. This chapter seeks to fill this information gap by conducting an in-depth study of household characteristics, soil types, cropping systems, and soil management practices in Ekwendeni, northern Malawi. In May-June 2007, a survey was conducted in the selected villages of Ekwendeni catchment working with the Soils Food and Healthy Communities (SFHC) project of Ekwendeni Mission Hospital. The objective was to characterize farming systems, associated soil properties, and farmer perceptions on soil fertility. Through a farmer survey, paired fields were selected at each farm, one with a history of legume crops grown in combination with the staple maize crop, designated the 'legume field', the other a continuous maize-dominated cropping sequence with no legumes ('maize field').

Information on cropping history and soil fertility management was collected on a field-specific basis and for the whole farm. Composite soil samples for chemical and physical analyses were collected from legume and maize fields from the 0-15 cm and 15-30 cm soil depths. The soil texture overall was coarse, generally sandy or sandy loam. Soil organic matter status was low (12 g kg^{-1}), extractable inorganic P varied from low to medium, exchangeable cations were adequate for production of most crops (calcium= 447 mg kg^{-1}; magnesium=112 mg kg^{-1}; and

potassium=117 mg kg^{-1}. The mean CEC was 4.3cmol kg^{-1}. No differences were observed between the legume and maize diversified field, except extractable inorganic P was lower in the legume field (26±18 mg kg^{-1}) than in the maize field (35±20 mg kg^{-1}) (p=0.012). Legumes were not grown on any specific soil type; although, there was a trend towards finer textured soils being preferred for soybean production. Farmer assessment of soil fertility status and indigenous terms used to describe soil types are discussed.

Grain legumes were grown in both sole and intercrop systems (doubled up legume-legume intercrop, or legume-maize intercrop). Fields primarily planted with legume-diversified cropping systems were smaller in size compared to fields that were primarily used to grow maize: 0.15 ha compared to 0.35 ha. This indicates there is a potential for building soil fertility through legume-derived biological nitrogen fixation, but the area devoted to legumes could limit the benefits. Preferred legume characteristics varied with legume species and these include high yield, nutritional value, food value, early maturity, grain storage characteristics, market potential, pest resistance and ability to improve soil fertility. High yield was the number one criterion for evaluating groundnut and common bean, while nutritional benefits of soybean for children were highly valued. Farmers valued pigeonpea primarily as a green manure crop to improve soil fertility. The findings were consistent with legumes being preferred that either 1) provided an early and nutritious grain that could be eaten or sold, or 2) provided a combination of some grain yield with organic matter inputs, enhancing soil nutrients. Extension information requested by farmers included advice on agronomic practices for legume production (e.g. planting pattern, varieties, pest and disease control), utilization (e.g. soya milk, groundnut oil extraction), marketing, and post harvest handling of legume products.

The cropping system diversity at this site has changed over time, with more legumes being grown now than 12 years ago. The grain legumes groundnut, common bean, cowpea and bambara groundnut have been grown for decades and in addition three new species are now being grown: pigeonpea, soybean, and velvet beans. Project farmers were designated as those who received training from the SFHC project; they were found to have adopted more legumes than control farmers. Twenty six percent and 38% more pigeonpea and soybean respectively were grown by project farmers than control farmers. About 40% of farmers surveyed grew velvet bean whether or not they worked with the SFHC project and 22% fish bean by project farmers only.

1.1 INTRODUCTION

Low soil fertility is one of the major constraints to increased soil productivity and crop yields in sub Saharan Africa. Nitrogen (N) and phosphorus (P) are the most limiting nutrients for plant productivity because they are required in high amounts. A specific challenge faced by Malawi smallholder farmers is that inorganic fertilizers are expensive and used in inadequate amounts in relation to crop requirement, and other nutrient losses from the field through crop harvests, runoff, leaching. In Malawi, where maize (*Zea mays,* L) is a staple food crop, a decline in soil fertility and its effects on maize production has been documented by many scientists (e.g., Phiri et al., 1999; Sakala and Mhango, 2003). The current average maize yield under smallholder production in Malawi is less than 1 ton ha^{-1} as compared to potential yields of 3-6 tons ha^{-1} for local and hybrid maize. Snapp et al., (1998) assessed soil nutrient levels on farm in Malawi based on sampling thousands of sites and reported that organic carbon (OC) content was generally medium for coarse soils, average of 14 g kg^{-1}; whereas organic N tended to be low (0.5 g kg^{-1}) and Mehlich III extracted inorganic P was low to medium (19 mg kg^{-1}).

An important agricultural management strategy to address N deficiency is through inclusion of legumes in cropping systems. Legumes are capable of improving soil N through biological nitrogen fixation (BNF). Addition of organic matter from crop residues increases N and P availability. Biological nitrogen fixation is the conversion of atmospheric N into ammonia through a symbiotic association between legumes and *Rhizobium*. Under good field management, groundnut and soybean can fix 150–200 kg N ha^{-1} and 108–152 kg N ha^{-1} respectively (Toomsan et al., 1995). Legume based cropping systems have the potential to reduce nitrogen losses through high organic matter inputs that help to improve microbial activities and soil aggregation thus increasing infiltration (Drinkwater et al., 1998; Biederbeck et al., 2005). The root exudates from some legumes such as pigeonpea (*Cajanus cajan*) unlock fixed P thus enhancing the efficiency of phosphorus cycling in agricultural systems (Ae et al., 1990; George et al., 2002). Legumes such as velvet beans (*Mucuna pruriens)* can be used as a cover crop to help suppress weeds and reduce nutrient leaching while improving soil fertility (Fujii et al., 1991; Giller et al., 1997; Udensi et al., 1999). In addition to enhancing soil fertility, food legumes are a source of income, vitamins and plant proteins.

1.1.1 Maize-legume based cropping systems in Malawi and soil fertility

Soil fertility enhancing technologies that include food legumes and leguminous tree species have been developed and promoted in various parts in Malawi. Such technologies include crop rotation (Mc Coll, 1989), intercropping and a number of agroforestry technologies such as alley cropping and improved fallows (Kwesiga and Coe, 1994). Best bet legumes (legume species that improve food security and soil fertility) have been identified for different agro-ecological zones and they include groundnuts (*Arachis hypogea)*, soybean (*Glycine max)*, pigeonpea *(Cajanun cajan)*, and velvet beans *(Mucuna pruriens*) and Fish bean (*Tephrosia volgelii)* (Kamanga et al., 1999; Snapp et al., 2002; Gilbert, 2004). Crop rotation is cultivation of an ordered succession of crops on the same piece of land. This helps to improve soil fertility and control carryover of pests and diseases from one season to another (Tilman et al., 2002). When legumes are included in cropping systems, they improve soil fertility and in particular N inputs through biological N fixation (Giller, 2001; Werner, 2005). The contributions vary with the type of legume species, crop and residue management practices, and the physical environment.

1.1.1.1 **Plant life forms:** Indeterminate crop growth is defined as a pattern of development in which the apical meristem remains vegetative so that new leaves and stems continue to be produced while flowers and fruits are also forming. Determinate plants are those in which the apical meristem differentiates into flowers, terminating the production of additional leaves and stems (Huxley and Van Houten, 1997). These usually flower once or twice during a growing period. Some farmers may not grow long duration crops because they cannot afford to wait for the products. Indeterminate legume crops and long duration legumes such as pigeonpea are better at improving soil fertility than short duration legumes because they fix nitrogen over a long period, prevent erosion through soil cover, and produce large amounts of biomass (Snapp et al., 2002).

1.1.1.2 **Current farming systems:** Malawi has a unimodal rainfall pattern where the growing season is from November to April or May. The cropping systems are dominated by maize, because it is the staple food crop for a majority. Farmer surveys reported by Snapp et al., (2002a) documented that maize occupied >70% of arable land. The major cropping systems are crop rotation, monocropping and intercropping.

Intercropping is the growing of two or crops on the same piece of land simultaneously (Hauggaard-Nielsen et al., 2008). This helps to maximize use of land, labor and other resources required in plant growth such as water. The traditional intercrop system consists of maize, pumpkins and legumes such as climbing beans, pigeon pea and cowpeas at a low density. Intercropping maize and grain legumes can help to increase food security compared to sole maize (Snapp et al., 2002a). In recent years, a technology involving doubled up legume intercrops of groundnut and pigeonpea is being experimented with in Ekwendeni, northern Malawi. This system involves combining the long duration pigeonpea and short duration, upright groundnut varieties in the first year, rotated with maize in the second year. This has the potential to improve soil fertility through increased biological nitrogen fixation rate per unit area, long period of N fixation by pigeonpea and large amounts of high quality crop residues.

Under intercropping, the relative proportion of each component species depend on the main crop of interest to the farmers, complimentarity in growth habits and rooting characteristic, and relative growth rates. In Malawi and most countries in sub Saharan Africa, the proportion of maize is usually higher (~two thirds) than the companion legume in most intercropping systems because maize is a staple food. Research by Rao and Mathuva (2000) and Tsumbo et al., (2005) used equal density of maize in both sole stand and intercrop system, but reduced the proportion of companion crop when intercropped because of the high food value attached to maize. However in maize-pigeonpea intercrop, same plant populations as in sole and intercropping systems can be maintained due to complimentarity in relative growth rates, maturity period and rooting characteristics (Sakala, 1994; Ministry of Agriculture, Irrigation and Food Security, 2005; Myaka et al., 2006). In this study, farmers reported that when maize is intercropped with grain legumes and/or pumpkins, the recommended population of maize is maintained; the companion crop planted at low density.

Intercrop systems and capture of resources: As already mentioned, intercropping can help to use land and labor inputs efficiently. Careful selection of component species in intercropping can also help to capture resources such as water, nutrients and light over space and time (Snapp, 2008). For example, in groundnut-pigeonpea intercrop, groundnut has a fibrous root system and will therefore explore the top soil layers, whereas pigeonpea with tap roots will go deeper into the soil profile. Intercropping C3 and C4 plants can help to maximize use of light while maximizing crop yield. A study by Szumigalski and Van Acker (2008) has demonstrated complimentarity in use of light over time by canola and field intercrop pea due to differences in canopy development and duration. They reported that canola developed canopy earlier than field pea, and later shed its leaves. In another study by Ghosh et al., (2006), intercropping soybean with sorghum increased crop growth rate, grain land equivalent ratio, and chlorophyll content in sorghum. However, intercropped soybean had lower chlorophyll content, nodule mass and biomass compared to sole stands probably due to shading. Intercropping species with different growth rates can help to maximize use of resources over time. This can be illustrated by maize-pigeonpea intercrop in which the two crops are planted at same time and on same ridge (Sakala, 1994). Maize has higher relative growth rate than pigeonpea and will therefore utilize the below and above ground resources before the pigeonpea gets established. Pigeonpea starts branching and put on more leaves after maize has reached physiological maturity. Therefore, pigeonpea can utilize above and below ground resources with minimal or no competition with maize.

1.1.2 Adoption and disadoption of legumes

According to Ajayi et al., (2007), Kiptot et al., (2007) and Pannel (1999), adoption process includes awareness phase during which a farmer is introduced to a new technology and its potential benefits. This is followed by testing phase where a farmer experiments on the technology over a certain period and this vary by technology. There are a number of factors that may influence testers and they include legume utilization; access to information; incentives such as provision of seed, markets, credit, and participation in seminars. The last phase is the adoption stage where there is continued use of technology by the farmer.

In adoption studies, it is important to clearly define "adoption" in context, understand the socio economic characteristics of households, and consider time frame on use of technology. Farmers can be categorized as adopters, testers, pseudo-adopters and non adopters. Another group can be of disadopters referring to individuals who after adoption decide to stop using a technology. The pseudo-adopters are those that adopt a technology due to benefits (e.g provision of seed) from an organization promoting technology (Kiptot et al., 2007). Time frame between awareness phase and adoption stage is important in evaluation of adoption. Technologies with long term benefits such as use of agroforestry tree species or perennial legumes such as long duration pigeonpea require more time than annual legumes.

There are a number of factors that affect adoption. Based on previous studies, household characteristics, legume benefits (e.g. food value, soil fertility, fodder, weed control, water conservation), markets, input costs, long term vs short term benefits influence adoption (Kiptot et al., 2007; Mafongoya et al., 2007; Kristjanson et al., 2005; Enyong et al., 1999). The relationship between these factors and adoption may be positive, negative or no effect depending on location, time and household characteristics. In general, edible legumes are more likely to be adopted than non food legumes.

Adoption of technology may change overtime depending on farmer's preferences and socio economic factors. Disadoption of technologies may occur due to changes in land use, availability of alternative strategies to improve soil fertility, change in markets. One example is adoption of velvet bean in Benin (Schultz et al, 2003). In the past, this legume was widely adopted for soil fertility improvement and weed management. However, over time, there was disadoption due to non food value of grain unless the seed processed in a special way to remove a poisonous substance called L-dopa (Pulangethi et al., 2005).

1.1.3 Factors influencing choice of legumes

Farmers have multiple reasons for growing legumes and their choices are influenced by social-economic and biophysical factors. A review by Snapp and Silim (2002) indicated that farmers in eastern and Southern Africa are interested in such factors as adaptation to local conditions, tolerance to low soil fertility, effect on soil fertility, maturity period, yield, food security, grain quality, market potential, secondary benefits such as forage, fuel wood, or reduced labor demands (Table 1.1). These are complex characteristics, and there are often tradeoffs involved: legumes that fit one set of farmer's preferred traits will frequently not have other desired traits. For example, if a legume is a rapidly maturing type, with determinant flowering and early pod production, this will meet requirements for early food production, but it will not be compatible with insect tolerance or secondary soil-building benefits from leafy vegetative growth. Freeman et al., (2002) found that high yield, drought resistance, good taste and short cooking time influenced choice of groundnut varieties.

Table 1.1: Characteristics of selected legumes that can influence small holder farmer preferences (Source: information on legume characteristics and use from Malawi Government, MOAIFS, 2005; Legume traits adapted from Snapp and Silim, 2002)

	Name of Legume					
Trait	Pigeon pea	Groundnut	Soybean	Cowpea	Velvet bean	Fish bean
Tolerance to low soil fertility	High	Med	Med –high	High	High	High
Tolerance to drought	High	Low	Low	High	Med-high	High
Improve soil fertility	High	Med	Med	Med	High	High
Market potential	Med	High	High	High	None or yes	None
Food value	Yes	Yes	Yes	Yes	None or yes[1]	None[2]
Grain yield	Low	Med-High	Med-High	Low	High	None
Suitability for green manure	Low	None	None	None	High	High
Maturity period	Long	Short-med	Short	short- med	short –med	Long
Labor demand	Med	High	High	Low	Low	Med
Intercropping potential	Very good[3]	Fair[4]	Fair[4]	Good (with maize)	None	Good (with maize)
Other secondary benefits	Yes (e.g. fuel wood)	None	None	None	Yes (weed control)	Yes (insecticide, fish bait, firewood)

Note: med=medium

[1] Velvet bean is usually grown as a green manure. However Velvet beans, if not well cooked and processed, can be poisonous. In Malawi, people in the southern region prepare delicious snacks from velvet beans. However, recipes are not well known in central and northern regions.

[2] not suitable for human consumption

[3] Pigeonpea can be intercropped with maize or groundnut; [4] Usually grown in pure stand. However, it can be intercropped with pigeon pea or maize.

1.1.4 Objectives

The main objective was to characterize farming systems and preferred legume species. Specific objectives included the following:

a) Identify factors that influence farmer preference for legume genotypes.

b) Conduct baseline characterization of soils and cropping systems in the study area and document farmer knowledge of soils and crops

c) Evaluate the influence of SFHC project participatory research and extension on farmer knowledge and utilization of legumes, including technical advice sought by farmers

1.1.5 *Research Hypothesis*

a) Most farmers will prefer early maturing edible legumes with high market potential over late maturing types that provide substantial soil fertility benefits.

b) Farmers who are actively involved in SFHC project will grow more legumes than non participating farmers

c) Soils in this region are of low fertility due to extensive long term cropping and soil properties will not be influenced by recent crop species choice.

1.2 MATERIALS AND METHODS

1.2.1 Brief description of Ekwendeni and the Hospital Soils, Food and Healthy Communities Project

The study was conducted in Ekwendeni, Mzimba District, in northern region of Malawi. Mzimba district is under Mzuzu Agricultural Development Division. Ekwendeni is located at 11^{0}20'S, 33^{0}53'E, with an elevation of 1200m. The area receives medium to high rainfall ranging from

800-1200 mm annum. Most of the soils are highly weathered, with low OM, nitrogen and phosphorus. The Ekwendeni mission hospital is located in this area and offers medical services to the entire watershed.

A long-term problem of concern to hospital staff is the poor nutrition among children from surrounding communities especially those below the age of 5. According to Bezner-Kerr and Chirwa (2005), people reported that low crop yields were among the factors that led to malnutrition. This was attributed to low soil fertility and the economic context, which includes expensive inorganic fertilizers, which are unaffordable for most smallholder farmers. Some farmers are able to purchase small quantities of fertilizer, but these are not enough to meet crop demands. In 2000, a project was initiated to specifically address these problems. It was called the Soils, Food and Healthy Communities (SFHC) Project of Ekwendeni Hospital and its initial focus was on promoting legume production, and educating farmers on residue management and food preparation. Some of the legumes promoted included improved varieties of groundnut, soybean and pigeonpea. New crops were introduced to the area, including velvet bean and fish bean which were integrated into traditional maize rotation and intercropping systems. To date, there has been an expansion of legume production in this area (Bezner-Kerr et al., 2007). In the intervention villages, the number of years of farmer involvement in legume production varies from 3 to 7 years depending on how long the Ekwendeni SFHC project has worked in the area. Intervention villages are those that have participated in legume trials under the Ekwendeni Hospital SFHC project.

1.2.2 Household survey

A baseline survey was conducted in 7 of the intervention villages working with the SFHC project from May to June 2007 using a structured questionnaire (Appendix 1.1). The main objective was to characterize crops, cropping systems and soils as perceived by farmers; and determine the preferred legumes, legume traits, and constraints to legume production. Data on demographic information, cropping systems and soil fertility management were collected as well.

1.2.2.1 Sampling procedure and selection of farmers

Selection of farmers for the interviews was done in two stages: first, purposeful sampling of areas where the SFHC activities were implemented since 2000 and thereafter random selection of villages and farmers from each village to be interviewed. Members of staff from SFHC project were consulted to provide a list of villages where SFHC activities were initiated since 2000. Four areas, Zombwe, Enyezini, Luhomero and Engcongolweni, were chosen based on the time they joined the SFHC project (Table 1.2) and soil types. These areas were described to have light to medium textured soils which are relatively poor in organic matter. Chilimba et al., (1999) described soils in Zombwe as fine kaolinitic, thermic, typic kandiustalfs. Within each area, two villages were randomly selected from a list of intervention villages except for Zombwe where only one village was chosen. After selection of villages, a list of project and control farmers was prepared by SFHC staff and farmer research team leaders based on involvement in legume production with the SFHC project. Project farmers were described as those who have are actively participating in SFHC project activities. The lists of project and control farmers from the list of SFHC-villages were entered in Microsoft Excel in separate spread sheets for each village and farmer category. Using Microsoft Excel programme, within each village, one-third of names from 'control' farmer lists (those farmers who have not interacted directly with the SFHC activities), and two-thirds from the 'intervention' farmer lists who have interacted with SFHC were randomly chosen. Six (6) farmers were randomly selected for interviews, 4 from the group of project farmers and 2 representing the control. A total of 44 household interviews were done.

Table 1.2: Selected villages for the baseline survey

Area	Village	Date since SFHC project implemented
Zombwe	Zulu Gondwe	2003
Enyezini	Daniel Soko	2002
	Yotamu Nkhambule	2002
Luhomero	Chipetupetu Chione	2002
	Chotha Tembo	2002
Engcongolweni	Lazaro Jere	2000
	Zungwala	2000

1.2.3 Farm field survey

Following the household interview, a two-part farm field survey was done to establish information concerning the two field types, the soils types and characteristics of the maize versus the legume field. A paired plot was identified and an underlying assumption was that the paired plots had similar soil nutrient levels and physical characteristics before putting them into cultivation. A legume field was defined as a farm where legumes were grown for the past 2-4 years or more. The maize field was a continuous maize field or a maize/tobacco rotation field.

Information collected through the survey included cropping history, soil quality management practices for the past three growing seasons, and farmer indigenous knowledge, which indicators were used to indicate soil fertility. From each field, composite soil samples (8-10 subsamples depending on size of the field) were collected using a Z-scheme to insure random collection. Two depths were sampled, 0-15 cm and 15-30 cm, for site characterization. The soils were then sieved through a 2 mm sieve. Soil texture and pH were done in-situ using the handtexturing method and Hellige TRUOG pH testing kit, respectively. A copy of the field soil test result was given to each farmer. After air-drying the samples, and sieving through a 2 mm mesh, analysis of texture using hydrometer method (Anderson and Ingram, 1996) and textural class determined according to USDA classification. Soil pH, exchangeable K, Ca and Mg were analyzed at A&L Great Lakes Lab, Fort Wayne, Indiana. The pH was determined in water (1:1 soil/water ratio), OM by loss on ignition; inorganic P extracted by sodium bicarbonate procedure and reported as Bray P; exchangeable K, Ca and Mg Mehlich 3 extraction. Cation exchange capacity (CEC) and percent base saturation (BS) were calculated.

1.2.4 Data Analysis

Data on household characteristics and preferred legume characteristics were analyzed using Statistical Package for Social Scientists (SPSS) 17.0 computer package. Descriptive statistics were calculated on the following continuous variables: age, household size, area of maize and legume fields. Frequencies and percentages were computed on categorical variables (marital status, occupation, educational level and preferred legume characteristics).

Chi square tests were performed to test if there was any association between legumes grown, utilization of legumes, and crop residue and soil management with farmer category using Statistical Analysis System (SAS) (SAS Institute, 2001).We also tested if project farmers report increased use of legumes for soil fertility practices, compared to control farmers. Soil chemical characteristics data for the legume and maize diversified fields were analyzed as paired t-tests in SAS program using proc univariate procedure. Statistical differences were determined at $P<0.05$.

Multiple regression was done to evaluate the relationship between OM and soil properties. Normality of residuals was checked using normal probability plots (Chartterjee and Hadi, 2006).The homogeneity of variances was assessed using plots of residuals versus predicted values. Presence of outliers was examined using Cook's D values. Three or four outliers were identified on Ca, clay and sand. These were excluded from the analysis. Multicollinearity was assessed using correlation procedure and variance inflation ratio (VIF). The correlation coefficients were <0.90 for all variables except for calcium and CEC (0.93). With OM as the dependent variable, VIF for CEC and calcium were higher (6.08-7.78) compared to 1.15-3.26, the range for the other six explanatory variables. Calcium was excluded from the model and this solved multicollinearity problem. Silt was deleted from the model before running the regression analysis because of the linear combination of sand, clay and silt. The best fitted model was selected based on step wise regression procedures. Data analysis was conducted using Proc Univariate and Proc Reg of SAS (SAS Institute, 2001). Statistical differences were determined at $p<0.05$.

1.3 RESULTS

1.3.1 Household characteristics

Table 1.3 shows results of household characteristics and land allocated to maize and legumes. Age of respondents ranged from 20 to 83 with a mean of 43 and standard deviation of 2.33. More than 50% of the respondents are married and living with spouses, 14% female headed households (FHH) and 11% male headed (MHH). The proportion of FHH is lower than 25%, the value reported by Benson *et al.,* (2002). In this area, the culture followed is patrilineal system whereby a wife relocates to the husband's home area, and man is the household head.

Household size: Average household size ranged from 1 to 11 with a mean of 5 persons. This is similar to >5.0, household size for Mzimba district (Benson et al., 2002) and not very different from 5.4, the mean household size for the rural areas in Malawi (Ministry of Economic

Planning and development et al., 2005). Snapp et al., (2002a) reported household size within 3.2-5.2 for Central (Dedza and Chisepo) and Southern (Mangochi) Malawi. Household size affects labor availability for farming activities. This is particularly important where all the agronomic practices are done manually. In this area, farming is the main occupation for the households (93%) with own family labor. Out of five people in a household, three participate in field management practices during the growing season.

Food security: Access to food is important for the health of individuals and it may also affect labor availability for farming activities during the growing season. Farmers were asked if they had adequate food from own maize stocks from May 2006 to April 2007. About 59% of the households had enough food from own farm produce throughout the year. A chi square analysis of independence indicated no association between food security and farmer category (project farmers versus control farmers). Within the 41% of the households who were not food secure, a majority (28%) had run out of food for 1 or 3 months, 6% for 2 months, 11% for 4 to 6 months, and 17% for 7 months.

Dependency ratio: This is the ratio of persons in "dependent" ages (under 15 years and over 64 years) to those in "economically productive" ages (15-64 years) (Benson et al., 2002). The dependency ratio ranged from 0 to 3 with an average of 0.89 which means that for every 10 working persons, there are 8.9 dependents. This is close to 0.906, the national dependency ratio for Malawi (Benson et al., 2002).

Education level: Education is important in agriculture because it affects the ability to read and write extension information on various farming technologies. Over 80% of the respondents have basic education (upper primary) and are therefore able to read and write**.** Among the farmers who had gone above upper primary education, 27% had gone through secondary education. The literacy level reported here are a characteristic of the northern region of Malawi in general but above the national average of 64% (Benson et al. 2002; National Statistical Office Malawi and ORC Macro, 2005).

Field size: The average maize field size was two-fold greater than the legume field (0.34 vs 0.15 ha). This is presumably due to food security reasons, as maize is the staple food in this region. Similar findings were reported by Snapp et al., (2002a) in central and southern Malawi where land allocated to maize was 3-9 times larger than groundnut field. This is an important challenge to improving reliance on biological N fixation for a sustainable farming system, as the total area planted to legumes is an important determinant of the amount of biologically fixed nitrogen in cropping systems (Giller, 2001).

1.3.2 Soil characteristics

Table 1.4 shows descriptive statistics and confidence intervals for soil nutrient levels, amount of clay, sand and silt across the 44 paired legume and maize fields, 0-15 cm and 15-30 cm soil depth. There was high variability of soil properties between farms. The soils are predominantly coarse to medium textured with average sand and clay content ranging from 72 to 86% and 9-22% respectively. In the 0-15 cm soil layer, 50% of farms have loamy sand (LS) soils, 28% sandy clay loams (SCL) and 22% sandy soils. In the 15-30 cm soil layer, soil texture for 31% of the farms is classified as SCL, 23-27% LS to sandy, and the remaining 19% SL. The mean soil pH is slightly acidic to neutral, 6.1±0.6 in 15-30 cm to 6.2±0.6 in 0-15 cm soil layer (Table 1.4). This is within the favorable range for growth of most crops.

Soil OM is very important as a store house of nutrients, and improving soil physical and biological properties. The mean soil OM was very low averaging 12±3.7 g kg^{-1} and 13±4.5 g kg^{-1} from the 0-15cm and 15-30cm soil depths respectively. Inorganic Bray P ranged from 4-142 mg kg^{-1}, and 1-130 mg kg^{-1} for 0-15 cm and 15-30 cm soil depths respectively. The amount of exchangeable Ca (414±244 mg kg^{-1} to 464±329 mg kg^{-1}), K (106±48 mg kg^{-1}), and Mg (121±58-123±65 mg kg^{-1}) are adequate for crop growth (Table 1.4). CEC averaged 4±1.4 cmol kg^{-1} and 4±1.7 cmol kg^{-1} in the 0-15 cm and 15-30 cm soil depth respectively.

1.3.2.1 SOM variability on smallholder farms

Effect of cropping history on soil OM, Legume diversified field: Cropping history for the past three seasons was grouped according to type of crops (legume only if sole or legume-legume intercrop; or cereal-legume intercrop) grown and number of seasons. The common legumes include groundnut, pigeonpea, soybean and common bean. For the sole and doubled up legumes, there were no differences in OM between different number of seasons. In the cereal-legume intercrop-legume rotations, a three year rotation system involving one season of sole legume plus two seasons of maize-legume intercrop had higher OM (54% over 2 year rotation of legume-maize+legume intercrop (Fig 1.1) . Cropping history for the previous three years had no significant effect on soil OM at both soil depths. However, there was a trend (p=0.08) of higher OM in top soils following one year of legume plus two seasons of maize-legume intercrop (16 g kg^{-1}) over 1-2 seasons of legumes only (12 g kg^{-1}).

Effect of soil chemical properties and texture on SOM: Across the paired legume and maize fields, there were significant positive correlations between OM and amount of K, Ca, Mg and CEC (P<0.05) in the top 0-15cm soil depth. The correlation coefficients were 0.35, 0.25, 0.32 and 0.43 for K, Ca, Mg and CEC respectively. Similar observations were observed in the 15-30cm soil layer except for Mg (Table 1.5). In the 0-15cm soil layer of maize and legume diversified fields, multiple regression analysis of OM as a function of soil pH, CEC, clay, sand, Mg and K showed that the model was significant (p<0.0001). Using stepwise regression to select best fit model, CEC was the only significant factor influencing OM across maize and legume diversified fields, $R^2 = 0.316$, that is, CEC could explain only 32% of the variation in OM (Table 1.6, Fig 1.2). The fitted regression model for relationship between OM (g kg^{-1}) and CEC (cmol kg^{-1}) was as follows: *OM = 6.11+1.36CEC*. The standard errors for intercept and slope for CEC were 1.01 and 0.22 respectively. However, there was no significant relationship between texture and OM.

On legume diversified field, 0-15cm soil depth, regression analysis with pH, CEC, inorganic P, Mg, K, clay and sand included in the model, showed that the model was significant (Pr>F= 0.0005) and R square was equal to 0.578, that is, the variables explained 58 % of the variation in OM. The intercept was not significantly different from zero and the slope for P, K and Mg were significant when all soil variables were included in the model. Based on step wise regression, the best fitted model selected included P, K and Mg as explanatory variables with slope for the three variables significant at $P<0.01$ (Table 1.6). The R square was equal to 0.551, that is, K, P and Mg explained 55% of the variation in OM. K was accounted for 50% of the model R^2. The intercept was significantly different from zero. The relationship between OM and properties was described by the following fitted regression equation:

$$OM = 5.8 + 0.08P + 0.08K - 0.04Mg$$

where OM (g kg^{-1}); and P, K and Mg (mg kg^{-1}).

The standard errors for intercept and parameter estimates for soil variable are included in Table 1.6. The linear relationship between CEC and OM was significant ($p = 0.0005$) only if all other variables were excluded from the model, $R^2 = 0.25$, and slope for intercept and CEC were 7.31 and 1.19 respectively, root MSE = 3.2. However, on maize diversified fields, no significant relationship was observed between OM content and soil chemical properties.

1.3.2.2 *Soil properties between paired legume and maize diversified fields*

Paired t-tests were done to compare soil characteristics between legume and maize diversified fields. Contrary to our hypothesis, inorganic P was significantly higher in the top 0-15 cm soil depth of maize fields (35±21 mg kg^{-1}) than legume fields (25±18 mg kg^{-1}) (P=0.012) (Table 1.7). However, there were no significant differences in soil pH, OM, CEC, BS, exchangeable cations (Ca, K and Mg) and texture between legume and maize diversified fields.

OM in top soils of legume fields ranged from 5-20 g kg^{-1} with a mean of 12±3.6 g kg^{-1}. Under maize diversified fields, OM ranged from 5-32 g kg^{-1} and mean equal to 13±4.9 g kg^{-1}. The grand mean for Ca, Mg, and K are 447 mg kg^{-1}, 112 mg kg^{-1}, and 116 mg kg^{-1} respectively. Base saturation (BS) in top soils ranged from 55-100%, mean = 76±15% on legume fields; and 55-100%, mean = 79±16% on maize fields. In sub soils, legume fields had BS values within 40-100% with a mean of 75±14%; whilst on maize fields, the range was 47 to 100%, mean equal to 76±16%.

1.3.3 Cropping Systems

The major cropping systems are sole cropping, intercropping and crop rotation. In 2004/05 to 2006/07 seasons, on legume fields, 27% was planted to doubled up legumes, 24% sole legume, and 17-21% to sole and intercropped maize (Table 1.8). The doubled up legumes were of mainly pigeonpea with either soybean or pigeonpea. Sole legumes were of mainly groundnut, dwarf common bean, soybean, velvet bean and fish bean. Sole stands of groundnut and dwarf beans are aimed at maximizing yield probably due to reduced competition for light and higher plant population compared to intercropped legume. The creeping habit of velvet bean makes it unsuitable for intercropping. Velvet bean is grown in sole stands because the creeping growth habit is not suitable for intercropping, whereas fish bean is grown as an improved fallow. On maize diversified field, a majority of farmers planted maize in sole stands (44%) compared to intercropping. Maize is grown in pure stands if planted using the Sasakawa method (1seed x 0.25m) or intercropped with grain legumes (climbing common beans) or pumpkins at 3 seeds/station x 75cm or 90cm. The domination of maize in the cropping systems signifies the importance of maize as a staple food crop.

Among the 36-49% of the farmers who practiced intercropping, 55% were of legume-legume intercrops, and 43-91% of maize-legume combinations, intercropped at low density. Farmers indicated that the main crop of interest usually takes a larger proportion in the intercrop, for instance, recommended maize density in sole stands is maintained. When groundnut is intercropped with pigeonpea, the density of groundnut is reduced as compared to sole stand due to replacement series design where one planting station is replaced by pigeonpea, and groundnut in planted approximately 20 cm away from the pigeonpea. In this area, the groundnut-pigeonpea intercrop technology has been adapted by farmers, showing local innovation. In the second season, pigeonpea is ratooned and intercropped with maize. Doubled up legume technology provides diversified source of food to households at different times of the year while improving soil fertility.

Crop rotation is another cropping system practiced by about 45% of the farmers in this area. The sole and intercropped legumes are rotated with maize in the subsequent season. Approximately 45% practice crop rotation and the preceding crops are either sole legume or intercrop of cereal-legume or doubled up legume. According to the farmers, the doubled up legume technology-maize rotation is assumed to provide more soil fertility benefits to the subsequent crop compared to sole cropping of each.

1.3.4 Traditional knowledge of soil types: Farmer perception of soil fertility status of legume and maize diversified fields

Farmers were asked to provide local soil name, rank soil fertility level as high, medium, low and exhausted, and also provide indicators for the fertility rank for the legume and maize diversified fields. Comparisons were made between farmer rating of soil fertility and pH, OM and nutrient levels on these two fields. A summary of results on local knowledge of soil fertility are shown in Table 1.9. Local soil names are chichenga (sandy), chigandasi (clay), katondo (red soils- sandy clay loams) and kanyevu (clayey) and “dongo lakusazgana” (mixed texture).

Farmers use both crop and soils indicators to assess soil fertility. Soil indicators include soil color and particle size. Crop indicators are largely related to crop performance and they include vigor during seedling and vegetative growth stages, response to small amount of fertilizer, proportion of groundnut pops and yield e.g of soybean and maize. In addition to soil and crop performance, soil tilth, presence of macro fauna such earthworms and presence of specific weed species are also used. Low fertility and exhausted soils were described as sandy, usually with poor crop establishment, and associated with low yield of soybean and maize, and high percentage of groundnut pops. The high fertility soils are black and fine textured. There are more maize fields (11%) on exhausted soils than legume fields (5%). This could probably be due to N fixation and more residue incorporation on legume fields than maize diversified fields. Overall, about 45% of the farmers indicated that soils on their farms have medium fertility levels.

A comparison between farmers rating of soil versus nutrient levels indicates that farmers are knowledgeable about soil fertility levels. Interestingly, on maize diversified fields, farmer rating of soil fertility was positively related to CEC, Ca and K (Table 1.9). Soils perceived to be highly fertile had significantly higher CEC, levels of Ca, and K than the medium to exhausted soil categories. Under legume diversified fields, there was no difference in soil nutrient levels between ranked soil fertility levels. However, it should be noted that the trend indicate higher levels of Ca, Mg, K and CEC correspond to high fertility rank.

1.3.5 Preferred legumes

The main legumes grown by farmers are groundnut, soybean, pigeonpea and common beans. Groundnut is grown by all farmers. Soybean, pigeonpea and dwarf common beans are grown by >85% of the farmers (Fig 1.3). Other legumes grown are cowpea, velvet bean, fish bean, bambara groundnut and chick pea. Overall, the results support the hypothesis that food legumes are greatly preferred over green manures. Soybean, pigeonpea, and velvet bean are new legumes that were not traditionally grown in the area >12 years ago (Table 1.10). For fish bean, 43% of the respondents indicated that this is not a new crop even though only <20% of the farmers are currently growing it. This is mainly due to non food value of this legume. Chickpea locally known as "*Tchana*" is relatively a new legume to this area grown by 3% of the farmers.

Soybean and pigeonpea are among the new legumes that were not traditionally grown decades ago. These legumes have been promoted by the SFHC project since the implementation of the project. In this survey, all project farmers grow soybean compared to 62% of control farmers (Table 1.11). Similarly, 94% of project farmers grow pigeonpea compared to 69% of the control farmers. A Chi square analysis to test whether more project farmers grow soybean and pigeonpea indicated a significance of 0.001 and 0.03 respectively implying that there is sufficient evidence to support the research hypotheses that farmers who are actively involved in SFHC project activities are more knowledgeable on production and utilization of the new legumes than non participating farmers. Another finding from this study is that none of the control farmers grew fish bean. Even though a chi square analysis of number of farmers growing fish bean was not statistically significant at 5% level, the results were significant at 10% level (p=0.086). This trend demonstrates that there are more project farmers growing fish bean than control farmers.

1.3.6 Utilization of Legumes

Table 1.12 show results on reasons for growing legume among project and control farmers. The reasons were ranked in order of importance. Child feeding describes use of legume particularly to enrich food for children while food or relish refers to consumption by all members of the household. It appears that grain legumes are grown mainly for food to improve family nutrition. The exception is pigeonpea, where both soil fertility improvement and food are cited as important goals. The high value attached to food reasons could explain why farmers grew more of grain legumes than green manures. Other reasons cited were marketing and child feeding. Velvet bean and fish bean are grown primarily for soil fertility improvement.

A chi square test of equal proportions was done to test if there is independence between farmer category and use of legumes. Results on groundnut indicate that both project and control farmers value food benefits more than soil fertility as their primary reason. It should be noted that none of the control farmers mentioned marketing as primary reason for growing groundnut as was the case with 13% of project farmers. This may suggest that project farmers get higher grain yields and sell surplus than control even though there is no sufficient evidence from the farm field survey. Farmers were not able to estimate yield obtained from a legume field in previous season. A comparison of project and control farmers demonstrates 3 times more of project farmers grow groundnut for soil fertility than control farmers (22% vs 8%). This finding supports our hypothesis that project farmers are more knowledgeable about use of legumes to improve soil fertility compared to non participating farmers. Marketing was cited as the major second reason for growing groundnut by all farmers

Pigeonpea, an annual to semi perennial crop, is one of the legumes promoted by the SFHC project. In this study, the major reasons for growing pigeonpea were soil fertility and food. The grain is cooked and eaten as relish or sauce to go with "nsima," staple food made from maize. There was no evidence that farmers use the pigeonpea differently which means that both soil fertility and food reasons are equally valued (Table 1.12). The other reason cited was marketing. Additional uses of pigeonpea include firewood (7%) and traditional medicine (7%). Firewood from pigeonpea can be a significant contribution to rural communities in some districts where high population and deforestation has led to clearing of natural forests forcing women to spend a lot of time to fetch firewood.

Soybean grain is one of the ingredients for baby weaning foods in Malawi. The grain is highly nutritious as a good source of vitamins, plant proteins (40%), lipids (20%), carbohydrates (35%) and ash (5%) (Liu, 1999). In this study, more than 60% of the households use soya to prepare food for children especially those under 12 years. Farmers reported that soybean has been promoted by the SFHC project to improve family nutrition and in particular of young children. Results from this survey suggest that project farmers use soya beans more for child feeding than soil fertility ($p=<0.001$) (Table 1.12). On the contrary, control farmers value both soil fertility and child feeding equally as a primary reason for growing this legume. Surprising, more control farmers use soybean for soil fertility than project farmers. This could be attributed to high promotion of soya for child feeding by the SFHC project. Other grain legumes grown are common beans, cowpea and bambara groundnut. These are primarily grown for food seconded by marketing (p=<0.0001). Soil fertility was mentioned by <15% of the farmers as secondary reason.

Velvet bean and fish bean are grown for soil fertility. Farmers indicated that these legumes are good at improving soil fertility but are not edible. It should be noted that velvet bean can be eaten if cooked properly. This legume is a traditional crop in some districts of southern Malawi where people use the grain to prepare various snacks. The cooking time may take as long as 8 hours to remove the L-dopa (3,4-dihydroxyphenylalanine), a toxic substance found in the grain that can lead to death if not well processed (Pulangethi et al., 2005, Fujii et al., 1991). In this study area, more control farmers (40%) are able to cook the grain than project farmers. A few farmers (~17%) indicated to have learnt the traditional recipe for cooking velvet beans. About 20% of the project farmers grow velvet bean for sale and specifically grain was sold to the SFHC as part of seed multiplication. Few project farmers (<20%) grew fish bean because of the non food value. In addition to soil fertility, 42% of the growers use fish bean as a bio-pesticide.

1.3.7 Preferred characteristics of legumes

Legume characteristics influence choice of legumes among farmers. Farmers were asked what traits they would want to see in a best legume type and/or variety. Frequencies and percentages were computed for each reason and specific legume within preferred and undesirable traits. Farmers gave multiple reasons and hence the values in a column within the preferred and undesirable traits do not add up to 100% (Table A1.1). The characteristics considered by farmers were yield potential, food value, maturity period, seed size, soil fertility benefits, adaptation to varied soil characteristics and rainfall, resistance to pests and diseases, and market potential. The top four preferred characteristics are shown in Table 1.13 and the detailed information in Table A1.1. High yield was the number one criterion used by farmers in selecting all grain legumes.

Farmers were also asked to indicate the undesired traits for legume varieties they are currently growing. The main concerns in pigeonpea were the long growth period to harvest grain (37%) hence prone to livestock grazing, beetles (29%) and low grain yield (11%). Pests and disease problems were also mentioned in common beans by 34% of the respondents. For groundnut, CG7 variety is widely grown. However, this variety is not preferred for flour that is used to season vegetables because of red seed coat and high oil content. In addition, farmers indicated that vegetables seasoned with CG7 flour are easily spoiled probably due to high oil content.

1.3.7.1 Farmer choice on where to grow legume

Soils were classified into light textured (sandy, sandy clay, sandy loam) and medium-heavy texture (SCL, Clay loams, Clay). A cross tabulation of legumes grown by soil texture was done. The number of farmers growing legume was expressed as a proportion of the total number of farms for a given soil textural category. Results indicate that soil type does not influence type of legume grown (Fig 1.4). A trend was observed in that only 84% of farmers with light textured soils grow soybean, as compared to 92% on fine textured soils.

1.3.8 *Soil fertility and crop residue management by cropping system*

1.3.8.1 **Soil fertility management on legume and maize field**

Cropping systems were grouped into four major categories; legumes, maize-legume intercrop, sole maize, tobacco and cassava-maize intercrop. The legume system includes improved fallow of fish bean, sole and doubled-up legumes groundnut, pigeonpea, soybean, common bean and cowpea. Maize-legume intercrop is of maize intercropped with any of the grain legumes grown. Sole maize includes pumpkins at very low (negligible) densities. Soil fertility management was classified as follows: legume residues (residue from legumes either in sole or doubled-up); maize residues, maize + legume residues, and either of these with inorganic fertilizer. Inorganic fertilizer includes 23:21:0+4S, UREA and CAN.

In 2006/07 season, less than half (41%) of legume fields were planted to sole legumes, 34% to maize-legume intercrops, 20% maize and 5% tobacco. Results on soil fertility management under different cropping systems are shown in Table 1.14. There were no significant differences in soil fertility management between project and control farmers on both legume and maize diversified fields, and therefore only results for cropping system x soil fertility management are presented. On both legume and maize fields, soil fertility management was dependent on cropping systems, p=0074 and p=0.0002, for legume and maize fields respectively. On legume field, 22-33% of the farmers incorporate crop residues of either maize or legume to improve fertility of legumes. In addition, about a third of the farmers did not do anything to improve fertility of the legume field. This is different from sole maize and maize-legume intercrops where approximately 74% of the farmers apply inorganic fertilizers to increase yield. Among the farmers who grew maize in rotation with legumes, about 56% of them applied inorganic fertilizer and legume residues to improve soil fertility, 22% used either inorganic fertilizer or legume residues only.

On maize field, maize was planted on >half of the fields sampled in 2006/2007 season. Sole and intercropped maize were planted on 55% and 41% of the fields respectively; remaining 4% left was allocated to tobacco, cassava and sweet potato (Table 1.14). Soil management options used were residue incorporation, inorganic fertilizer, compost and livestock manure. Inorganic fertilizer use in sole and intercropped maize systems was approximately 85%. Out of these, 6-22% combined inorganic fertilizer with crop residues of maize or legumes.

1.3.8.2 Crop residue management by cropping system

Cropping systems were grouped as described in section 3.7.1. There were no differences in residue management between project and control farmers at 5% level. However, residue management differed among the cropping systems on legume fields only, p= 0.0044 (Table 1.15). No significant differences observed on maize fields. The list of options includes residue incorporation, burn for ash or land preparation, livestock feed or bedding and compost manure.

On legume field, a majority of farmers (77-80%) incorporated all residues from sole or intercropped legumes compared to 56% residues of maize only. This was usually done between May-August soon after harvesting. Similar trend was observed on maize field with an exception of maize-legume intercrop systems where 44% incorporated residues from maize-legume systems, and 22% used residues for livestock feed or bedding. Farmed indicated that pigeonpea leafy biomass is usually incorporated late in the season (around September), the harvest time for this legume. Partial incorporation of small stalks of maize was practiced by 11% of the farmers. Maize residues seemed to have more competing uses with soil fertility in that 23% of the farmers indicated use for livestock feed or bedding compared to 11% of legume residues. On average, 9% of the farmers used compost manure made from a combination of maize and legume residues. Few farmers (8%) burned maize or legume residues for ash or land preparation. Tobacco stalks are uprooted and burned to control nematodes and facilitate land preparation. Overall, the study showed that farmers are aware of benefits of early incorporation of crop residues from legumes and maize systems to improve soil fertility for the subsequent crop. However, households who own cattle or goats face a challenge of whether to incorporate residues or feed livestock.

1.3.9 *Extension advice sought by farmers*

Access to information on recommended cultural practices is key to increasing crop yields. Farmers can access this information through fellow farmers, extension workers, bulletins and radios. During the survey, farmers were asked to indicate if they need advice on legumes. Farmers sought agronomic information (all recommended cultural practices to optimize yield, planting pattern), post harvest handing of pigeonpea and CG7 groundnut to prevent losses, identification of markets, and utilization of food (food recipes and value adding activities in soybean, groundnut and velvet bean (Table 1.16). This baseline information is quite useful for developing training materials for farmers and educators on recommended cultural practices for each legume, as well as planning interventions on legume based technologies.

1.3.10 *Constraints to legume production*

Crop yield is depends on genotype by environment interactions such as legume variety, seed quality, field management practices, and environment factors such as rainfall and soil fertility.

Farmer's responses on constraints to legume production were grouped into technical, socio economic, biophysical, natural, and cultural factors. For almost all legumes, farmers raised a concern regarding seed shortage either due to lack of money or seed availability in the area (Table 1.17).

Groundnut, CG7 variety, contains 48% oil (Malawi Government, MoAIFS, 2005). This characteristic is a good for improving human nutrition. However, farmers mentioned that the high oil content makes storage difficult as the groundnut can rot easily. For pigeonpea, specific challenges to protect seed from field pests and weevils were highlighted. The major field pests are beetles which such pollen from flowers resulting in excessive defoliation and consequently low grain yield. Another issue raised on pigeonpea was late maturing varieties. Farmers are interested in growing pigeonpea varieties that mature earlier and also provide more soil fertility benefits. All these issues are a challenge for plant breeders on developing varieties that meet local quality traits. On soybean, farmers have noted low yields associated with infertile soils. The soils in this area have low OM (12 g kg^{-1}) and therefore cannot support soybean growth. Other constraints mentioned were marketing for velvet bean and bambara groundnut. For velvet bean, this could be related to processing problems.

1.4 DISCUSSION

1.4.1 Soils properties

This on-farm study evaluated soil characteristics of fields that have been managed with either maize-dominated cropping systems or legume-diversified systems. Overall, soil fertility was variable and highly depleted as shown by the low soil organic matter (Table 1.4). Mhango et al., (2008) reported OC level equal to 0.61% (~11 g kg^{-1} OM) for soils under smallholder farms in Champhira, northern Malawi. However, higher OM values of about 25 g kg^{-1} and 18-33 g kg^{-1} have been reported by Snapp et al., (1998) and Beedy (2008) in some areas within Malawi. Surprisingly, the soil cation status and soil pH were within a range favorable for production of most crops where critical values in Malawi for Ca, Mg, K and Mg:Ca are 50 mg kg^{-1}, 75 mg kg^{-1}, 70 mg kg^{-1} and >0.07, respectively (Wendt ,1995). Soil texture was variable among farms and this could be related to differences in the nature of parent material (Tisdale et al., 1993).

Promotion of legume diversification over the last decade has been successful in terms of farmer adoption of more grain legumes (Table 1.10), but there was no difference noted between the two field types with the exception of the topsoil where a moderately higher soil P status was observed in maize fields than in legume fields (Table 1.7). The finding of maize fields being of better soil quality than legume fields may be attributed to farmers' strategic allocation of maize to soils of good fertility. Other research has shown that farmers tend to focus soil fertility amendments on maize produced on the highest soil quality portions of their farm, as shown in a large-scale smallholder study in Kenya (Tittonnel et al., 2006). Even so, the P values (13±13 mg kg^{-1} in the 15-30cm soil layer to 35±20 mg kg^{-1} top soil layer) indicates a sustainability issue, as these levels cannot sustain production of most arable crops that require relatively high levels of P unless complemented by other sources. In Malawi, critical levels of inorganic Bray P are 20mg kg^{-1} for maize (Chilimba et al., 1999). Other studies have reported 20 mg kg^{-1}, Mehlich 3 P (Wendt, 1995) and 13 mg kg^{-1} Bray P (Mallarino and Blackmer, 1992). The variation of inorganic P among farms was also reported in earlier studies by Snapp (1998) and Wendt (1995) and this could be as a result of different soil management practices and cropping history.

1.4.2 Local soil fertility indicators

Generally, farmers are knowledgeable of assessing soil fertility status on their farms as evidenced by positive correlations between farmer rating and some soil chemical properties. Farmers use both soil and crop indicators to assess soil fertility including soil texture, soil color, crop performance, plant response to inorganic fertilizer and yield. These findings are similar to earlier reports by Mairura et al., (2007) and Murage et al, (2000) where productive fields had higher content of silt, pH, exchangeable cations, particulate organic carbon, and inorganic N than non productive soils. However, in our study farmers did not mention such indicators as specific weed species and invertebrate animals such as earthworms.

Productive soils were described as black soils *"dongo lipifa*", with reasonable amount of clay (*chigandasi*) or mixed texture. Unproductive soils are sandy, locally known as "*chichenga*" associated with very poor yield. The description of chichenga (sandy soils) and black soils is similar to findings reported by Kamanga (2002) but differ on classification of katondo soils. In this study, katondo soils were classified as of low to medium fertility depending on expected yield. Kamanga (2002) quotes (Lowole 1995; and Young and Brown, 1962) in a description of chichenga (sandy soils), katondo, and black soils according to Malawi Soil classification. Chichenga (sandy) soils are described as sandy ferrallitic soils, low in organic matter and water holding capacity. What farmers described as Katondo soils correspond with the Malawi soil classification of a ferruginous/ferric rhodustalf, sandy clay loams, dark red, CEC = 5.4 cmol kg^{-1} soil and are most productive. Black soils are described as hydromorphic, very fertile soils with medium to high CEC.

1.4.3 Legume cropping systems and preferred legume characteristics:

There is high preference for food legumes to non food legumes and this agrees with Bezner-Kerr et al., (2007). Farmer preferences for legumes in order of frequency were groundnut, soybean, pigeonpea, common bean, cowpea, velvet bean, bambara groundnut and fish bean. There was high diversity of legumes among project farmers than control farmers. A larger proportion of project farmers grew soybean and pigeonpea than control farmers. Soybean has been promoted widely in the Ekwendeni catchment by the SFHC project both in terms of production and training in various recipes such as preparation of soya porridge, extraction on soya milk, and use of soya flour to season porridge or vegetables, and many more (Bezner-Kerr et al., 2007). We also found that fish bean was grown by project farmers only primarily for soil fertility even though this is not necessarily a new legume. These findings demonstrate the impact of the SFHC project on promotion and adoption of legumes in this area. Project farmers are educated in production and utilization of legumes by the SFHC project.

There is a broad diversity of legume based cropping systems in Ekwendeni. As farmers have adopted new species and cropping system arrangements, they are meeting a range of objectives: sole cropped groundnut and common bean maximize grain yield whereas intercropped doubled up legumes (pigeonpea and groundnut, pigeonpea and soybean) provide for multiple products, soil fertility and child feeding along with some grain production. Soil fertility enhancement through sole cropped fish bean and velvet bean was rare (Table 1.10) but adopted by some farmers, only those working with the project adopted fish bean for soil fertility and as a bio-pesticide. Example of a success story on use of fish bean in pest management was reported by Koona and Dorn (2005) in which they found 90% reduction in bruchid infestation of stored legume grain compared to the untreated. Project farmers have been trained on the role of legumes to improve soil fertility (Bezner-Kerr et al, 2007). In the literature, adoption of legumes has been rare, and has been primarily limited to grain crops (Mafongoya et al., 2007), or green manures like velvet bean that suppress weeds (Talawali et al., 1999).

1.4.4 Sustainability

Even in this study which has unprecedented levels of legume adoption, the area of legume fields is still smaller than that of maize dominated cropping system. Further, the Preferred legume characteristics are edibility, high grain yield, early maturing, improve soil fertility, wide adaptation and resistant to pests and diseases. This poses two major challenges on reliance of legumes to improve rate of N inputs in cropping systems. The first is total area allocated to legume compared to maize. Legumes occupy a small portion of total arable land. In this study, even on legume field, legumes were grown on <50% of the sampled field. This is a challenge if we rely on legumes to increase rate of N inputs per area (Giller, 2001). The second challenge is preference for grain legumes with high NHI like soybean and groundnut to non food legumes such as fish bean and velvet bean. At the same time, farmer's goal is to maximize both soil fertility and grain yield. Legumes that provide high yield tend to have high nitrogen harvest index (NHI) and a tradeoff of low soil N benefits (Giller et al., 2002). This objective may not be possible because of tradeoffs associated with resource allocation by the plant, although the doubled up legume system provides one means to enhance both residues and grain legume production. There is need for continued research by breeders, agronomists and farmers to come up with varieties and cropping systems that meet farmers' preferred traits.

Farmers did not apparently plant legumes in a specific soil type, as shown by the similarity of soil characteristics for maize and legume-dominated fields. There was a trend observed in that soybean production was associated with fine textured soils, which could be related to poor performance of soybean on poor fertility, sandy soils in Northern Malawi. Wendt and Atemkeng (2004) reported yield reduction of soybean with low levels of phosphorus (<15 mg kg^{-1}) and magnesium, compared to pigeonpea where nutrient levels had no effect on yield. Earlier farmers in this area reported observing very poor growth of soybean on sandy soils, and farmers have repeatedly requested technical advice on how to grow more vigorous, high performing soybeans (Snapp, personal communication, 2006).

1.4.5 Crop residue and soil fertility management

The findings on residue incorporation on legume field agree with previous study by Bezner-Kerr et al., (2007) who reported 70% residue incorporation. Another study by Snapp et al., (2002) found that 23-50% of the farmers incorporate residues early whilst 20-64% incorporate late during land preparation. Maize residues may not be incorporated as frequently due to immobilization associated with lower quality (low N content) residues compared to legume residues (Sakala et al., 2002). This study has also demonstrated that a combination of crop residues from legumes and cereals may help to build SOM in the long term rather than sole legumes alone in areas characterized by warm to hot climate and a short (3-4 months) rainfall season.

The high proportion of both project and control farmers incorporating crop residues is a positive step towards building SOM. Low SOM (Table 1.4) could be related to rapid decomposition of residues by the high temperatures experienced in the tropics in addition to high amount of sand (Burke et al., 1989). Another factor is low quantity of residues incorporated. In this study, we found competing uses of crop residues for soil fertility, livestock feed or bedding and burning for ash or land preparation. In some cases, there was deliberate choice of incorporating small maize stalks only which also limits the amount of OM added to the soil.

Farmers have noticed that reliance of incorporating crop residues (legumes or combined with maize residues) alone do not effectively support maize growth in the reproductive stage. When maize is grown after a legume or intercropped with legume, a >70% of the farmers compliment crop residues with inorganic fertilizer to increase grain yields. Kabambe et al., (2008) and Mwato et al., (1999) reported on yield benefits due to integrated use of organic and inorganic fertilizers.

1.4.6 Constraints to legume production

The major constraint for almost all legumes is seed shortage either due to lack of money or availability within this area. Work by Snapp et al., (2002) reported that legume seed was a problem for 50% of the small holder farmers. Certified seed for legumes is expensive and hence not affordable by the smallholder farmers. In addition, low yield of legumes and high demand at household level prevents farmers from keeping enough farm saved seed. The other scenario where seed is not available in the area has implication on policy. Governmental and non-governmental organizations and communities should discuss ways to ensure that seed is distributed in locations easily accessed by smallholder farmers. Other constraints cited were labor, pests and low yield.

A specific problem of poor soybean grain yield on soils with low fertility was also highlighted. This observation agrees with findings by Mhango (2008) where on a site with 0.61% OC, application of 23:20:4 and 46:40:8 kg ha^{-1} of N:P:S fertilizer increased soybean grain yield by 27 and 71% respectively over the control. In addition, there was no difference in yields on soils with 1.14% OC. Therefore, on poor soils, there may be a need for a starter up of nitrogen fertilizer to boost initial growth of soybean. Specific soybean varieties require inoculation in order to nodulate and fix nitrogen for its growth, whist promiscuous varieties such as Magoye can be grown without inoculation (Mpepereki et al., 2000). The varieties promoted in this area have been promiscuous types, although these have not preformed as expected and inoculation may need to be investigated.

For new legumes (soybean and pigeonpea), therefore, there is need for more on-farm experimentation to train farmers on agronomy and field management practices. Participatory on farm demonstrations and field days on these topics would build capacity among farmers (Norton et al., 1999). However, for the traditional legumes, most of the issues raised are socio-economic. Marketing concerns with velvet bean and pigeonpea were also raised by smallholder farmers in Mangochi district of Southern Malawi (Kabambe et al., 2008).

The crop-livestock related problems in pigeonpea mentioned are common with long duration crops that remain in the field after the month of June when most of the crops are harvested (Kabambe et al., 2008). Pigeonpea is prone to grazing because during this period, goats and cattle are usually left on free range grazing system. As for bambara groundnut production, the cultural belief associated with management of bambara groundnut fields was also noted by Mhango (2002) at another location in northern Malawi.

Overall, these constraints are both biophysical and social economic and hence addressing these challenges require a multidisciplinary approach. For example, involvement of agro dealers in marketing of legume seed in rural areas would help to increase seed availability. The packaging of seed in smaller quantities would increase access to low income farmers. It is recommended that local seed multiplication programs and seed banks should be implemented at a larger scale to increase availability of high quality seed. This initiative should be supported by government agricultural research institutions and CGIAR centers. Of importance also is to educate farmers on appropriate field management practices in seed production of specific legumes and post harvest handling.

1.5 CONCLUSION

This study has shown that soil fertility status is degraded in the Ekwendeni and multiple ISFM strategies are required. Fields with a history of maize production had significantly higher inorganic P than legume fields. No evidence was found for enhanced soil fertility in fields with a history of legume production. This could be due to underlying variability in soil properties on smallholder farms, or nutrient export through grain harvest, a nutrient demand which may only be partially offset by processes such as nitrogen fixation, mineralization and solubilization processes. We are also aware that farmer choice for crop placement may have influenced soil nutrient status associated with maize and legume-diversified fields. Farmers may allocate the highest soil quality portions of their farm to maize, rather than legume crops, as a means to insure sufficient production of the staple maize crop.

Legume species grown by farmers in order of decreasing frequency were groundnut, soybean, pigeonpea, common beans, cowpea, velvet bean, bambara groundnut and fish bean. These legumes were grown in a range of patterns, sole stands or intercropped with cereals or legumes, and rotated with maize in subsequent season. The choice of legume depends mainly on food value, yield potential, soil fertility benefits and adaptation to varied soil types and rainfall pattern. Other preferred characteristics are early maturity, resistance to pests and diseases, and high market potential. The results support the hypothesis that farmers prefer early maturing food legumes with high yield potential more than green manures. There is high diversity of legumes among project farmers with more growing pigeonpea, soybean, and fish bean than control farmers. Farmers reported growing more legumes in recent years compared to 12 years ago.

Legume adoption and residue incorporation are rare in SSA partly due to seed availability, labor constraints, small land holding size and competing uses of residues. However, in this community, nutrition education, introduction of new legume species, on farm demonstrations and local seed banks have influenced legume adoption and residue incorporation. This study has shown that adoption of legumes is possible without new markets and marketing concerns may come later when there is surplus production.

The main reasons for growing legumes are food, soil fertility and market. For groundnut and common bean, farmers value food benefits more than soil fertility. There was a difference in soybean utilization where project farmers use it more for child nutrition (children <12 years) than soil fertility, whilst control farmers value both soil fertility and child feeding equally. Pigeonpea is grown for both soil fertility and food. Legumes grown for soil fertility are pigeon pea, velvet bean and fish bean. Constraints to increased legume production are both socio-economic and agronomic and therefore strategies to address the issues require multidisciplinary approach.

Table 1.3: Descriptive statistics of household characteristics

Characteristic of household	Frequency (N=44)	Mean (N=44)	Std Dev
Age		43 (2.33)	15.5
Household size		5 (0.36)	2.39
Children <5years		0.8 (0.15)	0.99
Children 5-12 years		1.4 (0.17)	1.10
Adults[a] per family		2.9 (0.22)	1.48
Dependency ratio		0.89 (0.10)	0.67
No. of people to farm[b]		2.9 (0.27)	1.82
Legume field (ha)		0.15 (0.26)	0.17
Maize field (ha)		0.34 (0.34)	0.42
Food secure[c] (%)	26	59	
Marital status			
Married (%)	28	64	
FHH (%)	6	14	
MHH (%)	5	11	
Polygamous (%)	5	11	
Occupation			
Farming (%)	41	93	
Others (%)	3	7	
Education level (%)			
Secondary	12	27	
Upper primary: std 5-8	25	57	
Lower primary: std 1-4	6	14	
None	1	2	

Number in parenthesis is standard error for continuous variables.
[a]People above 12 years in the household were included as adults; [b]Number of people per household who help with farm activities;
[c] Food secure from May 2006 to April 2007; FHH= female headed household, widowed or separated; MHH=Male headed household, single or separated

Table 1.4: Soil properties across legume and maize diversified fields, 0-15 and 15-30 cm

Variable	Depth (cm)	Mean N=88	Std deviation	Min	Max	LCL	UCL
pH (in H_2O)	0-15	6.2	0.56	5.1	7.9	6.2	6.4
	15-30	6.1	0.62	4.8	7.9	6.0	6.2
OM (g kg^{-1})	0-15	12	3.72	5	21	12	13
	15-30	13	4.49	5	32	12	14
POM (g kg^{-1})	0-15	4	1.87	1.0	10	3	4
POMC (mg kg^{-1})	0-15	695	234	291	1261	645	745
POMN (mg kg^{-1})	0-15	34	13.04	13	80	32	37
C:N in POM	0-15	21	2.28	16	28	20	21
Bray P (mg kg^{-1})	0-15	33	25.7	4	142	28	39
	15-30	16	22.8	1	130	12	21
Ca (mg kg^{-1})	0-15	414	244	150	1350	363	466
	15-30	464	329	100	1500	394	534
Mg (mg kg^{-1})	0-15	123	65	29	464	110	137
	15-30	121	58	33	311	109	133
K (mg kg^{-1})	0-15	106	49	43	325	95	116
	15-30	106	48	50	283	96	116
CEC (cmol kg^{-1})	0-15	4.3	1.38	1.7	9	4.0	4.6
	15-30	4.4	1.69	2.1	10	4.0	4.8
Sand (%)	0-15	86	3.96	76	93	85	87
	15-30	72	8.99	51	91	70	74
Clay (%)	0-15	9	3.20	4	16	9	10
	15-30	22	7.70	6	40	20	23
Silt %	0-15	5	2.4	2	15	5	6
	15-30	6	3.3	2	21	6	7

LCL= Lower 95% confidence limit for mean; UCL= Upper 95% confidence limit for mean

Table 1.5: Pearson correlation coefficients and significance between OM and soil properties, 0-15 cm and 15-30 cm soil depth

Variable	0-15 cm		15-30 cm	
	Coefficient	Pr>|r|	Coefficient	Pr>|r|
pH	0.168	NS	-0.059	NS
Bray P	0.125	NS	0.087	NS
CEC	0.427	<0.0001	0.522	<0.0001
Ca	0.254	0.0168	0.392	0.0002
K	0.353	0.0008	0.521	<0.0001
Mg	0.322	0.0022	0.191	NS
Clay	0.003	NS	-0.166	NS
Sand	-0.004	NS	0.203	NS
Silt	0.073	NS	-0.186	NS

NS = not significant at p<0.05

Table 1.6: Soil organic matter (g kg^{-1}), summary of stepwise regression on maize and legume fields, 0-15cm and 15-30cm soil depths

Variable entered	SE parameter estimate	Partial R-Square	Model R-Square	C(p)	Pr>F
0-15 cm soil depth					
OM across legume and maize fields					
CEC	0.22	0.32	0.32	1.35	<0.0001
OM, legume field					
K	0.02	0.27	0.27	16.62	0.0012
Bray P	0.03	0.17	0.44	7.22	0.0032
Mg	0.01	0.11	0.55	1.81	0.0082
OM, maize field					
All variables	-	-	-	-	NS
15-30 cm soil depth					
OM across legume and maize fields					
K	0.01	0.27	0.27	28.08	<0.0001
pH	0.65	0.10	0.37	15.60	0.0006
CEC	0.33	0.07	0.44	9.93	0.0023
Mg	0.01	0.04	0.47	5.67	0.0196
OM, legume field					
CEC	0.35	0.44	0.44	21.95	<0.0001
P	0.02	0.06	0.50	17.35	0.033
K	0.02	0.06	0.56	13.10	0.030
pH	0.81	0.07	0.63	7.41	0.011
Mg	0.01	0.04	0.67	5.05	0.041
OM, maize field					
pH	1.07	0.17	0.17	7.47	0.004
K	0.02	0.11	0.27	15.84	0.03

NS = not significant at p<0.05

Table 1.7: Soil characteristics of legume and maize diversified fields, 0-15 and 15-30 cm

Variable	Depth cm	Legume field	Maize Field	SE	Pr>(t)
pH (in H_2O)	0-15	6.2	6.3	0.10	0.749
	15-30	6.1	6.1	0.11	0.849
OM (g kg^{-1})	0-15	12	13	0.62	0.137
	15-30	13	13	0.57	0.813
POM (g kg^{-1})	0-15	4	4	0.24	0.635
POMC (mg kg^{-1})	0-15	673	713	37.1	0.287
POMN (mg kg^{-1})	0-15	33	36	2.03	0.140
C:N in POM	0-15	21	20	0.645	0.252
Bray P (mg kg^{-1})	0-15	24a	34b	3.53	0.012*
	15-30	14	13	2.39	0.381
Ca (mg kg^{-1})	0-15	418	494	61.12	0.220
	15-30	411	434	47.99	0.638
Mg (mg kg^{-1})	0-15	101	126	6.18	0.855
	15-30	100	121	7.73	0.503
K (mg kg^{-1})	0-15	110	121	9.34	0.746
	15-30	113	121	10.42	0.974
CEC (cmol kg^{-1})	0-15	4.1	4.4	0.31	0.401
	15-30	4.4	4.4	0.22	0.950
%Base saturation	0-15	76	79	3.05	NS
	15-30	75	76	2.69	NS
Sand (%)	0-15	86	86	0.74	0.594
	15-30	73	73	1.45	0.919
Clay (%)	0-15	9	9	0.62	0.832
	15-30	21	21	1.27	0.748
Silt %	0-15	5	5	0.49	0.970
	15-30	6	6	0.60	0.353

Means in a row followed by same letters are not statistically significant at $p<0.05$;
SE = standard error of the difference for the paired fields; NS = not statistically significant at $p<0.05$.

Table 1.8: Cropping system on legume and maize fields in 2005, 2006 and 2007 cropping seasons

Cropping system	Crop	Legume field, N=44				Maize field, N=44			
		2005	2006	2007	Mean	2005	2006	2007	mean
Sole	Maize	18*	11	20	17	39*	39	55	44
	Legume	21	27	25	24	0	5	0	2
	Tobacco	2	0	5	2	16	7	7	10
	Cassava	9	0	0	3	5	2	0	2
Intercrop	Maize-legume	11	21	32	21	25	39	34	33
	Legume-legume	25	39	18	27	0	0	0	0
	Maize-cassava/sweet potato	0	0	0	0	0	7	5	4
Fallow		14	2	0	5	16	2	0	6

*values reported in percent; 2005=2004/2005 season; 2006=2005/2006 season; 2007= 2006/2007 season

Table 1.9: Local soil fertility indicators and rating as perceived by farmers, and analyzed chemical characteristics

Field type	Soil fertility status: Category	% N=44	Local name of soil	Indicators used by farmers: Soils	Indicators used by farmers: Crops	OM (%)	Ca (mg kg^{-1})	K(mg kg^{-1})	CEC (meq/100g)	pH
Legume diversified	High	11	1. Black soil; 2. Chigandasi (clay)	Black soils; Fine or mixed texture	High seedling vigor; high yield	1.3	540	117	4.8	6.2
	Medium	52	1. Chigandasi or kanyevu; 2. Katondo (red soils, SCL); 3. Mixed soil	mixed soil texture	Good maize establishment and crop stand in vegetative stage; medium grain yield.	1.2	408	107	4.1	6.6
	Low	32	1. Chichenga (sandy) 2. Katondo	Sandy	Poor crop establishment; low yield of soybean or maize; groundnut pops;	1.3	407	114	4.1	6.4
	Exhausted	5	Chichenga	Sandy	very poor crop stands e.g. stunted, chlorosis	0.8	300	93	3.7	6.5
Maize diversified	High	14	1. Chigandasi 2. Mixed soil	mixed soil texture	High seedling vigor; high yield	1.7b	942b	152b	6.7b	6.4
	Medium	43	1. Chigandasi, or kanyevu; 2. Katondo 3. Mixed soil	mixed soil texture	Medium yield, good maize response to fertilizer, good seedling vigor,	1.2a	450a	109b	4.2a	6.4
	Low	32	Chichenga	Sandy	Low crop yield, poor maize yield without fertilizer	1.2a	414a	94a	3.9a	6.2
	Exhausted	11	1. Chichenga 2. Katondo	Sandy	Low maize yield with low inorganic fertilizer input	1.4ab	131a	131b	4.0a	6.3

SCL=sandy clay loam; Katondo = red soils, SCL; chichenga= sandy soil; chigandasi=clay soil.
Means in a column by field type followed by same letter are not statistically different at P=0.05

Table 1.10: Legume species grown 12 years ago, and adoption of legumes over the last 4 seasons since 2007

Legume	N	Legume grown 12 years ago		% growing legume in the last "n" years			
		Yes	No	1 out of 4 yrs	2 out of 4 yrs	3 out of 4 yrs	4 out of 4 yrs
Groundnut	44	92	9	5	18	11	66
Soybean	39	3	97	5	10	26	59
Pigeonpea	38	8	92	5	34	13	47
Common bean	32	100	0	0	3	9	88
Cowpea	18	83	17	17	17	11	28
Bambara nut	11	98	2	27	27	18	27
Velvet bean	18	6	94	22	39	11	28
Fish bean	7	43	57	29	29	29	14

2007= 2006/2007 growing season

Table 1.11: Number of farmers growing legume species in 2007, and proportion indicating legume is new to the area

Variable	Farmer category	Pigeonpea	Groundnut	Soybean	Common bean	Velvet bean	Fish Bean
Legume growers	Project	94*b	100	100b	71	42	22
	Control	69a	100	62a	77	39	0
	Mean	82	100	81	73	40	11
	Prob.	0.04	NS	0.0012	NS	NS	0.086
New legume	Project	97	6	97	0	100	57[y]
	Control	78	15	100	0	80	0
	Mean	92	9	97	0	94	-
	Prob	0.068	NS	NS	NS	0.097	-

*Figure reported as percent growers within the farmer category;

NS = not significant at $p<0.05$; [y]= none of control farmers grew fish bean

Means in a column followed by same letters are not different at $p<0.05$

Table 1.12: Reasons for growing legumes among project and control farmers ranked in order of importance

Legume	Farmer category	Reason	Soil fertility	Food/ relish†	Market	Child feeding	χ^2 Prob[a]
Groundnut	Project	1	26*	55	13	7	0.0007
		2	23	32	39	7	0.0623
	Control	1	8	92	0	0	0.0023
		2	8	15	62	8	0.0021
Soybean	Project	1	19	7	0	74	<0.0001
		2	29	16	39	16	0.2137
	Control	1[b]	50	0	0	50	1.000
		2	13	38	25	25	0.8013
Pigeonpea	Project	1	48	52	0	0	0.8527
		2	46	32	21	0	0.2668
	Control	1	45	56	0	0	0.7389
		2	13	50	38	0	0.4169
Common bean (dwarf)	Project	1	5	91	0	5	<0.0001
		2[c]	5	5	77	5	<0.0001
	Control	1	10	90	0	0	0.0114
		2	10	0	80	0	0.0074

† Relish is the local name used to describe the sauce that accompanies the staple maize dish, a key ingredient for food security; * value in percent/proportion of farmers citing reason

[a] A chi-squared test of equal proportion among the 4 categories of reasons

[b] Legume grown for two reasons, therefore 0.50:0.50 proportions

[c] sum is <100 because the farmer had no second reason for growing this legume

Table 1.13: Summary of top four preferred characteristics of grain legumes

	Preferred Traits ranked in order of importance			
Legume	1	2	3	4
Groundnut	High yield	Wide adaptation to varied soil types and rainfall distribution	High oil content	Improve soil fertility
Pigeonpea	Improve soil fertility	High yield	Early maturity	Grain taste as relish
Soybean	High nutritional value[a]	High yield	Improve soil fertility	Marketable
Common bean	High yield	Grain taste as relish†	Early maturing; resistant to pests and diseases; Improve soil fertility	Marketable
Cowpea	High yield	Grain taste as relish	Early maturing; resistant to pests and diseases; marketable	None

[a]Farmers indicated interested in child feeding with this crop, and thus high nutritional value for this purpose

†Relish is the local name used to describe the sauce that accompanies the staple maize dish, a key ingredient for food security

Table 1.14: Soil fertility management on legume and maize fields under different cropping system, 2007 season

Field type/ Farmer	Cropping system	% of total (N=44)	None	LR	MR	MR +LR	Fert	Fert + LR	Fert+ MR	LVM	Fert +MR + LR	CM	Prob.
Legume	Legume	40.9	33*	33	22	11	0	0	-	-	-	-	0.0074
	Maize	20.5	0	22	0	0	22	56	-	-	-	-	
	Maize-legume	34.1	7	20	0	0	20	53	-	-	-	-	
	Tobacco	4.6	0	0	0	0	0	100	-	-	-	-	
Maize	Maize	54.5	8	0	9	-	50	13	21	0	0	0	0.0002
	Maize-legume	40.9	0	0	6	-	56	6	22	6	6	0	
	Tobacco	2.3	0	0	0	-	0	0	100	0	0	0	
	Cassava-maize[a]	4.6	0	0	0	-	0	0	0	0	0	100	
Legume													
Project	All	70	13	32	10	3	7	35	-	-	-	-	NS
Control	All	30	23	8	8	8	23	31	-	-	-	-	
Maize													
Project	All	70	7	0	7	0	52	7	23	3	3	0	NS
Control	All	30	0	0	8	0	46	15	23	0	0	8	

Key: LR=Legume residue; MR=Maize residue; Fert=inorganic fertilizer, include UREA, 23:21:0+4S, CAN; LVM= Livestock manure; CM= compost manure; NS = not significant at $p<0.05$

* value in %; [a]maize density is negligible, includes sweetpotato at very low density; 2007 season= 2006/2007 season

Table 1.15: Crop residue management on legume and maize fields under different cropping systems, 2006/07 season

Field type/ Farmer	Cropping system	% of total (N=44)	INC Early	INC Late	INC small stalks only	INC legume residue only	IF	Burn for ash	Burn for land preparation	Uproot &burn	Compost	LF or bedding	Prob
Legume	Legume	41	72*	6	0	0	6	6	-	0	0	11	0.004
	Maize	21	56	0	11	0	0	11	-	0	0	22	
	Maize-legume	34	80	0	0	7	0	0	-	0	13	0	
	Tobacco	5	0	0	0	0	0	50	-	50	0	0	
Maize	Maize	55	54	4	4	0	-	4	8	0	0	25	NS
	Maize-legume	41	44	0	6	6	-	11	6	0	6	22	
	Tobacco	2	0	0	0	0	-	0	0	0	0	0	
	CSV-maize[a]	2	100	0	0	0	-	0	0	100	0	0	
Legume													
Project	All	70	68	3	3	3	3	3	-	3	3	8	NS
Control	All	30	69	0	0	0	0	0	-	0	8	8	
Maize													
Project	All	70	48	3	6	3	-	3	3	3	3	26	NS
Control	All	30	54	0	0	0	-	8	23	0	0	15	

CSV = cassava; IF = Improved fallow; LF = Livestock feed; INC = incorporate; early =April-Aug; late = Sept-Dec
*value in percentage; NS = not significant at $p<0.05$

Table 1.16: Demand driven extension information

Category	Legume information	Pigeonpea	Groundnut	Soybean	Common Bean	Velvet bean	Chickpea
Agronomic	All recommended practices	20*	23.1	34.6	19.1	16.7	2.3
	Planting time	0	0	11.5	9.5	0	0
	Planting pattern/spacing	15	15.4	19.2	0	16.7	0
	Intercrop combination	10	7.7	3.9	4.8	0	0
	Identification and control of pests and diseases	15	23.1	11.5	9.5	0	0
	Varieties	5.3	4.5	2.6	-	-	2.3
Storage	Post harvest handling of grain legumes	20	3.9	3.9	-	-	-
Marketing	Market outlets	15	11.5	19.2	4.8	8.3	2.3
Utilization	Food recipes	10	-	-	4.8	50	
	How to make soya meat	-	-	19.2	-	-	
	How to make soya milk	-	-	26.9	-	-	
	Groundnut oil extraction	-	30.8	-	-	-	

*values reported in percent for each legume. Values for each legume (in a column) are <100% if other reasons not cited, or >100% due to multiple reasons

Table 1.17: Major constraints to production of legumes

Legume	Constraints	Category of constraint
Groundnut	Lack of money to buy seed Storage of CG7 grain	Socio economic - Household Agronomy, post harvest handling
Pigeonpea	Pests in the field and storage Late maturity Low yield	Agronomic
Soybean	Low yield on low fertility soils	Agronomic
Common beans	Lack of money to buy seed Seed not available low yield; insects pests; inadequate or too much rainfall	Socio economic- Household Socio economic - Policy Agronomic Natural
Bambara groundnut	Lack of money to buy seed No markets Cultural belief that who ever has not lost a child cannot work in a field of ground beans	Socio economic- Household Socio economic - Policy Cultural belief
Cowpea	Seed not available Low yield	Socio economic Agronomic
Velvet bean	Lack of markets; seed not available	Socio economic- Policy
Fish bean	Not edible	Socio economic - Household

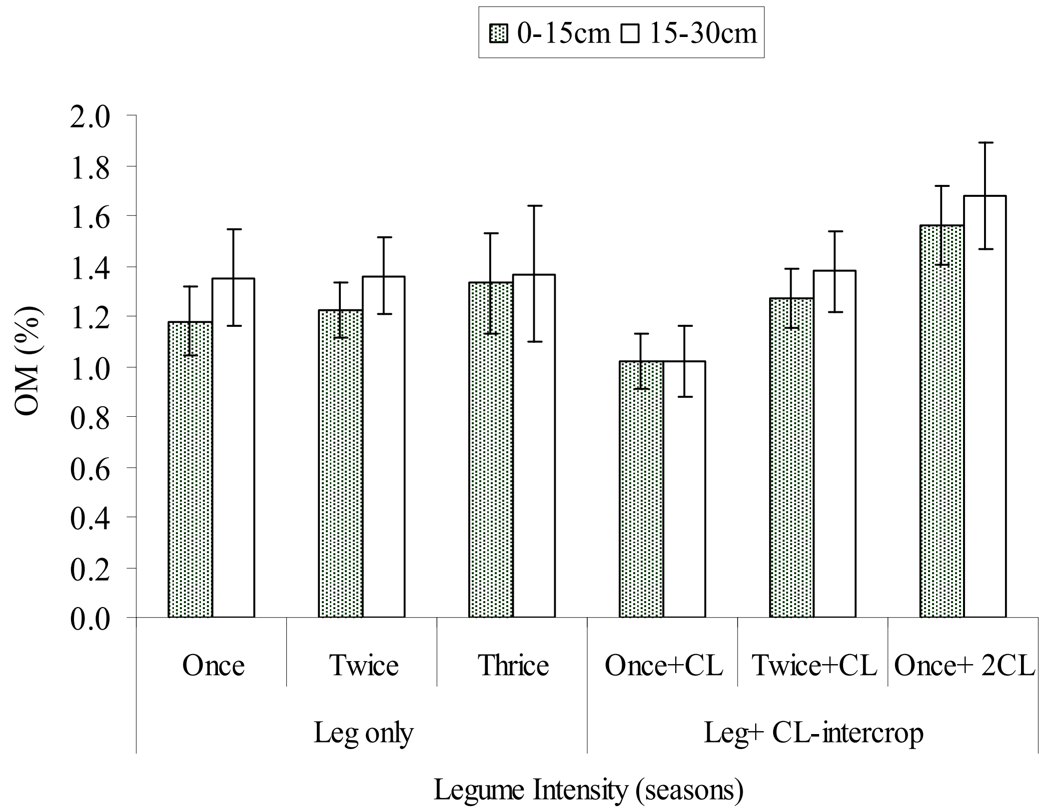

Fig 1.1: Soil organic matter on fields previously grown to legume cropping systems within three seasons, 0-15 cm and 15-30 cm soil depth

Leg only= sole or doubled up legumes; once= one season; once+CL= one season of legume only + 1 season of cereal + legume intercrop; Twice+CL= Two seasons of legumes only+ one season of cereal-legume intercrop; Once+2CL= one season of legumes only+ two seasons of cereal+ legume intercrop

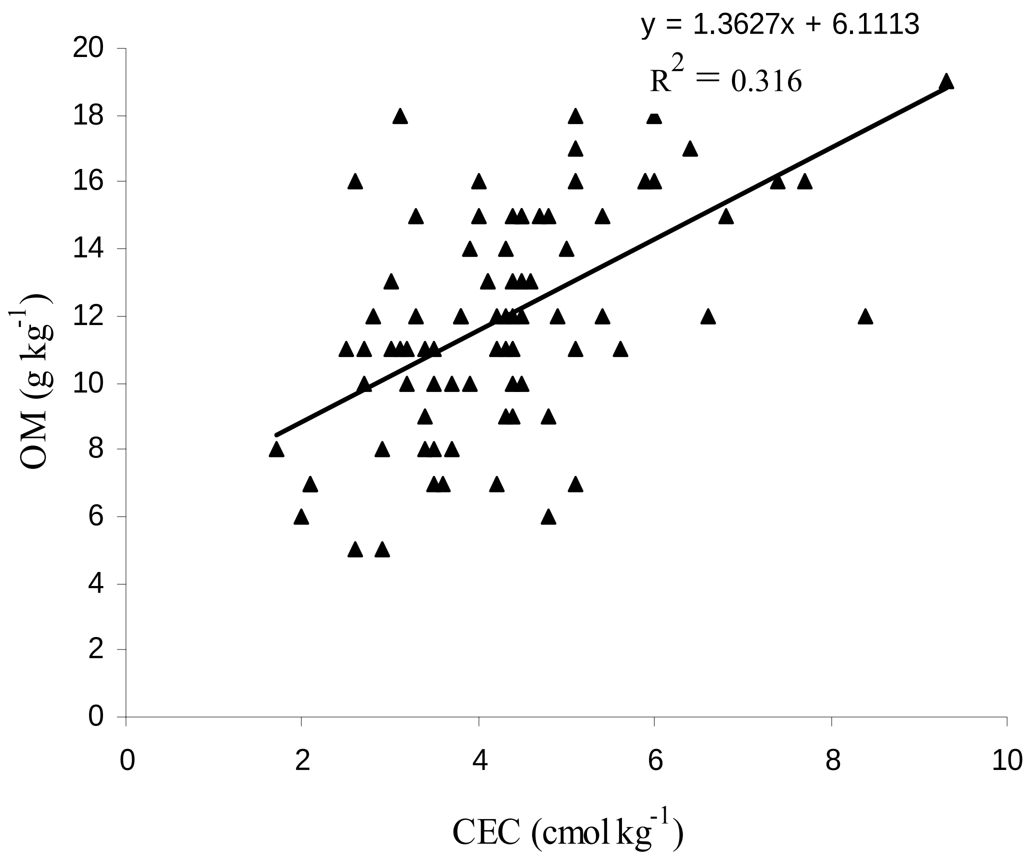

Fig 1.2: Relationship between soil organic matter (OM) as affected cation exchange capacity (CEC) across maize and legume diversified fields, 0-15 cm soil depth

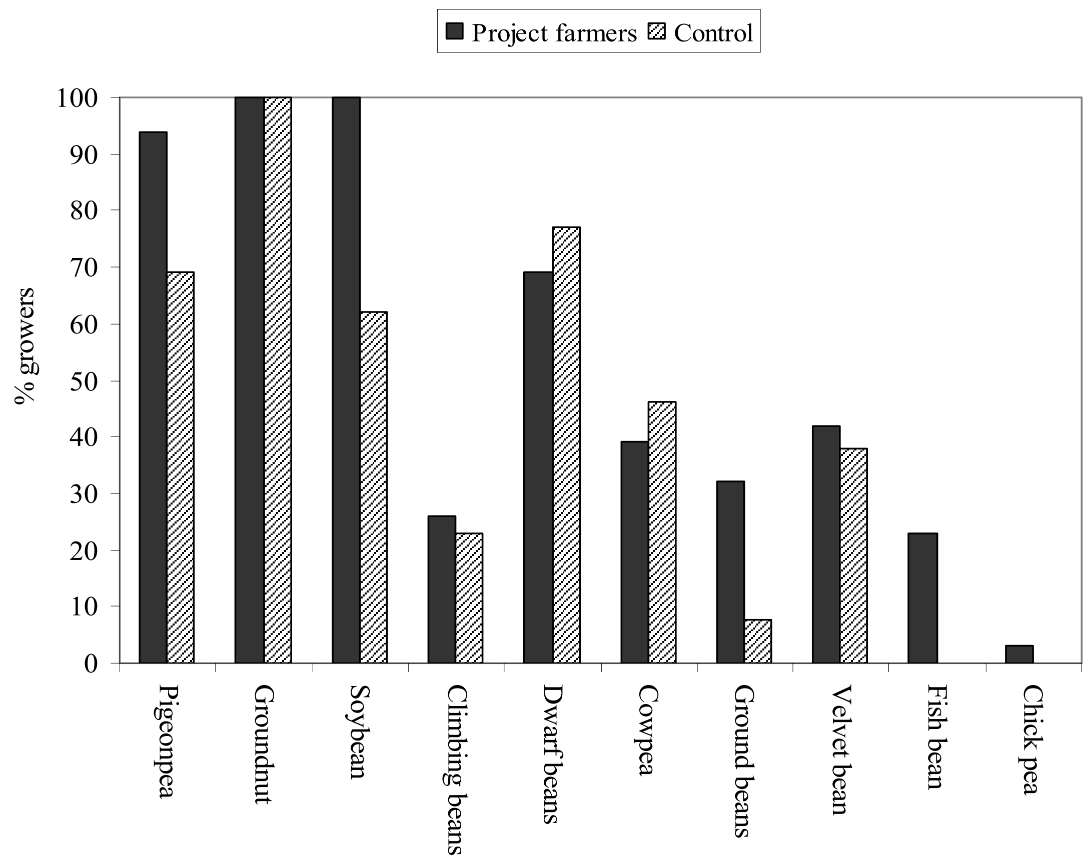

Fig 1.3: Number of farmers growing legumes in Ekwendeni

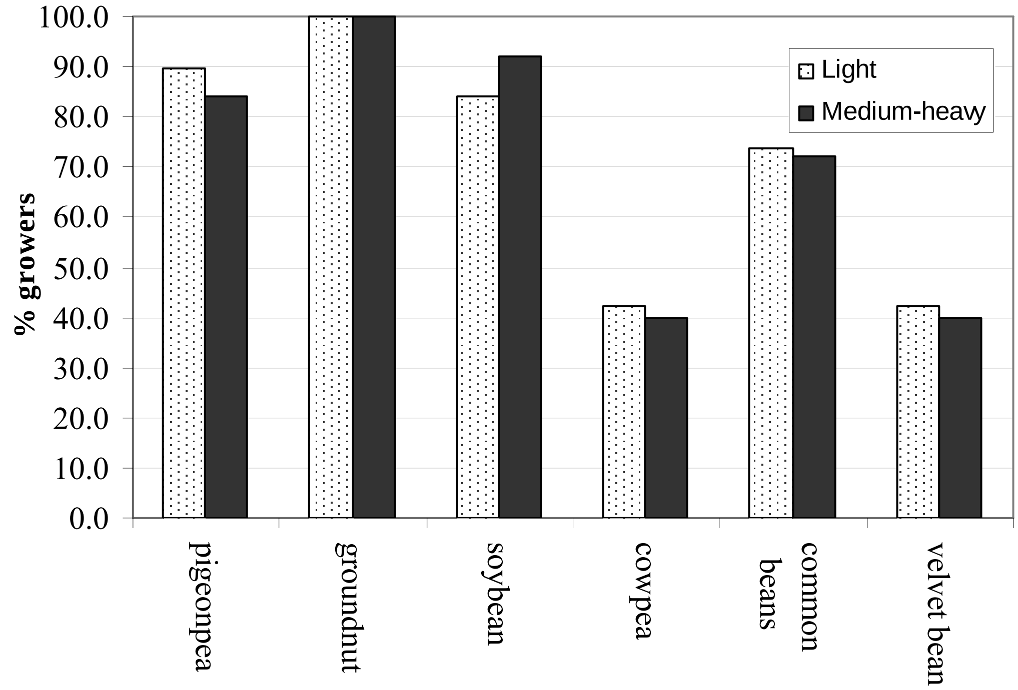

Fig 1.4: Legume crop production reported by farmers for specific fields, presented in relationship to the soil type as determined by texture analysis.

APPENDICES

Appendix 1.1: Household and Farm field survey questionnaire

Project title: Legume best bets to acquire phosphorus and nitrogen and improve family nutrition

Consent form was administered orally in the local language before administering the survey.

Household Survey Questionnaire

Interviewer's name: ______________________ Date: ____________
Household code number____ (number consecutively, 1, 2, 3)
Village: _________________

Respondent agrees to participate in the survey ☐Yes ☐ No

1. Name of respondent: ______________________________
   Gender: 1 = Male 2= Female
   Marital Status of Respondent: _____
   1= Married and living with spouse
   2= Married and heading household while spouse works or lives elsewhere
   3= Separated
   4= Widowed
   5= Single
   6= polygamous ..(indicate whether it is first or junior wife)_____________
   7=Other (specify)______________________

   Age: ______ Occupation:___________________
   Highest level of education achieved:________________

2. House status: (tick all that are observable, do not ask). ☐iron sheets ☐thatch roof
   ☐ burnt bricks ☐ unfired bricks

3. What are the sources of income for your household? *(tick all that apply and rank according to important source)*

1= crop produce sales	☐	2= ganyu	☐
3= pension money	☐	4= remittances	☐
5= firewood, etc. sales (or other natural resources,specify)	☐	6= manufactured goods sales (e.g., small shop)	☐
7= job ☐		8= other (specify)	☐ __________

4. What type of livestock do you have? (Tick all that apply). How many of each of them do you have?

1= cattle	☐	2= goats	☐	5 = swine	☐
3= poultry	☐	4=sheep	☐	6 =other (specify)	☐

5. Does your household have access to food from own maize stocks throughout the year? ☐ Yes ☐ No.
   If no, which month did you run out food last year, in 2006/07?___________________

6. We would like to better understand your farm layout and crops grown. Would you be willing to draw a simple map of your farm, indicating the main fields and what crops are grown there? This map is not complicated or a test. It is to help us discuss with you crops and soils on your farm, indicating on the map where they occur.

Legume field identification: Ask the farmer to identify on the map which field has had the most legumes grown in recent years. Discuss which were the recent crops grown in each field that appears to have a lot of legume. Once a field has been identified that has had the most diversified legume rotation (such as a groundnut pigeonpea intercrop, velvet bean, groundnut-soybean-pigeonpea or similar systems) this will be referred to in the interview as the 'legume field 1'. Label it on the map as legume field 1. (Enumerator: Be sure to clarify for all questions related to this field that questions about management and crop refer to this field specifically)

Maize field identification: Ask the farmer to identify on the map which field has had a lot of maize grown in recent years, and very little legumes. Try to avoid fields which had pigeonpea or velvet bean grown in the last 4 years. Discuss which were the recent crops grown in each field that appears to have a lot of maize. Once a field has been identified that has had very little legume (continuous maize would be best, but if that can not be found a field with a maize rotation with tobacco could be used). If possible, try to choose a maize field that meets the following criteria: NOT close to the house; NOT close to a dambo; and if possible a similar soil type (ask the farmer to determine this) to the legume field 1. Once the maize field is identified, this will be referred to in the interview as the 'maize field 2'. Label it on the map as maize field 2. (Enumerator: Be sure to clarify for all questions related to this field that questions about management and crop refer to this field specifically)

For each field on the map, indicate the total area or acreage

Farm size (crop field acreage):_____________acres

Field	Acres
Legume field- Field 1	
Maize field – Field 2	
Additional farm area not cropped	

7. Farmer assessment of soil fertility indicators and description of the fields being studied. There may be more than one soil fertility status for a given field; farmers often characterize different portions of a field with specific soil types so record all indicated.

Field	Farmer name for soil types present	Soil fertility level at field*	Describe indicators farmer used to determine soil fertility
Legume field 1			
Maize field 2			

*1=high fertility soil; 2= medium fertility soil; 3=low fertility soil and 4=exhausted soil

Draw farm map and identify main crops grown on each field. Indicate which field is considered primarily a maize field, which a legume diversified field (with introduced legumes such as pigeonpea, velvet bean and tephrosia).

8. We would like to learn about the crops grown in a field where you grow a lot of legumes:

Field	Season	Q. 8-1 Crops grown (Codes)	Q. 8-2 Cropping system 1=monocrop 2= intercrop low density 3=intercrop high density	Q. 8-3 Did you do anything to improve the soil? Yes □ No□ If yes, what did you do? (Use codes)	Q.8-4 Amount produced (if possible, specify No. of bags, oxcarts or pails….etc) If not, then rate for each crop	Q. 8-5 What did you do with residues from this plot (codes)
Legume field 1	This year 2006/07					
	Last year 2005/06					
	Year before last 2004/05					
	Next year 07/08 Plans					
Codes for crops: 1. Pigeonpea 2 = groundnuts 3= climbing beans 4= dwarf beans 5= ground beans 6= cowpea 7= soybean 8= mucuna 9= Tephrosia 10= cassava 11 = pumpkins 12 = sweet potatoes 13 = vegetables 14 = paprika 15 = sugarcane 16 = maize 17= tobacco 18 = millet 19= sorghum 20= fruits 21= Other (specify)				Codes for soil improvement practices (list as many as apply): 1= maize residues 2= p'pea res. 3 = mucuna res. 4= soybean res. 5= groundnut res. 6= tephrosia res. 7= Urea 8= 23:21 9= Can 10=manure 11= other (specify)	1= high yield 2= medium yield 3= poor yield 4 = very poor yield	Residue management codes: 1=Remove to feed animals 2= Incorporate early, April-Aug 3=Leave in field, Incorporate late 4=Burn for ash 5=Burn for land preparation 6= construction 7= fuel wood 8=Other (specify)

Note for Q8: enumerator should use the map the farmer has drawn to discuss the field.

9. We would like to learn about the crops grown in your field which has the most amount of maize:

Field	Season	Q. 9-1 Crops grown (Codes)	Q. 9-2 Cropping system 1=monocrop 2= intercrop low density 3=intercrop high density	Q. 9-3 Did you do anything to improve the soil? Yes □ No □ If yes, what did you do? (Use codes)	Q. 9-4 Amount produced (if possible, specify No. of bags, oxcarts or pails….etc) If not, then rate for each crop	Q. 9-5 What did you do with residues from this plot (codes)
Maize field 2	This year 2006/07					
	Last year 2005/06					
	Year before last 2004/05					
	Plans for Next year 07/08					
Codes for crops: 1. Pigeonpea 2 = groundnuts 3= climbing beans 4= dwarf beans 5= ground beans 6= cowpea 7= soybean 8= mucuna 9= Tephrosia 10= cassava 11 = pumpkins 12 = sweet potatoes 13 = vegetables 14 = paprika 15 = sugarcane 16 = maize 17= tobacco 18 = millet 19= sorghum 20= fruits 21= Other (specify				Codes for soil improvement practices (list as many as apply): 1= maize residues 2= p'pea res. 3 = mucuna res. 4= soybean res. 5= groundnut res. 6= tephrosia res. 7= Urea 8= 23:21 9= CAN 10=manure 11= other (specify)	1= high yield 2= medium yield 3= poor yield 4 = very poor yield	Residue management codes: 1=Remove to feed animals 2= Incorporate early, April-Aug 3=Leave in field, Incorporate late 4=Burn for ash 5=Burn for land preparation 6= construction 7= fuel wood 8=Other (specify)

Note for Q9: enumerator should use the map the farmer has drawn to discuss the field.

10. Among the legumes that you grow, we would like to know the reasons you grow these crops.

Name of legume	List the varieties grown in 2006/07	Was legume grown decades ago?	No. of years grown in last 4 years	No. 1 reason this legume is grown	No. 2 reason this legume is grown	No. 3 reason this legume is grown	How did you learn about this legume
Codes for crops: 1. Pigeonpea 2 = groundnuts 3= climbing beans 4= dwarf beans 5= ground beans 6= cowpea 7= soybean 8= mucuna 9= Tephrosia 10= Other (specify		Indicate Yes or No		1=porridge/child feeding 2=relish/food 3= market 4=soil fertility 5= livestock 6=medicine 7=weed control 8= fuel wood 9= other (specify)			1=Parents 2= Ancestors 2=Friends/neighbor 3=SFHC 4=Other (specify)

11. Are there legumes that you would like to grow but are not grown at the moment?
☐Yes ☐ No. If yes, answer the questions in the table below

Legume	Why wish to grow this legume?	Why can't you grow now?
Codes for legumes and mixtures: 1 = pigeonpea; 2 = groundnuts; 3= climbing beans; 4 = dwarf beans; 5 = ground beans; 6= cowpea; 7= soybean; 8= mucuna; 9 = Tephrosia ; 10=soybean+pigeonpea mixture 11= groundnut+pigeonpea mixture 12= Other (specify)		

12. Are there legumes that you used to grow but have now stopped?
☐Yes ☐ No. If yes, answer the questions in the table below

Legume or mixture (code above)	Why stopped
Codes for legumes and mixtures:	Codes for crops: 1. Pigeonpea; 2 = groundnuts; 3= climbing beans ; 4= dwarf beans; 5= ground beans; 6= cowpea; 7= soybean; 8= mucuna 9= Tephrosia; 10= soybean+ Pigeonpea; 11. Groundnuts+Pigeonpea mixture ; 12= Other (specify

- *Note: briefly explain some of the responses*

Codes for constraints/reasons why stopped growing:

1=Seed is not available	2= Seed poor quality (storage problems)
3=Seed too expensive	4= Insect pests
5=Lack of markets	6= Disease
7=High labor requirement	8= Labor conflict with other crops
9= Low yield	10=Lack of knowledge regarding crop

11= other (specify)____________________________

13. What traits in a legume would you like to see, if you could design an improved legume variety.

Legume (code)	Describe what traits you like about this legume variety Are there any characteristics you would like to change?
Codes for legumes and mixtures: 1. Pigeonpea 2 = groundnuts 3= climbing beans 4= dwarf beans 5= ground beans 6= cowpea 7= soybean 8= mucuna 9= Tephrosia 10=soybean+pigeonpea mixture 11 = groundnut+pigeonpea mixture 12= Other (specify)	

14. Have you heard about *Striga*/witchweed? □ Yes □ No.

a). Do you have *Striga* weed problems in your field: □ Yes □ No

if Yes,

Have you observed a difference in *Striga* weed populations between fields with maize and those with maize/legume intercrops or legume-maize rotations? □ Yes □ No

If Yes, what differences have you observed?

16. We would like to learn more about any agricultural experiments or practices you are trying out:

Describe experiment What was the source of the idea for this experiment?

17. Is there any information you would like to receive about legumes?
□ Yes □ No. If so, please describe:

18. We would like to learn about the people living and working in the household.

No. of children who are under 5 years of age?______
No. of children who are 12 year old or younger?______
No. of adults older than 12? _______
No. of adults (indicate whether male or female) working on the farm? _______ No. of part time ganyu? ____

19. Do you have any questions for us?

20. Soil sampling at two field sites. Go to the fields with the farmer and take a photo, then describe the site in terms of slope and nearby vegetation using the table below. Use the GPS to determine size and location.

Field site description:

Field	Field size	GPS coordinates	Describe nearby vegetation#	Slope of field*
Legume field 1				
Maize field 2				

1= some bush fallow, 2= maize fields, 3=other crops, 4= other (specify)
*Slope 1=flat, 2=moderately flat, 3=steep and 4=very steep

Table A1.1: Preferred and undesired characteristics of different types of food legumes among farmers

Legume characteristic	PP N=38	GN N=44	Soybean N=39	Common bean N=32	Cowpea N=18
Preferred characteristics					
Improve soil fertility	63[a]	16	21	16	0
High yield	37	68	33	34	33
High nutritional value	0	0	67	0	0
Adapted to varied soil types and rainfall	0	23	0	9	0
High oil content	0	20	0	0	0
Early maturing	21	14	3	16	6
Food – tasty relish/seasoning	18	14	0	19	33
Marketable	0	14	15	13	6
Resistant to field pests and/or diseases	11		0	16	6
Easy to store[a]	5	11	-	-	-
Drought resistant	3	-	-	-	-
Large seed size	3	7	5	6	0
Upright varieties to be intercropped	-	2	0	3	0
Undesirable characteristics					
Late maturing	37	5*	3	-	-
Susceptible to pests in field and/or storage	29	-	-	34	-
Low yield	11	2	8	6	-
Difficult to store, rots easily	-	9	-		-
Not good for seasoning vegetables	-	11	-		-
No market	-	-	3		-
Not edible as raw	-	-	3		-
Not adapted to low soil fertility and low rain	-	-	3	3	-

PP= pigeonpea; GN= groundnut; * Chalimbana variety

[a]value as a percentage for each legume (in a column) and within each category. Note that values do not add up to 100% because of multiple responses given by a farmer

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CHAPTER TWO

BIOLOGICAL NITROGEN FIXATION OF SOLE AND INTERCROPPED GROUNDNUT AND PIGEONPEA

ABSTRACT

Biological nitrogen fixation is one of the techniques that can help to improve soil nitrogen (N). Little is known about how legume crops fix N and grow under stressed smallholder farmer environment. Participatory on-farm trials were conducted in Ekwendeni, northern Malawi in 2007/08 (season 1) and 2008/09 (season 2) crop seasons to evaluate BNF by sole and intercropped groundnut and pigeonpea. We tested the hypothesis of whether N fixation rate will be enhanced by cereal-legume or legume-legume intercrops versus sole stands of either. The treatments included sole stands of groundnut, pigeonpea and maize; intercrops of groundnut-pigeonpea (doubled up legumes) and pigeonpea-maize. BNF was determined by natural abundance method. The experiments were researcher designed but managed by farmers.

Under low yield environments, sole groundnut and doubled up legumes produced more calories than the other cropping systems. In contrast, in high yield environments, sole cropped maize with fertilizer produced more calories than legume diversified maize cropping. Generally, by design, cropping systems were optimized for maize interms of row spacing and plant population and this has implications for groundnut and pigeonpea production. Soil fertility interms of inorganic P was higher on maize dominated fields than on maize fields.

Biomass production was not optimized in a season with inadequate rainfall and this may have negative implications for crop residue N accumulation and BNF. Cropping system had no effect on nodule numbers per plant for both legumes. There was no evidence of higher total BNF rate per area from doubled up legumes (legume-legume intercrop) compared to sole stands. On area

basis, sole groundnut fixed 63% more N than sole pigeonpea as expected in the dry year. Interspecific competition reduced BNF per plant in pigeonpea. Grain yield of pigeonpea and maize averaged 255 kg ha^{-1} and 784 kg ha^{-1} respectively and were not affected by cropping system. LERs were 1.56 and 1.50 for maize-pigeonpea and groundnut-pigeonpea intercrops indicating that intercropped species were more efficient at utilizing resources than sole stands.

2.1 INTRODUCTION

Nitrogen (N) is the most limiting nutrient in crop production because it is required in high quantities. The major sources of N in agro-ecosystems include use of inorganic fertilizers, livestock manures, compost manures, and biological nitrogen fixation (BNF). BNF involves a symbiotic association between legumes and specific bacteria (Giller, 2001). This is particularly important for small holder farmers as it is relatively cheaper compared to inorganic fertilizers, less prone to losses through leaching and denitrification. In Malawi and many countries in SSA, where maize is the staple food crop, use of legumes can help to boost grain yields while improving soil fertility. Legumes are grown in sole stands, intercrops with cereals or other legumes. The sole or intercropped legumes are usually part of a short term long term rotation system. The major legumes grown in Malawi are groundnut, common beans, soybean, pigeonpea, cowpea, green manures such as velvet bean, fish bean and a number of agroforestry species. A description of legume based cropping systems in Malawi, and design and cropping patterns for intercrops is included in Chapter 1.

2.1.1 Intercropping and plant density

Hauggaard-Nielsen et al., (2008) defined intercropping as the growing of two or more crop species on the same piece of land at the same time. Benefits from intercropping include increasing soil N, control of pests, efficient use of labor, land and other growth resources such as water, nutrients and light (Hauggaard-Nielsen et al., 2008; Gathumbi et al., 2002; Sakala et al., 2002). One of the key determinants to successful intercropping is to minimize competition for both above and below ground resources. Selection of component crops should consider complimentarity in pattern of using resources above and below ground with respect to timing, forms, and soil profiles (Szumigalski and Van Acker, 2008; Tobita et al., 1994). Kumar Rao et al., (1983) reported that yields of pigeonpea and sorghum were not reduced by intercropping.

Time and space are important to consider to minimize competition. When designing intercropping systems, critical analysis of maturity dates will influence choice of crop and time of planting. Crops with dissimilar maturity dates tend to differ on peak requirements for growth resources. For example, in pigeonpea/maize or pigeonpea/groundnut, pigeonpea flowers after the companion crop has reached physiological maturity. This minimizes competition for nutrients, water and light. Root depth and density affect below ground competition (Casper and Jackson, 1997). Crops with similar root systems tap nutrients and water from same zone and this will result into competition. Other things to consider in maximizing yields of component crops are spatial arrangement, plant architecture and density.

Plant populations in the intercrop depend on the compatibility of the component species and the main crop of interest to the farmer. Gathumbi et al., (2002) conducted a field study to evaluate resource use efficiency under sole and intercropped woody and non woody species. They observed that the relative proportion of plant population in mixtures was a critical factor influencing crop performance. A 50:50 ratio of woody and non woody crops resulted into competition for growth resources resulting in reduced biomass and N accumulation. In Malawi, maize is the staple food and as such farmers aim to maximize the population of maize in maize based intercropping systems. However, for maize-pigeonpea intercrops, same plant populations in sole and intercrops can be maintained because of the differences in plant growth rates and characteristics. The recommended plant population for each species in an intercrop is 37037 plants/ha (0.90 m x 0.90m x 3) (Malawi Government MOAIFS, 2005). Another way to design an intercrop system is by using replacement series, in which the total density of intercrop and sole stands is equal (Hauggaard-Nielsen, 2008).

2.1.2 *Role of legumes in cropping systems*

Legumes can fix N through symbiotic association with Rhizobia and thus do not require nitrogen fertilizer. Groundnut can fix 32-206 kg N ha^{-1} (Giller et al., 1987; Unkovinch and Pate, 2000; Werner, 2005). Pigeonpea can fix 69-100 kg N ha^{-1} (Kumar Rao et al., 1987; Werner, 2005). In addition to BNF, legumes can help to build soil OM and N through incorporation of crop residues. Crop residues from legumes have low C:N ratio (C:N<30) which decrease N immobilization and increase nutrient availability to subsequent crops in short term rotation systems. The high quality crop residues are a good source of food to soil organisms thereby increasing microbial activities.

The benefits of legumes on soil N and OM depends on the quality and quantity of biomass, and nitrogen harvest index (NHI). The quality of crop residues vary with legume species, soil nutrient levels, plant density, planting type and field management practices (Reddy et al., 2003). Pigeonpea shoots contain 0.8% N (Kumar Rao et al., 1983) and total N uptake was higher in sole stand (26 kg ha^{-1}) than intercrop (10 kg ha^{-1}). The amount of N added to the system is positively related to the tissue N content and amount of leafy biomass returned to the soil. NHI expresses the proportion on N that is exported from the field through harvestable products (Giller, 2001). Previous studies have shown that grain legumes with high NHI such as soybean and groundnut largely end up with low N inputs or net N removal from the cropping systems (Toomsan et al., 1995). Toomsan et al., (1995) reported that groundnut can fix 150-200 kg N ha^{-1} and a net N contribution of 13-100 kg ha^{-1} if crop residues are incorporated in the soils. They also found that high NHI in soybean resulted into net N removal of 37-46 kg N ha^{-1}. Egbe et al., (2007) reported a net N benefit of 0.93 to 26 kg N ha^{-1} for long-duration pigeonpea varieties.

2.1.3 *Factors that affect BNF*

Legumes have the capacity to improve soil nitrogen through BNF. The amount of N fixed through BNF is influenced by type of legume, crop duration, inorganic N, phosphorus, pH, environmental factors such as rainfall and temperature (Bordeleau and Provost, 1994; Zahran, 1999; Giller, 2001; Maskey et al., 2001; Tsvetkova and Georgiev, 2003; Corre-Hellou et al., 2006; and Edwards, 2006).

Type of legume: There is variation in amount of N fixed by legumes between legume species and variety. Groundnut can fix 32-206 kg N ha^{-1} (Giller et al., 1987; Unkovinch and Pate, 2000; Werner, 2005). Pigeonpea can fix 69-100 kg N ha^{-1} (Kumar Rao et al., 1987; Werner, 2005). The growth duration of a legume influence BNF. Generally, perennial or long duration legumes with indeterminate growth, for instance, long duration pigeonpea varieties have more time to fix N than annual or short duration species such as groundnut and soybean (Maskey et al., 2001). Intercropping climbing indeterminate legumes (e.g. common bean, siratro) with cereals had no effect on BNF but decreased N fixation in determinate soybean (Fujita et al., 1992).

The process of BNF starts with formation of nodules. There are specific legumes that require inoculation to enhance nodulation and increase crop yield. Inoculation is the addition of specific bacteria to legume seed before planting. However, groundnut and pigeonpea can nodulate with indigenous *Rhizobium* (Giller, 2001).

Under legume-cereal intercropping systems, BNF can be influenced by species, density of component crops and their competitive ability (Fujita et al., 1992). There is high potential for competition for light, food and water if component species have similar rooting patterns, growth rates and above ground architecture. Competition negatively affects plant growth as well as N fixed per unit area.

Inorganic N, P and pH: On low fertility soils, legumes require substantial amount of nutrients such N to boost seedling growth and P for root establishment before they can fix N and produce more biomass. There are critical levels of inorganic N required to boost legume growth and BNF (Fujita et al., 1992). On low N soils, application of small doses of N up to 25 kg ha^{-1} can help to increase BNF (Ofori et al., 1987; Fugita et al., 1992; Ghosh et al., 2006b). The responses to N can vary with legume type, for example, bambara groundnut does not respond to inorganic N fertilizer. However, positive yield and BNF responses to N rates of 20-50 kg N ha^{-1} have been reported in some varieties of soybean (Hardason et al., 1984; Gan et al., 2002). High levels of inorganic N reduce the proportion of N derived from the atmosphere and total BNF as this interferes with recognition and root infection processes, activity of nitrogenase, transfer of assimilates to the rhizobium and (Zahran, 1999; Giller, 2001). Bell et al., (1990) found that application of adequate levels of inorganic N reduced significantly reduced nodule numbers (almost zero nodules) and weight in pigeonpea, however in groundnut, application of inorganic fertilizer plus inoculation increased nodule number over the non-inoculated, and nodule size over the low N with inoculation. Depending on inorganic soil N status, legume-cereal intercropping may boost BNF due to depletion of available N by the cereal crop (Giller, 2001).

Phosphorus is important in BNF as it required for root development and synthesis of ATP, important for energy driven plant growth processes such as BNF. Phosphorus enhances N fixation rate in legumes by increasing shoot and root growth, nodule number and size (Tsvetkova and Georgiev, 2003; Jemo et al., 2006). Hoa et al., (2002) reported that P fertilizer was positively correlated with amount of N fixed by groundnut. Similar findings were reported by Jemo et al., (2006) in which P application increased N fixation, shoot biomass, and grain yield of the cowpea, soybean and subsequent maize. Edwards et al., (2006) found 119% increase in N fixation by white clover with addition of P.

Soil pH: Rhizobium species are sensitive to acidic soils (Graham and Vance, 2000) and have specific optimum temperatures ranges for activity. Bordeleau and Provost (1994) reported that low pH soils reduce N fixation due to the negative effects on availability of P, molybdenum, and Ca, essential for root development and N fixation. Levels of toxic elements like aluminium and manganese increase at low soil pH and this negatively affects the growth of legume and *Rhizobium.*

Soil moisture: Adequate soil moisture is necessary for survival of *Rhizobium*, nodulation process and growth of the legume (Fujita et al., 1992; Zahran, 1999; Giller, 2001). Too much or inadequate soil moisture negatively affects BNF. A study by Pimratch et al., (2008) found that in groundnut, N fixation can be reduced by 44-69% under severe drought stress conditions depending on variety. Similarly, waterlogged conditions are not conducive for root respiration and survival of bacteria.

2.1.3.1 Effect of cropping system on N fixation rate

The process of BNF is symbiotic and requires effective nodulation. The legume provide carbon to the *Rhizobium* while the later fixes N for the plant. Cereal-legume intercrops are very common and have been practiced for decades. Under these systems, cereals are better competitors and efficient at using soil N than legumes and this may stimulate the legume to fix more N (Giller, 2001). Corre-Hellou et al., (2006) found that in barley-pea intercropping systems, competition for N increased amount of N derived from N fixation by the pea. Similar results were reported for pigeonpea in which the proportion of N derived from the atmosphere (Ndfa) was higher under cereal-pigeonpea intercrops than pigeonpea-groundnut or pigeonpea-cowpea intercrop (Katayama et al., 1995). In this study, the focus is on BNF of cereal-legume and legume-legume combinations. The assumption is that under legume-legume intercrop, depending on legume combination, higher population per unit area and extension of N fixation period by the companion legume versus sole legume can increase the amount of nitrogen fixed per total area. For example, when groundnut is intercropped with long duration pigeonpea, both legumes will fix N during a certain period in their growth cycle. As a long duration crop, pigeonpea continues to fix N after groundnut has stopped fixing or been harvested. In addition, pigeonpea has lower nitrogen harvest index compared to groundnut and therefore larger proportion of fixed N is left in the soil. However, Katayama et al., (1995) observed that intercropping groundnut and pigeonpea reduced the proportion of Ndfa in groundnut but no effect on pigeonpea.

Studies on growth and yield of legumes, and economic benefits under legume-legume intercrops of soybean, groundnut or cowpea with pigeonpea and rotation effects on subsequent maize have been reported (Katayama et al., 1995; Snapp et al., 2002; Rao and Mathuva, 2000; Ghosh et al., 2006). Ghosh et al., (2006) found that intercrop of soybean-pigeonpea reduced number of pods and pod weight per plant by 22 and 18% in soybean; and 48 and 5% in pigeonpea. However, seed weight of pigeonpea was 9% higher from intercrop than sole stands.

Choice of legumes species and soil fertility management are key to minimize competition and optimize crop yields in an intercrop. According to Ghosh et al., (2006b), under low fertility soils, legume species with faster growth rate has more competing power for the available N and this can significantly reduce biomass of companion crop. They further observed that cropping systems with integrated nutrient management (NPK fertilizer + farm yard manure) yielded higher than the control or those with NPK fertilizer only. Intercropping soybean and pigeonpea was advantageous only under integrated soil nutrient management. Soybean was found to be strong competitor for N during the vegetative stage of pigeonpea and this led to a reduction in dry matter production in pigeonpea. This study evaluated BNF of groundnut and pigeonpea under sole, groundnut-pigeonpea intercrop and maize-pigeonpea intercrop systems.

2.1.4 Nutrient budgets in farming systems

A nutrient budget illustrates the nutrient flows into and out of a farming system (Watson and Atkinson, 1999; De Ridder et al., 2004). It helps to monitor soil fertility changes under different farming practices and environmental conditions. This knowledge helps to plan appropriate nutrient management practices in cropping systems and thus provide useful information to researchers, farmers and extension educators on which systems cycle nutrients better. In order to have a complete picture of nutrient budget of a particular farming system, it is recommended to include information about boundaries in both space and time, for instance, the soil depth, specify how many seasons or rotation systems.

2.1.4.1 Types of nutrient budgets

Watson et al., (2002) described three types of nutrient budgets including gate budgets, biological budgets and the system balance budgets. All calculations are made with an underlying assumption that nutrient input and output give the net nutrients in the system.

The gate budget is also known as an economic input: output budget, describes the flow of purchased inputs entering and leaving the system. This method does not include all uncontrollable inputs such as N fixation. This has been widely used in policy analysis but is not useful for detailed field nutrient budgets. The second method, the biological input:output budget, also known as surface budgets looks at difference between inputs and removal in crop uptake. This method also include determination of uncontrollable inputs such as nitrogen fixed through BNF but not the fate of the nutrient in the system e.g. nitrogen immobilization, mineralization, denitrification. Scholefield et al., (1991) estimated N mineralization in beef farming systems using the N cycle model. Biological budgets are widely used to determine crop nutrient requirement at field scale. Leaching losses and nutrient inputs such as atmospheric N can be estimated using existing literature. Berry et al., (2003) estimated atmospheric N and P deposition of 30-40 kg ha^{-1} yr^{-1} and 0.5 kg ha^{-1} yr^{-1} depending on proximity to whether the location is in a rural area or close to urban. Lastly, the system balance, also known as soil system balance or Transfer: recycle: input:output budget refer to detailed farm budgets. This system includes inputs, outputs, losses and nutrient transformations such as immobilization and mineralization. It helps to predict the internal cycling of N within farming systems. A study on N budgets by Watson and Atkinson (1999) reported that the systems balance approach accounts for more N inputs than the biological approach. More N was unaccounted for under grass-clover & fertilized systems in the economic input-output budget (17-285 kg ha^{-1} yr^{-1}), followed by biological approach (103-212 kg ha^{-1} yr^{-1}) and lastly systems budgets (79-188 kg ha^{-1} yr^{-1}). However, the authors also highlighted that both methods overestimated the unaccounted N leaching losses probably due to more N losses as NH_4 and any other soluble N in the organic matter. In this study, a simple input-output model was used to calculate N budget.

2.1.4.2 Determination of nitrogen budget

The input flows for N in maize-legume based cropping system include organic and mineral fertilizers, BNF and atmospheric deposition. The outflows include biomass taken away from field such as grain yield and woody stems, erosion, leaching and denitrification as shown in Fig. 2.1. Cropping systems that include food legumes such as groundnut, soybean, cowpea export more nitrogen from the field through the grain harvests as compared to cover crops where all biomass is incorporated in the soil (Giller, 2001). It has already been mentioned that soybean fix more N than groundnut. However, in soybeans, the high N harvest index (NHI) up to 0.88 results is net export of N (Toomsan et al., 1995). The yield potentials for pigeonpea and groundnut varieties used in this study are 1500 and 2500 kg ha^{-1} respectively. Pigeon pea can export 25% of fixed N in the grain, and still provide a net N contribution of 60 kg ha^{-1} in maize-pigeonpea intercropping systems provide (Myaka et al., 2006). The groundnut-pigeonpea intercrop was hypothesized to have higher N budgets because of low NHI in pigeonpea, larger amount of crop residues incorporated, and high N fixation rate per unit area as compared to sole stands of either or the maize+pigeonpea system.

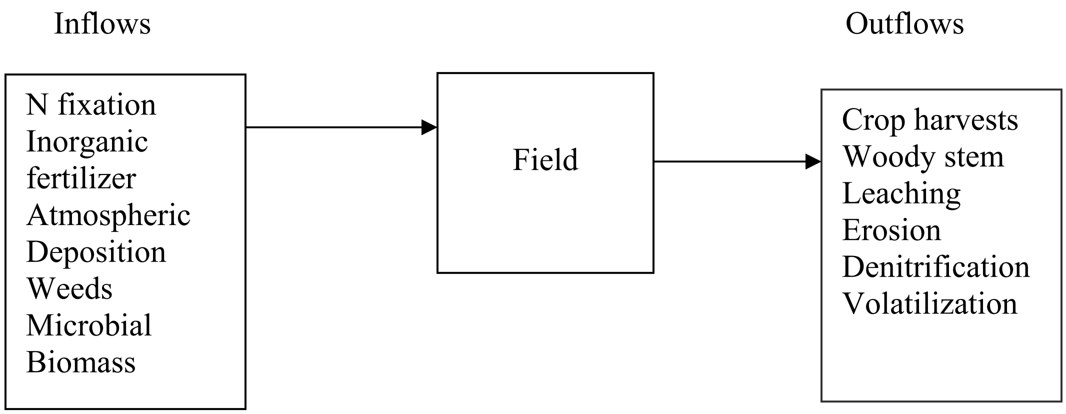

Fig 2.1: Conceptual diagram of nutrient flows of a legume based cropping system

2.1.5 Objectives

a) Evaluate how much N is fixed by pigeonpea and groundnut in sole stands and when pigeonpea is intercropped with either groundnut or maize.

b) Assess yield of sole and intercropped groundnut, pigeonpea and maize

c) Establish N budget for the two legume based cropping systems.

This study was carried under the following research hypothesis:

Objective 1: Evaluate how much N is fixed by pigeonpea and groundnut in sole stands and when pigeonpea is intercropped with either groundnut or maize.

The goal was to test if legumes had a higher N fixation rate when located next to cereals versus legumes intercropped with legumes.

a) Nitrogen fixation rate per area basis will be higher in groundnut+pigeonpea intercrop than pure stands of each or maize+pigeonpea intercrop.
b) Nitrogen fixation rate per legume basis will be higher from pigeonpea intercropped with maize than GNPP or pure stands of either.
c) Pigeonpea will fix more N than groundnut

Objective 2: Assess yield of sole and intercropped groundnut, pigeonpea and maize

a) The amount of N recycled through crop residues will be higher in doubled up groundnut and pigeonpea than sole stands of either.
b) An intercrop of groundnut-pigeonpea will recycle more N through leafy biomass than maize+pigeonpea system

Objective 3: Establish nitrogen budgets for the different legume based cropping systems.

a) Nitrogen balance of sole pigeonpea will be higher than sole groundnut
b) Nitrogen balance of doubled up legume system of groundnut+pigeonpea will be higher than that of maize+pigeonpea or sole stands of either

2.2 MATERIALS AND METHODS

2. 2.1 Site description

On-farm farmer managed trials were conducted in Ekwendeni area, of Mzimba District in northern Malawi in 2007/08 growing season. Mzimba district is under Mzuzu Agricultural Development Division. Ekwendeni is located at 33^{o} 53'E and 11^{o} 20'S. The average elevation is 1200m. The annual rainfall is within 800-1200 mm, with a unimodal distribution from

November/December to April/May. Most soils are sandy clays to sandy clay loams. Ekwendeni soils are classified as ferruginous latosols (Young and Brown, 1962).

2.2.2 Cropping history

Before establishment of trials, information on cropping history for the past three growing seasons was collected for each farm (Table 2.1). This included crops grown and soil fertility management practices. Maize and tobacco were intercropped with pumpkins and/or common beans at low density. About 35% of the fields had been under continuous maize systems in the previous three seasons, 30% maize-legume rotations, 15% tobacco-maize rotation systems and others 20%. Most farmers incorporated crop residues and inorganic fertilizer was applied to maize and tobacco

Table 2.1: Cropping history of experimental sites for the past three growing seasons since 2006/07

Farm	Crops grown past 3 growing seasons *2003/04– 2005/06 – 2006/07*	Soil fertility management
1	Tobacco – Maize – Maize	Fertilizer (UREA, CAN and 23:21:0+4S) applied to maize and tobacco. Maize stovers fed by cattle, remaining residues were burnt. Tobacco stems uprooted and burnt
2	Maize-Maize-Maize	Fertilizer and crop residues applied in 2004/05 and 2005/06 seasons
3	Maize-Sweet potato-Cassava + pigeonpea	No inorganic fertilizer. Some N fixed by pigeonpea.
4	Groundnut-groundnut groundnut	All crop residues incorporated
5	Maize-Maize- Maize	Fertilizer applied in 2006/07. Crop residues incorporated
6	Groundnut – Maize – Maize	Fertilizer applied to maize. Maize stover and groundnut residues incorporated
7	Fallow-Fallow- sweet potatoes	Natural ecosystem during fallow
8	Maize-Maize- Maize	Applied fertilizer (UREA and 23:21:0+4S) and crop residues
9	New field - soybean and beans	Residues incorporated.
10	Maize-Tobacco-Maize	Maize stover and tobacco stalks burnt. UREA and 23:21:0+4S applied to both crops in years 1 and 2
11	Maize - Cassava-Cassava	All maize residues incorporated.
12	Maize – Maize- Soybean	Soybean residues thrown on fields near home. Maize residues eaten by cattle.
13	Tobacco – Maize –Maize	Applied fertilizer (23:21:0+4S, UREA and CAN) and crop residues
14	New field - maize	UREA applied to maize. Maize stovers burnt, very few incorporated
15	Fallow – Tobacco – Maize	UREA, CAN and 23:21:0+4S fertilizer applied to maize and tobacco. Maize residues incorporated. Tobacco residues burnt
16	Fallow – Groundnut - Groundnut	Residues incorporated
17	Groundnut - Fallow-Sweet potatoes	Groundnut residues incorporated
18	Maize – Maize – Maize	Field under zero tillage. Herbicides applied to control weeds. All maize stover incorporated. 23:21:0+4S and UREA fertilizer applied to maize
19	Maize - Groundnut- Maize	Fertilizer applied to maize. Maize stover and groundnut haulms fed by livestock
20	Groundnut- Maize – ½ Groundnut, ½ maize	Fertilizer (UREA) applied to maize Part of groundnut residues incorporated, leftovers and maize stover are fed by cattle

Note: Pumpkins and/or common beans intercropped with maize and tobacco systems at low density

2.2.3 *Experiment description and data collection*

The experiment treatments are shown in Table 2.2. They consisted of six cropping system treatments, three sole crop systems, maize (*Zea mays)*, groundnut (*Arachis hypogaea)* and pigeonpea (*Cajanus cajan*); and three intercrop systems, maize-pigeonpea intercrop (MZPP) and two groundnut-pigeonpea intercrop (GNPP) systems. One of the groundnut-pigeonpea treatments was managed identical to the sole groundnut treatment with residues being incorporated directly after harvest and the other groundnut-pigeonpea treatment investigated a farmer practice in which pigeonpea was ratooned at harvest and the second year growth of pigeonpea was intercropped with maize in the subsequent season. Maize was grown as a sole crop in the second year for all treatments, except for treatment 6 which consisted of maize intercropped with pigeonpea (regrowth after ratooning of year one pigeonpea, see description in Table 2.2. The focus of this chapter is on year 1 of the cropping systems.

The varieties grown were CG7 groundnut, ICEAP 00040 pigeonpea and ZM621 maize. CG7 groundnut is characterized by bunch growth habit, high oil content averaging 48%, takes 4-5 months to mature and wide adaptation to varied soils (Malawi Government MoAIFS, 2006). The yield potential is 2500 kg ha^{-1}. Pigeonpea is a leguminous shrub that grows up to 2-4 m high (Werner, 2005). This legume has deep root system and initial growth rates are slower compared to groundnut or maize. ICEAP00040 is a long duration variety that takes 8-9 months to mature, and a yield potential of 1500 kg ha^{-1}. ZM621 maize is a recommended open pollinated variety that matures within 4-5 months with a flint type of grain, preferred by farmers (Malawi Government MoAIFS, 2006).

The experiment was laid out as a randomized complete block design with 6 treatments. Each treatment was replicated 20 times on farm, one replicate per farm. Treatment plot size was 10m by 10m, and consisted of 11 rows (aligned on a ridge following farmer practice in Malawi), each 10m long and spaced at 0.90m. The net plot used for measurements of grain and biomass consisted of the interior 8m of 7 centrally located ridges, to reduce border effects by not monitoring the external 1m of row . The goal for the planting pattern for intercrops was based on maximizing the plant population of the main crop for all cropping systems, as shown in Table 2.2. Plant population density followed recommended practice, seeding at a 0.20m and 0.90m within row spacing for groundnut and pigeonpea respectively to achieve 43,210 plants ha^{-1} (0.90x0.2x1) and 55,555 plants ha^{-1} (0.90x0.20x1) for intercropped and sole groundnut respectively, with an additional 37,000 plants ha^{-1} of maize or pigeonpea in the intercrop treatments. Maize and pigeonpea were seeded alternately in the intercrop, along rows in stations of three plants each, spaced at 0.45m intervals. The planting pattern for maize and pigeonpea was an additive design, sole crop and intercrop all planted at 37,000 plants ha^{-1} density for both crops. All plots received a uniform basal application of 10 kg N ha^{-1} at one week after planting based on observations that soils were highly N deficient, to improve uniformity of plant stands and early vigor while remaining consistent with the limited use of external inputs which can be afforded by smallholder farmers in Malawi (Snapp et al., 2002) . All field management practices were conducted by participating farmers.

In the 2008/09 crop season, year two was implemented by planting a maize crop sole cropped at a 37,000 plant ha^{-1} density after all treatments (Table 2.2), while year one treatments were replicated in time by planting adjacent plots. The varieties and planting pattern were the same as described for year 1.

Table 2.2: Treatments and Plant population

Treatment	Crop Year 1*	Cropping system	Planting Pattern	Plant population per hectare
1	Groundnut (GN)	Sole	1 seeds x 0.20m	55555
2	Pigeonpea (PP)	Sole	2 seeds x 0.60m	37000
3	GNPP	Intercrop	GN:1 seed x 0.20m in-between pigeonpea in the same row PP: 3 seeds x 0.90m	GN: 35210 PP: 37000
4	Maize (MZ)	Sole	3 seeds x 0.90m	37000
5	MZPP	Intercrop	MZ: 3 seeds x 0.90m PP: 3 seeds x 0.90m	MZ: 37000 PP: 37000
6	GNPP	Intercrop	Same as treatment 3. PP ratooned for year 2	Same as treatment 3

*Crop grown in year two is maize for all treatments, a sole maize crop in treatments 1-5 and an intercrop of maize-2nd year pigeonpea in treatment 6.

2.2.4 Soil sampling and analysis

At planting, composite soil samples (8-10 subsamples) were collected from each farm using a Z-scheme to ensure random collection. Two depths were sampled, 0-15cm and 15-30cm, for site characterization. These were air dried and sieved through a 2mm sieve. Soil texture was determined using the hydrometer method (Anderson and Ingram, 1991). Particulate organic matter (POM) were analyzed on ungrounded soil samples using a modification of the light-large particulate organic matter (POM) fractionation method described by Cambardella and Elliott (1993) and Cambardella and Elliot (1992). Soils were mechanically separated by shaking with 0.5 g L^{-1} sodium hexametaphosphate for 17 hours. After shaking, soils were sieved through a 53 micron sieve and washed with deionised water until effluent run clear. The fraction remaining on sieve was carefully transferred into canning glass jars with deionised water and dried in an oven at 60^0C for 48 hours. After oven drying, the samples were transferred into 50 ml plastic conical centrifuge tubes, and 35 ml of sodium polytungstate of density 1.85 g ml^{-1} was added. The sample was then centrifuged at 1200rpm for 30 minutes. Thereafter, POM plus sodium polytungstate was decanted onto a 20 micron nylon mesh connected to a vacuum filtration system. The POM remaining on the mesh was rinsed thoroughly with deionized water to remove all sodium polytungstate. The POM on mesh was transferred onto preweighed tin and dried for 24 hours at 60° C. Sodium polytungstate was recycled according to Six et al., (1999). After POM extraction and weighing, the sample was ground into powder with a clean mortar and pestle. POMC and POMN were determined using a dry combustion C and N Analyzer (Costech ECS 4010, Costech Analytical Technologies, Valencia, CA).

The remaining soil samples were ground and sent to A and L Great lakes Lab in Fort Wayne, Indiana for analysis of the following variables: pH in a 1:1 ratio in H_2O, OM (combustion method), inorganic P (Bray P), and Mehlich 3 extraction of Ca, K, Mg (Mehlich, 1984). Cation exchange capacity (CEC), and percent base calculation (BS) were calculated.

2.2.5 *Plant monitoring*

2.2.5.1 Plant nitrogen status: Chlorophyll readings were collected from all crops at 8 WAP using a Minolta SPAD 502 meter (Konica Minolta, Ramsey, New Jersey, USA). Readings were taken from the middle part of the leaf averaged across 30 leaves per treatment per replicate.

2.2.5.2 Assessment of nitrogen fixation by legumes

Nodulation efficiency: Destructive sampling of plants was done at about 50% flowering to assess nodulation of groundnut and pigeonpea. From each plot, three plants were uprooted. All soil was carefully removed from the roots. Roots that broke off with nodules were recovered. Nodules were stripped off from the roots. The total number of nodules per plant and nodule fresh weight was recorded. Thereafter, 10 nodules were dissected to check nodule color. Dry weight of nodules and plants was determined after oven drying samples for 48 hours at 75^0C.

Plant sampling for N fixation measurements: At harvest, destructive sampling of plants was done from two randomly selected $1m^2$ quadrants within the net plot of each treatment. Maize was used as the non-fixing reference plant in the natural abundance method. Previous research conducted on-farm in eastern Africa has used maize and weeds such as black jack *(Bidens pilosa*) as reference crops (Ojiem et al., 2006). Samples were collected from black jack weed as well but this species proved to mature too early in this Northern Malawi environment to provide a reliable plant and maize was used as the only reference species. The total fresh weight of legume and reference plants was measured in the field. Thereafter, plant samples were separated into roots, shoots, grain, shells and cores. The roots were triple washed with tap water and thereafter rinsed with distilled water to remove all dirt. Samples were oven dried for 48 hours at 75^0C or until no change in dry weights occurred, whereupon dry weights were obtained. Dried grain samples were ground into fine powder using a Wiley mill to pass a sieve size of 1mm, then carefully subsampled and weighed into capsules before ^{15}N and ^{14}N mass spectrophotometer analysis conducted at University of California Davis, USA.

Method to determine N fixation

The proportion of N fixed through BNF was determined using ^{15}N natural abundance method.

The amount of N derived from atmosphere was calculated according to Shearer and Khol (1986) and Peoples et al., (1989) as follows:

$$\%Ndfa = 100\frac{\left(\delta^{15}Nref - \delta^{15}Nlegume\right)}{\delta^{15}Nref - B}$$

Where $\delta^{15}N_{ref}$ is the ^{15}N natural abundance of grain of the reference plant (maize) grown on same soil as the legume; $\delta^{15}N_{legume}$ is the ^{15}N natural abundance of the grain of the legume crop; B is the $\delta^{15}N$ of the test legume where the only N source is atmospheric N. The lowest $\delta^{15}N$ for each legume were used as B values (Hansen and Vinther, 2001)

2.2.5.3 *Grain and stover yields*

Grain yield and biomass were determined from the net plot. Groundnut and maize were harvested in June 2008 whilst pigeonpea was harvested in September 2008 after full physiological maturity when vegetation was largely senescent. The total yield from the net plot was the summation of biomass from the quadrant samples and the rest of the net plot. Grain moisture was determined by wet weight basis of oven dried sub sample of grain. Grain yields were adjusted to 12.5%, 8% and 15% moisture content for maize, groundnut and pigeonpea respectively using the following formula: $\frac{BM1xY}{BM2}$, where Y=grain yield; BM1= is the dry matter of grain when yield was determined i.e. 100-determined moisture content; BM2 is dry matter of grain at standard moisture content, for example, in maize, this would be 100-12.5=87.5. Harvest indices (HI) and shelling percentage (SP) were calculated for each cropping system as follows:

$$\text{HI} = \frac{grainweight}{(grain + stover)weight} * 100$$

$$\text{SP} = \frac{grainweight}{(core + grain)weight} * 100$$

The biological efficiency of doubled up legume technology and maize+pigeonpea intercrop versus sole cropping was evaluated using the land equivalent ratio (LER) (Jolliffe, 1997). LER is the ratio of the area needed under sole cropping to that of intercropping at the same management level required to give same yield. LER is calculated as $\frac{InterYA}{SoleYA} + \frac{InterYB}{SoleYB}$, where YA and YB are yield of crop A and B respectively; interYA and intercYB=yield of crop A and B under intercropping, soleYA and soleYB= yield of crop A and B in sole stands. LER >1 indicate that intercropping is advantageous and the opposite is true for LER<1.

2.2.6 Management and determination of crop residue quality at harvest:

Plant samples for grain, leafy biomass, and big stems were analyzed for N content using $H_2SO_4^-$ Selenium acid digestion procedure (Anderson and Ingram, 1993). Plant samples were digested in selenium-euphoric acid mixture. Hydrogen peroxide was added to facilitate digestion process. Total N was read colorimetrically on a spectrophotometer at 650nm after addition of N1 and N2 solutions. N1 was a mixture of sodium (Na) salycylate, Na citrate, Na tartarate and Na nitroprusside. N2 was made of Na hydroxide and Na hypochlorite. The amount of N was converted to mass/area by multiplying nutrient concentration of tissues by dry weight of the plant tissue. This allowed estimation of residue N incorporated at end of the season. Immediately after harvest, all leafy biomass were spread evenly in the net plot and incorporated. For pigeonpea, all big stems were removed from the field following a farmer practice using stems for biofuel (Snapp et al., 2003). For the groundnut-pigeonpea intercrop, in treatment 5, both legumes species were uprooted, and all leafy biomass incorporated in the field at harvest. In treatment 6, all leafy biomass from the two legume species were incorporated, and pigeonpea was ratooned (branches cut) at 45cm above ground. The ratooned pigeonpea was intercropped with maize in the subsequent season

2.2.7 Calculation of nitrogen budgets

A simplified input:output model was used to establish N budgets for sole and intercropped groundnut and pigeonpea systems. The N balance was the difference between total N inflows and outflows. Variables included as N inflows were N from BNF, inorganic fertilizer, and estimated residue N input from previous season. The following equation was used to calculate a simplified form of N budget without taking into account the difficult to measure N pathways such as denitrification, erosion and leaching:

$$N\ budget\ (kg\ ha^{-1}) = [\{Inorganic\ fertilizer\ N + BNF\}\ kg\ ha^{-1}] - [\{grain\ N + woody\ stem\ N + shells\ N + cores\ N\}\ kg\ ha^{-1}]$$

2.2.8 Data analysis: All response variables on soil nutrient and plant analysis, biomass yield were analyzed as a RCBD using SAS Proc mixed procedure (SAS Institute, 2001). Where variances were not homogenous, data were analyzed with unequal variances assumption in proc mixed procedure. The residuals were checked for normality using normal probability plots. For initial soil characterization, the probability plots showed that pH, total N, total P, Ca, CEC, sand and clay content were approximately normally distributed. However, outliers were observed on inorganic P, Mg, K, and silt content data. Outliers were deleted and this solved the normality problem.

Data on number of nodules were log transformed to stabilize variances. The Akaike Information Criterion (AIC) value for log transformed data was smaller (groundnut= 35.4; pigeonpea=118.6) than untransformed data (groundnut= 348; pigeonpea=380.2).

Multiple regression analysis was conducted to assess if there was a relationship between soil organic matter and soil chemical properties. Multicollinearity was checked using variance inflation factors (VIF) and correlation procedures. CEC and Ca were highly correlated ($P<0.0001$, correlation coefficient=0.95). Calcium was deleted from the model before running the analysis. VIF values ranged from 1.93 to 3.33 for all seven soil variables except sand (VIF=11.24) and clay (VIF=12.28). Either sand or clay was excluded from the model. Model selection was based on step wise regression procedures. All data were analyzed in SAS Proc mixed program. Significant differences were determined at p=0.05.

2.2.9 Adaptability analysis: Adaptability analysis is a method that helps to evaluate performance and adaptation of crop species to specific environments (Hilderbrand and Russell, 1996). The environment includes both socioeconomic and biophysical factors that influence crop productivity. Adaptability analysis was conducted to evaluate performance of diversified legume cropping systems and maize under different environments according to Hilderbrand and Russell (1996). To compare systems that produced grain from different species and thus different quality of grain, grain yield was converted to calories yield for each treatment using the following formulas, derived from similar studies conducted of the same crop species in southern Africa (Gilbert, 2004): Groundnut, 5.79/1000*grain yield; Pigeonpea, 3.38/1000*grain yield; and maize, 3.63/1000*grain yield

Calories for intercrops were summed up before calculating the EI. Then an environmental index (EI) was calculated based on calories where average calorie at site was used as an estimate of the yield potential (environmental index) of the site, and the calorie per treatment was regressed on the EI (Hilderbrand and Russell, 1996). Simple linear regression was done on calories as a dependent variable on environmental index.

2.3 RESULTS

2.3.1 Rainfall and environmental conditions

In the 2007/08 season (October/November 2007 to March 2008), rainfall was considerably below average at 669mm (Fig 2.2). This was much less than 800-1200mm, the expected range for this agroecological zone. Precipitation was high (~45-50% of total) between last half of December 2007 to end of January which caused sheet erosion on some farm sites depending on the slope of the field, and could well have resulted in leaching of nutrients (personal observation). This might have resulted into leaching of some nutrients. Another concern was poor seedling development at some sites possibly due to saturated soil. From the second half of February 2008, the area experienced a dry spell and this coincided with grain and pod filling growth stages in maize and groundnut respectively. Pigeonpea was still at a vegetative stage. Scattered rain showers fell in March 2008 but this was not adequate to support optimum growth of the crops.

In the 2008/2009 season (November 2008-April 2009), the area received 826mm of rainfall (Fig 2.2) and this was adequate for growth of legumes and maize.

2.3.2 Soil characterization

Table 2.3 show results regarding the soil chemical characteristics and texture. Soils properties were highly variable between farms, at both depths monitored. Soil pH ranged from 5.5-6.5 at 0-15cm depth with a mean= 5.9±0.3. The soils are predominantly sandy loams to sandy clay loams with 18±7.7, 74±9.8, and 8±4.4 percent clay, sand and silt respectively.

A majority of soils are characterized by low OM ranging from 12±3.5 g kg^{-1} at 0-15 cm depth to 12±5.1g kg^{-1} in the 15-30 cm soil layer. POMC formed about 2-27% of POM with a mean of

11±7.3% in the 0-15cm, and 0.4-18%, mean of 5±4.8% at 15-30cm depth (Fig 2.3). The amount of total N averaged 0.69±0.3 g kg^{-1} to 0.62±0.2 g kg^{-1} in the lower and top soil layers respectively. Within the POM fraction, the proportion of N was 0.36±0.22%, equivalent to 0.02±0.001 g N kg^{-1} of POM. POMN was found to be lower at 15-30cm (0.01±0.002 g kg^{-1}) compared to top soil layer. The C:N ratio in POM was three times higher than the whole soil (28 vs 10).

Inorganic Bray P varied from very low to high (1-85mg kg^{-1}, mean = 16±20.4 mg kg^{-1} at 0-15cm depth; 1-66 mg kg^{-1}, mean = 11±17.5 mg kg^{-1} at 15-30cm depth). Ca, Mg and K are adequate to support growth of most crops. The exchangeable bases (Ca, Mg and K) occupy 65-70% of the exchange sites. The remaining 25-30% of the exchange sites is occupied by H^{+}.

In the top 0-15cm soil layer, results from multiple regression analysis of OM as a function of CEC, P, N, Mg, K and texture showed that only CEC was significant when all variables were included in the model, R^2 =0.60. Based on step wise regression, the best fitted model included CEC and sand content, and the model was significant at p=0.0103 (Table 2.5). R^2 value was equal to 0.42, that is, CEC and sand explained 42% of the variation in OM. CEC was the major variable accounting for 31% of the variation. The relationship between OM (g kg^{-1}) as a dependant variable on CEC (cmol kg^{-1}) and sand (%) was explained by the following fitted equation:

$$OM = 16.17 + 0.98CEC - 0.12sand$$

The intercept was significantly different from zero and the standard error estimates for parameters are shown in Table 2.5. However, the linear relationships between OM and either sand or clay were significant when all other variables were excluded from the model. OM levels were negatively and positively related to amount of sand (p=0.028, *r* = -0.49) and clay (p=0.024, *r*=0.502) respectively (Table 2.4; Figs 2.4 and 2.5).

Linear regression between OM as a dependent variable and sand as the explanatory variable showed that the model was significant at p=0.0336 and the R-square was equal to 0.24, that is, sand content explained 24% of the variation in soil with a correlation coefficient. The relationship between OM and sand was described by the following fitted regression model: $OM\ (g\ kg^{-1}) = 20.73 - 0.127 sand(\%)$. The root MSE was equal to 2.30. The standard errors for parameter estimates were equal to 4.13 and 0.055 for intercept and slope respectively.

There was a positive linear relationship between OM and clay content (p=0.029) and R^2 = 0.2508, that is, amount of clay accounted for 25% of the variation in OM. The relationship between OM (g kg^{-1}) and clay content (%) was described by the following fitted regression model: $OM = 8.51 - 0.156 clay$. The standard errors for parameter estimates were equal to 1.27 and 0.065 for intercept and slope respectively. The root MSE was equal to 2.28.

2.3.3 Plant dry weight and chlorophyll at 8.5 weeks after planting, 2007/08 season

Cropping system had no effect on plant weight of either sole and intercropped groundnut or pigeonpea at 8.5 weeks after planting (Table 2.6). This may imply that there was no interspecific competition between the two legumes or maize and pigeonpea under intercropping. The mean dry weights per plant at 8.5 WAP were 17g and 9g for groundnut and pigeonpea respectively.

Chlorophyll ranged from 37 in maize to 47 in sole pigeonpea. There were significant differences in chlorophyll content between the crop species, $p<0.0001$. For each crop species, cropping systems had no effect on chlorophyll (Fig 2.6). Between species, sole pigeonpea had significantly higher chlorophyll (47±3.2) than sole (44±2.7) and intercropped groundnut (44±1.7). The two legumes had 24% more chlorophyll than maize.

2.3.4 Biomass production from sole and intercropped groundnut, pigeonpea and maize

2.3.4.1 Grain and stover yield of groundnut

In 2007/08 season, the average grain yields for sole and intercropped groundnut were 598 and 435 kg ha^{-1} respectively in 2007/08 season; and 1101 kg ha^{-1} (sole) and 650 kg ha^{-1} in 2008/09 season. The interaction of cropping system and season were significant, $p=0.0026$ (Table 2.7). Sole groundnut yielded 37% and 69% higher in season 1 and 2 than the intercrop system. Grain yield from sole stand were 84% and 50% higher in 2008/09 than 2007/08 season.

The LERs for the GNPP was equal to 1.50-1.53 indicating complementarities in the intercrop system (Table 2.7). Based on LER values, total productivity was 52% higher under intercropping than sole stands, that is, 52% more land would be required in sole stands to produce same yields as in intercropping.

The yield of haulms (leafy biomass) of groundnut varied with season and cropping system ($p<0001$) (Table 2.7). Sole groundnut produced more haulms (2.5 t ha^{-1}) compared to intercropped groundnut (1.7 ton ha^{-1}). Across seasons, the quantity of haulms in 2008/09 was 89% more than 2007/08 season.

There were no significant differences in harvest index (HI), seed size and shelling percent between the cropping systems (Table 2.8). The mean HI was equal to 0.25. The average 100 seed weight and shelling percent were 0.25, 62 g and 66% respectively. However, seed size and shelling percent varied with season. The 100 seed weight in 2007/08 was bigger (68 g) than 2008/09 season (56 g). Shelling percent was 62% in 2007/08 and 72% in 2008/09.

2.3.4.2 Does cropping system influence grain yield of groundnut on plant basis?

Cropping system by season interaction was significant on yield per plant, p=0.014 (Table 2.8). In 2007/08 season, the average grain yield per plant was 14 g. However, sole groundnut produced more grain per plant than when intercropped (26 g vs 20 g). This was 84% and 37% higher than yield of sole and intercropped groundnut in season 1.

In 2007/08 season, results from analysis of covariance with plant population as a covariate showed no difference in grain yield of sole and intercropped groundnut, and plant population was significant (p=0.0161) (Table A2.1). The mean grain yields at 37849 plants ha^{-1} were 523 and 481 kg ha^{-1} for sole and intercropped groundnut. The slopes for the relationship between grain yield from the two cropping systems and plant density were not different (Fig 2.7). Therefore, one slope was used for all yield-plant density relationships as follows:

Yield (kg ha^{-1}) = 108 +0.01*plant population ha^{-1}*, for sole groundnut.

Yield (kg ha^{-1}) = 66 +0.01*plant population ha^{-1}*, for groundnut intercropped with pigeonpea.

Analysis of covariance on leafy biomass (haulms) with plant density as a covariate indicated a trend of higher biomass from sole stand than intercropped groundnut, p=0.099. The average yield at 36247 plants ha^{-1} was 1700 and 1355 kg ha^{-1} for sole and intercropped groundnut respectively (Fig A2.1).

2.3.4.3 Grain and biomass of pigeonpea

Effect of season and cropping systems on pigeonpea biomass: The effects of season and cropping system were not significant on grain yield of pigeonpea (Table 2.9). The grand mean was equal to 284 kg ha^{-1}. Total biomass varied with cropping systems ($p<0.0001$) and season ($p=0.03$). Sole pigeonpea produced 100% more biomass than intercrop system (4 ton ha^{-1} vs 2 ton ha^{-1}). Comparing season effects, biomass was 37% higher in 2008/09 than 2007/08 season (3333 vs 2426 kg ha^{-1})

Cropping system and season had no effect on grain yield per plant and shelling percent. The average yield per plant and shelling percent were 12g and 42% (Table 2.10). The seed size was found to be 16% bigger in 2008/09 than 2007/08 season, with a 100 seed weight of 22g and 19g for the two seasons.

Pigeonpea biomass under sole, legume-legume and cereal-legume intercrop, 2007/08 season: In 2007/08 season, pigeonpea grain yields were very low averaging 0.3 ton ha^{-1} (Table A2.2). Cropping system had no effect on grain yield. Sole pigeonpea and pigeonpea intercropped with groundnut yielded 32-36% more than pigeonpea intercropped with maize but this was not statistically different. Cropping system had no effect seed size and shelling percent. The average 100 seed weight was 19g. MZPP system was advantageous over sole cropping, LER = 1.56.

The total leafy biomass and woody stems averaged 1.5 ton ha^{-1} for pigeonpea intercropped with groundnut to 3.1 ton ha^{-1} under sole stands (Table A2.2). Out of this, 51% and 60% were of leafy biomass for intercropped and sole pigeonpea respectively. The remaining proportion was of woody biomass and these were not incorporated after grain was harvested. Cropping system had significant effect on total biomass production, $p<0.0001$. Sole pigeonpea accumulated 85 and 140% more leafy biomass than pigeonpea intercropped with maize and groundnut respectively. A comparison of leafy biomass between the intercrop systems with plant density as a covariate indicated that treatments were significant ($p=0.029$), and a trend on number of plants ($p=0.046$). Pigeonpea intercropped with maize accumulated 20-30% more leafy biomass than when intercropped with groundnut at pigeonpea density of 16000-37000 plants per hectare ($p=0.0293$) (Fig 2.8).

Pigeonpea biomass after ratoon practice, 2008/09 season: Total pigeonpea biomass ranged from 2332 to 5233 kg ha^{-1}. Analysis of covariance with plant density as covariate showed significant differences in total biomass produced from pigeonpea established from seed or ratooning practice, $p=0.0059$. Ratooning pigeonpea increased vegetative biomass of pigeonpea by 107-124% over a one season of pigeonpea established from seed, $p=0.006$ for (Fig 2.9, Table A2.3).

2.3.4.4 Grain and stover yield of sole and intercropped maize

Maize grain yield in sole and intercrop systems averaged 874 and 694 kg ha^{-1} respectively (Table A2.4). These values are within the expected range under smallholder management with no fertilizer inputs. Cropping system had no effect on the grain yield of maize. There were no differences in stover yield under sole and intercropped maize. The mean values were 1590 kg ha^{-1} in sole stands and 1701 kg ha^{-1} for intercropped maize. Intercropping maize with pigeonpea was advantageous as evidenced by LERs of 1.56 implying that total productivity was 56% higher intercropping than sole stands of either.

2.3.5 Nitrogen accumulation in grain, leafy biomass and big stems at harvest

Plant N characteristics are shown in Tables A2.5, A2.6 and A2.7. All crop species had higher N concentration in grain than other in leafy biomass or woody stems averaging 1.2%, 3.7% and 3.3% in maize, groundnut and pigeonpea respectively. Intercropped groundnut had significantly lower N in haulms N (1.3%) compared to sole groundnut (1.6%) ($p=0.0029$). In pigeonpea, N% in leafy biomass varied with cropping system, $p=0.028$. Pigeonpea intercropped with maize had higher N concentration than sole or pigeonpea intercropped with groundnut. The opposite was observed in grain and woody stems of pigeonpea where pigeonpea intercropped with maize had lower N than the other two pigeonpea systems. However, cropping systems had no effect on N content of shells and cores, groundnut grain, and maize stover.

Total crop N at harvest by cropping system was variable between farms. Sole groundnut accumulated largest amount of N ranging from 25-124 kg N ha^{-1}, mean=57 kg N ha^{-1}, and the least was under sole maize, 5-32 kg N ha^{-1}, mean=16 kg N ha^{-1} (Table A2.6). Doubled up legumes accumulated more N than sole pigeonpea ($p=0.0012$) but similar to sole groundnut. Total crop N was 43% higher under sole groundnut than sole pigeonpea, $p=0.0018$. The GNPP accumulated more N than MZPP system, $p<0.0001$ (55 vs 30 kg N ha^{-1})

The highest leafy biomass N were observed from sole groundnut (33 kg N ha^{-1}), followed by groundnut-pigeonpea intercrop (26 kg N ha^{-1}) and sole pigeonpea (25 kg N ha^{-1}). Stover N inputs from maize were very low.

Does doubled up legume increase crop residue N over sole legumes? There was no evidence of doubled up legumes accumulating more N in crop residues than sole groundnut and pigeonpea (Fig 2.10). However, a trend of higher N accumulation in groundnut than pigeonpea stover was observed, $p=0.067$.

A comparison of the two intercrop systems indicated that GNPP recycled more N through leafy biomass than the traditional MZPP intercrop ($p=0.0010$) (Fig 2.11).

Effect of legumes on N cycling in cropping systems: Planned contrasts on N accumulation in leafy biomass of legume cropping systems versus sole maize showed that sole groundnut and pigeonpea accumulated 8 times more N than sole maize, $p<0.0001$ (Fig 2.12). Similarly, intercropping maize with pigeonpea increased leafy biomass N by 320% over sole maize, $p=0.0035$

Nitrogen harvest index (NHI) ranged from 0.13 in sole pigeonpea to 0.78 under MZPP (Table A2.6). Despite having low stover N, sole and intercropped maize had the highest NHI (0.52-0.78), seconded by GNPP (0.65) and sole groundnut (0.42). Pigeonpea had significantly lower NHI than doubled up legumes ($p<0.0001$) and the rest of the cropping systems. Similarly, NHI was higher for doubled up legumes compared to sole groundnut ($p<0.001$). A comparison of the two intercrop systems showed a trend of higher NHI under MZPP than GNPP, $p=0.0637$.

2.3.6 Biological nitrogen fixation of sole and intercropped legumes

2.3.6.1 Nodule number per plant of sole and intercropped groundnut and pigeonpea

Table 2.11 show results on nodule number per plant and nodule weight. Results on nodule number are based on log transformed values. Cropping system had no effect on nodule numbers per plant of both legumes at 8 WAP. The main effects of season were significant on nodule number in groundnut and pigeonpea, $p<0.05$. Surprisingly, groundnut formed more nodules in 2007/08 season than season 2 ($p=0.0002$) (Table 2.11). The mean nodule number per plant in groundnut for transformed data was equal to 4±0.4 and 91±8 for untransformed data.

Pigeonpea formed more nodules in 2008/09 and 2007/08 season ($p=0.022$) (Table 2.11) to support nodule formation. The mean number of nodules per plant was 2±0.1 (10±1.4 for untransformed values). When pigeonpea had reached flowering stage (approximately 20 WAP), the number of nodules per plant were lower (5±0.83) compared to 10±1.4, the mean at 8 WAP. The number of nodules per plant were 136% more for groundnut than pigeonpea, $p=<0.0001$. However, pigeonpea nodules were bigger (9 mg) than of groundnut (2 mg), $p=<0.0001$).

2.3.6.2 Nodule weight of sole and intercropped groundnut and pigeonpea

The higher number of nodules from groundnut in 2007/08 season than season 2 did not translate to bigger nodules (Table 2.11). The nodules were 58% bigger in 2008/09 season than season 1 ($p=0.0044$). Intercropping reduced nodule size in groundnut by 29% (1.9 vs 1.5 mg).

Season and cropping system had no effect on nodule size pigeonpea. The mean nodule weight ranged from 9mg in sole pigeonpea to 10mg for pigeonpea intercropped with maize respectively (Fig 2.13).

2.3.6.2 Nitrogen fixation rate by sole and intercropped groundnut and pigeonpea, 2007/08 season

Effect of sole and intercropping on N fixed per unit area: Table 2.12 show results on proportion of N derived from atmosphere (%Ndfa), N fixed per unit area or plant basis, and cropping system. In groundnut, the %Ndfa ranged from 57-99% with an overall mean of 78%. There was no significant difference in %Ndfa between sole and intercropped groundnut. Under sole cropping, the %Ndfa was positively correlated with plant density (r=0.65), POM (r=0.68), crop N (r=0.98) and P (r=0.59) (Table 2.13) (Fig 2.14). The proportion of N derived from the atmosphere (%Ndfa) was positively related to plant density (r=0.75). No significant linear relationship observed between N fixed per area and inorganic P or density when groundnut was intercropped with pigeonpea. Sole groundnut fixed 76% more N than when intercropped (29±7.3 kg ha^{-1}), p= 0.0177.

In pigeonpea, the %Ndfa ranged from 41 to 99%, mean =76±20 (Table 2.12). This did not differ between sole and intercropped pigeonpea. Bray P and %Ndfa were positively correlated with N fixation, r=0.78 and 0.73, respectively in sole pigeonpea; and r=0.857 and 0.68 in pigeonpea intercropped with maize (Table 2.14). Total N fixed per area ranged from 4-27, mean=13 kg ha^{-1} under maize+pigeonpea intercrop to 32 ± 16.0 kg ha^{-1} in sole pigeonpea.

Do cropping systems influence total N fixed per unit area?: Total N fixed ranged from 22-102 kg ha^{-1} in sole groundnut; 29-68 kg ha^{-1} in GNPP, 11-64 kg ha^{-1} in sole pigeonpea, and 6-25 kg ha^{-1} for pigeonpea intercropped with maize. Cropping systems effects were significant on N fixed per unit area, p=<0.0002. Doubled up legumes fixed more N per unit area compared to the traditional maize-pigeonpea intercrop (42±12.3 vs 12±6.11 kg ha^{-1}), p=0.0005 (Table 2.12). Contrary to the hypothesis, there was no evidence of higher N fixation rate per area basis under doubled up legumes compared to sole stands of either groundnut or pigeonpea. Significant differences were observed on sole cropped legumes in which groundnut fixed more N per unit area than pigeonpea (p=0.015).

Do cropping systems influence N fixed per plant basis: Total N fixed on a per plant basis ranged from 160 to 1200 mg in sole groundnut and 300-2170 mg in groundnut intercropped with pigeonpea. Sole groundnut fixed 25% more N per plant than intercropped groundnut but this was not statistically significant (Table 2.12).

In pigeonpea, N fixed per plant varied from 71-2241 mg, 87-2007 mg, and 221-1403 mg for sole pigeonpea, pigeonpea intercropped with groundnut and pigeonpea intercropped with maize respectively. The mean values for N fixed per plant were 1248 mg, 782 mg and 822 mg for sole, and pigeonpea intercropped with groundnut and maize. Sole cropping increased N fixation rate per plant of pigeonpea than intercropping with groundnut (p=0.0234) or maize (p=0.0360). However, there were no differences between the two intercropped pigeonpea systems.

2.3.7 Nitrogen balance

Table 2.15 show results on a simplified N budget for sole and intercropped pigeonpea in 2007/08 season. The N balance did not take into account of losses through leaching or denitrification or atmospheric N inputs. Under double up legume system, total N inflow from BNF was 56 kg N ha^{-1} against an outflow of 29 kg N ha^{-1}, and net N gain of 26 kg ha^{-1}. This translates to 69% of fixed N used for legume growth. Sole groundnut contributed the highest amount of N (39 kg N ha^{-1}) with N flows of up to 64 kg ha^{-1} versus N exports equal to 25 kg ha^{-1}. Out of the 50 kg of N fixed, 50% was used by sole groundnut for its own growth. Excluding the N fertilizer input, the net BNF per unit area were 25, 15, 13 and -6 kg ha^{-1} for sole groundnut, sole pigeonpea, doubled up legumes, and MZPP. The net N balance from sole maize was -14 kg ha^{-1} indicating a net N loss from this cropping system.

2.3.8 Adaptability analysis of sole and intercropped grain legumes

Fig 2.15 shows plot of calories against environmental index (EI) for specific cropping systems in 2007/08 season. There was a positive linear relationship between calories and EI. The R^2 values were 0.27, 0.39, 0.55, 0.74 and 0.76 for sole pigeonpea, sole groundnut, GNPP, sole maize and MZPP respectively. The mean calories for each cropping system are shown in Table A2.8. Sole pigeonpea had the lowest calories compared to the other four cropping systems. The cropping system x EI interaction showed significant difference between slopes, p=0.0099. A comparison of mean calories from cropping systems at different levels of EI showed that under less productive environments (EI<1.5x10^6 calories), sole groundnut and GNPP produced more calories than sole pigeonpea, maize and MZPP (Fig 2.15). Similar trends were observed interms of higher calories being from groundnut or doubled up legumes compared to maize and maize-pigeonpea intercrop. However, under medium to moderately high production domains (EI>2.5<4.5x10^6 calories), all cropping systems except pigeonpea produced similar same calories. Interestingly, sole or intercropped maize were highly responsive under to very productive environments with EI>4.5x10^6 calories. Using OM as an EI, there was no linear relationship between OM and calories from the different cropping systems.

In 2008/09 season, regression of calories on EI showed a positive linear relationship for all cropping systems except for sole pigeonpea (Fig 2.16). The R^2 values were 0.27, 0.54, 0.60 and 0.00005 for sole groundnut, GNPP, maize and pigeonpea respectively. Sole groundnut was more adapted to low yielding environments with EI<3.0x10^6 calories than sole maize and pigeonpea. As the environment improved (EI >3 < 4.6 x 10^6 calories), maize produced more calories than doubled up legumes and was superior in environments with mean EI > 4.6 x 10^6 calories.

Fig 2.17 shows adaptability analysis on calorie production from sole and intercropped groundnut and pigeonpea across two seasons, 2007-2009. The R^2 values for the relationship between calories and EI were 0.35, 0.59 and 0.60 and 0.00006 for GNPP, sole groundnut, sole maize and sole pigeonpea respectively. In general, the results show that under low productive environments, farmers would optimize calorie production from growing sole and GNPP than sole maize or pigeonpea. Sole maize systems are highly sensitive to environmental characteristics and grain yield is optimized under high productive domains. Based on calorie production, pigeonpea showed adaptation to wide range of environments over the two growing seasons.

2.4 DISCUSSION

Soil fertility: Soils in this area have very low fertility as evidenced by low OM, N and inorganic P (Table 2.2). The levels of exchangeable cations (Ca, Mg and K) are adequate for production of arable crops. There is high variability of soil fertility between farms probably due to differences in CEC and soil texture (Figs 2.3 and 2.4) and cropping history. Variability of soils under smaller farmers was reported in earlier studies by Snapp (1998).

Effect of season and cropping system on grain and stover yields:

In general, growth and yield of crops in 2007/08 season were affected by early cessation of rainfall. As mentioned earlier, the area experienced a dry spell when groundnut and maize were at pod and grain filling stage respectively, while pigeonpea was at vegetative stage. This study has shown that under low yielding environments, farmers can optimize calorie production by growing sole groundnut or doubled up legumes than sole maize with no inorganic fertilizer inputs. Adaptability analysis across two seasons also demonstrated wide adaptation of legumes across varied environments. The significant effects of season and cropping system interaction on biomass production and yield components illustrate the importance of soil moisture on crop production. Season effects were more intense on grain yield of annual crop species (groundnut) than long duration pigeonpea implying wide adaptation of pigeonpea.

The grain yield of groundnut is within the average yields of 450 kg ha^{-1} under smallholder farmers in Malawi (Malawi Government, MoAIFS, 2005) and on-farm experiments by Kamanga (2002) but approximately 140% lower than trials conducted on research stations (Kabambe et al., 2008). Harvest index of 0.25 in groundnut is comparable to 0.24-0.33, values reported in earlier studies by Katayama et al., (1995) for sole and intercropped groundnut.

Pigeonpea grain yields were not very different from previous studies by Chamango (2004) and Twomlow et al., (2004). They reported grain yield of 155-348 kg ha^{-1} for pigeonpea intercropped with maize in central Malawi. The yields from pigeonpea are generally low partly due blister beetles (*Mylabris species*) observed on all pigeonpea plots and pod feeders. Blister beetles feed on pigeonpea flowers resulting in significant yield reduction (Singh, 1979; Boehringer and Caldwell, 1989). The seed size of 19g is not very different from 22g, the standard seed weight for this ICEAP00040 pigeonpea variety (Malawi Government, MoAIFS, 2005). Ghosh et al., (2006) found that grain harvested from intercropped pigeonpea was 9% bigger than under sole cropping.

The reduction in vegetative biomass production (leafy and woody stems) for intercropped pigeonpea could be attributed to interspecific competition with maize or groundnut. Rao and Mathuva (2000) reported a 42% yield decrease from pigeonpea when intercropped with cowpea. This was rather surprising as pigeonpea was expected to accumulate more biomass after groundnut had reached physiological maturity. This could be related to similar reasons of interspecific competition. Future research should evaluate the effect of planting groundnut 1-2 weeks before pigeonpea on biomass production.

Low maize yields (0.7-0.8 ton ha^{-1}) are within the expected values under smallholder farmers and could be attributed to low N and inorganic P (Table 2.3) and inadequate rainfall (Fig 2.1). The results from this study also illustrate the biological efficiency of intercropping over sole stands, LER>1 for both groundnut-pigeonpea and maize-pigeonpea intercrops.

Effect of cropping systems on BNF of sole and intercropped groundnut and pigeonpea

In groundnut, the number of nodules per plant is within the range of 82-144 at 40-60 DAP (Giri and De, 1980) at 40-60 DAP but lower than 164 at 60 DAP (Phoomthaisong et al., 2003). The number of pigeonpea nodules per plant is not different from 12, values reported by Kumar Rao et al., (1996) for long duration pigeonpea variety at about 8 WAP. The decrease in nodule number at 20 WAP was also reported by Kumar Rao (1996) in long duration pigeonpea varieties in which he observed an increase in nodule number with age up to 17 WAP and thereafter decreased. In this study, the effects of drought might have negatively affected nodulation soils. As mentioned earlier, this area experienced dry spell when pigeonpea was at vegetative stage.

The difference in nodule numbers and size between pigeonpea and groundnut could be related to genetic differences (Giri and De, 1980). However, nodules for both legumes were bigger than those reported by Giri and De (1980) probably due to varietal differences. Intercropping decreased size of groundnut nodules in 2007/08 season by 29% and this may be due to competition for soil moisture. Season effects were significant on nodule numbers of both legumes. The major difference between the two seasons was rainfall amount and distribution and therefore differences in nodulation characteristics could be attributed to soil moisture content as it affects survival of rhizobium and legume growth (Fujita et al., 1992; Zahran, 1999; Giller, 2001) on nodulation characteristics. Effects of season on nodule weight were species specific observed in groundnut only (annual legume) and no effect on long duration pigeonpea.

The non significance of proportion of Ndfa between sole and doubled up legumes is consistent with Katayama et al., (1995) but differ in that they reported higher %Ndfa by pigeonpea when intercropped with cereals (84%) compared to sole or doubled up legumes (52-70%). Groundnut met 78% of its N requirement from BNF. This was higher than 22 to 67% as reported by Katayama et al., (1995), Giller (2001) and Phoomthaisong et al., (2003). The total amount of N fixed per area were lower than those reported by Ojiem et al, (2007) for CG7 groundnut probably due to low inorganic P (Table 2.2), and plant density. Ojiem et al., (2007) reported 115-124 kg ha^{-1} as N fixed with application of 30 kg P ha^{-1} and higher plant densities almost 1.5 times than the density in this study. Since crop N was positively correlated with amount of N fixed by legume, inadequate soil moisture during reproductive growth stage of groundnut limited pod formation and grain filling consequently reducing total crop N accumulation.

Long duration pigeonpea is expected to fix more N due to long N fixation period and high biomass production. Findings on the proportion of Ndfa are consistent with Giller (2001). Nitrogen fixed by pigeonpea is lower compared to values of 46-118 kg ha^{-1} reported in earlier studies for ICEAP00040 variety in Malawi (Adu-Gyamfi et al., 2007). Sole pigeonpea fixed 30 kg ha^{-1} and this is within 20-60 kg N ha^{-1}, values reported for the same variety on selected sites in Tanzania. In this study, the low N fixation rates by pigeonpea can be attributed to low inorganic P (Table 2.3) and inadequate soil moisture to support biomass production following a dry spell that occurred when pigeonpea was still at early vegetative stage. High values of total N fixed by pigeonpea have been reported with correction of N:P:K deficiency. Egbe et al., (2007) reported of 82-96 kg N ha^{-1} fixed by pigeonpea with application of 30:13:25 kg ha^{-1} starter up N:P:K fertilizer.

Phosphorus is important for root development and growth of legume species. Positive correlations observed between inorganic P and N fixed by pigeonpea could be related effects of P on nodulation, biomass production and BNF process (Hoa et al, 2002; Jemo et al, 2006). Another finding was the non-significant correlation between P and N fixed for pigeonpea that was intercropped with groundnut. This may suggest that pigeonpea intercropped with maize were accessing same P pools (Makumba et al., 2009).

Role of grain legumes on N cycling in arable lands: Inclusion of legumes in maize based cropping systems can contribute to sustainability of smallholder agriculture through BNF and incorporation on high quality crop residues as evidenced by positive net N balances. This study has also shown that doubled up legumes can help to build soil N than the traditional cereal-legume intercrop due to high N fixation rates per unit area (Table 2.10) and N additions as crop residues. In 2007/08 season, crop residue N inputs from groundnut were lower than findings by Toomsan et al., (1995) and Phoomthaisong et al., (2003) due to low biomass of 1.3-1.9 ton ha^{-1}. Toomsan et al., (1995) and Phoomthaisong et al., (2003) reported crop residue N inputs of up to 69-166 kg N ha^{-1} with leafy biomass yields of 4-8 ton ha^{-1} for nodulating groundnut genotypes. The NHI of 0.42 is not different from 0.47, value reported by Phoomthaisong et al., (2003).
Long duration pigeonpea is one of the food legumes suitable for soil N build up due to low NHI and long period of N fixation. In 2007/08 season, N accumulation in pigeonpea leafy biomass were generally low (12-26 kg N ha^{-1}) but comparable to findings by Myaka et al., (2006) where leafy biomass N over three seasons averaged 10-30 kg ha^{-1} on selected sites in Malawi and Tanzania. Mapfumo and Mtambanenge (2004) found a mean shoot N of 18 kg ha^{-1} in a season

with poor rainfall distribution and low soil fertility. However, in a season with good rainfall pattern, pigeonpea accumulated up to 157 kg N ha^{-1} in stover. In another study, Ncube et al., (2007) reported 24-75 kg N ha^{-1} of N accumulation in leafy biomass of short duration pigeonpea across three seasons.

In this study, lower N accumulation for intercropped pigeonpea relative to sole stands could be related to negative effects of interspecific competition on biomass production. Makumba et al., (2009) reported a high probability of competition between maize and pigeonpea during the reproductive phase of maize due to similar peak rooting patterns at 9 WAP.

The increase in biomass N under MZPP compared to sole maize have been previously reported (Myaka et al., 2006). Sole maize produced the least stover N (3 kg ha^{-1}) and this is lower than values reported by Myaka et al., (2006) of 8-24 kg ha^{-1} for hybrid maize in southern Malawi. This could be attributed to varietal differences (composite vs hybrid maize), poor rainfall distribution in 2007/08 season, and poor soil fertility, specifically low N and inorganic P (Table 2.3).

Benefits of legumes on soil N depends on net N inputs. In this study, N inputs from maize stover were low but similar to value reported by Harawa et al., (2009) of 2.8 kg ha^{-1} $year^{-1}$. Total N outflows for sole pigeonpea and MZPP were lower relative to sole groundnut or GNPP system probably due to low NHI. The positive N balances observed from sole and doubled up legumes indicate potential of legume based cropping systems to build soil N. Negative and positive N balances have been reported for sole or intercropped pigeonpea depending on genotype and location (Adu-Gyamfi et al., 2007; Egbe et al., 2007). The net N balance were -30 to +26 kg ha^{-1} for different pigeonpea genotypes (Egbe et al., 2007), -2 to +26 kg ha^{-1} for pigeonpea in Malawi (Adu Gyamfi et al., 2007), and +22 kg ha^{-1} for nodulating groundnut genotypes (Phoomthaisong et al., 2003). The net N benefits from BNF sole and doubled up legumes are within the range reported by (Phoomthaisong et al., 2003) for groundnut, and Adu Gyamfi et al., 2007) for pigeonpea. The findings are also comparable to Harawa et al., (2009) in which they reported N balance of 25-45 kg ha^{-1} year^{-1} in two water sheds in southern Malawi. However, the two studies differ in that Harawa et al., (2009) looked at N budget of entire agricultural watershed and a large proportion of N inputs (~74%) were from inorganic N fertilizers and only 13% from BNF. Surprisingly, net N balance from doubled up legumes was 44% lower than of sole groundnut this could be attributed to low biomass production under doubled up legumes.

2.5 CONCLUSION

This study evaluated effect of sole and intercropping on performance and BNF of groundnut and pigeonpea. Intercropping of groundnut and pigeonpea or the traditional cereal-legume intercrops were more efficient at utilizing resources than sole cropping. Cropping system had no effect on grain yield of pigeonpea per plant basis, but influenced vegetative biomass production and BNF. In a season with adequate rainfall, sole cropping of groundnut increased legume productivity per plant basis compared to intercropping.

Sole and doubled up legumes can help to build soil N in legume/maize rotations. Doubled up legumes did not optimize total N fixed per area over sole legumes.

Table 2.3: Soil chemical properties and texture on fields planted to sole and intercropped legumes, 2007/08 crop season

Variable	Depth (cm)	Mean N=20	Std Deviation	Min	Max	LCL	UCL
pH (in H_2O)	0-15	5.9	0.26	5.5	6.5	5.7	6.0
	15-30	5.9	0.38	5.1	6.9	5.8	6.1
OM (g kg^{-1})	0-15	12	3.46	7	22	10	13
	15-30	12	5.10	4	28	10	14
TOC (g kg^{-1})	0-15	6	2.06	3	11	5	7
	15-30	5	2.23	2	11	4	6
TN (g kg^{-1})	0-15	0.5	0.12	0.4	0.8	0.5	0.6
	15-30	0.5	0.19	0.3	1.1	0.4	0.6
C:N	0-15	11	2.18	5.0	15	10	12
	15-30	11	2.02	7.3	15	10	118
POM (g kg^{-1})	0-15	5	2.57	2	12	4	6
	15-30	5	2.22	2	10	4	6
POMC (g kg^{-1})	0-15	0.4	0.21	0.2	0.9	0.34	0.5
	15-30	0.2	0.27	0.03	1.3	0.10	0.4
POMN (g kg^{-1})	0-15	0.02	0.008	0.008	0.04	0.01	0.02
	15-30	0.01	0.002	0.003	0.04	0.004	0.01
C:N in POM	0-15	28	5.56	18	43	26	31
	15-30	28	10.8	8	43	23	33
Bray P (mg kg^{-1})	0-15	16	20.4	1	85	6	25
	15-30	11	17.5	1	66	3	20
Ca (mg kg^{-1})	0-15	425	189.5	150	800	336	514
	15-30	418	183.0	100	700	332	503
Mg (mg kg^{-1})	0-15	121	53.5	60	265	96	146
	15-30	150	60.9	75	350	122	179
K (mg kg^{-1})	0-15	120	37.4	78	231	103	138
	15-30	122	47.8	72	232	100	144
CEC (cmol kg^{-1})	0-15	5.8	1.56	2.7	8.1	4.1	5.6
	15-30	4.9	1.37	1.6	7.4	4.2	5.5
% BS, Ca	0-15	42	8.83	24	56.1	38	47
	15-30	42	11.6	14	57.7	37	47
% BS, Mg	0-15	21	4.86	14	32.20	19	23
	15-30	26	7.78	15	41.30	23	30
% BS, K	0-15	7	2.17	3	10.2	6	8
	15-30	7	3.31	3	15.2	5	9
Sand (%)	0-15	74	9.78	56	91.6	69	78
	15-30	72	10.7	56	93.6	67	77
Clay (%)	0-15	18	8.19	4	34.8	14	22
	15-30	21	8.78	6	33.6	18	26
Silt %	0-15	8	4.36	3	22.4	6	10
	15-30	7	2.86	3	13.4	6	9

Key for Table 2.3:
LCL= Lower 95% confidence limit for mean; UCL= Upper 95% confidence limit for mean; BS= Base saturation; H=Hydrogen; POMC=particulate organic matter carbon; POMN=particulate organic matter nitrogen

Table 2.4: Pearson correlation coefficients and significance between OM and soil properties, 0-15cm and 15-30cm soil depth

Variable	0-15cm		15-30 cm	
	Coefficient	Pr>|r|	Coefficient	Pr>|r|
pH	-0.128	NS	0.069	NS
Total N	-0.006	NS	-0.200	NS
Bray P	-0.338	NS	-0.279	NS
CEC	0.555	0.011	0.517	0.0197
Ca	0.522	0.018	0.481	0.032
K	0.267	NS	0.186	NS
Mg	0.314	NS	0.377	NS
Clay	0.502	0.024	0.577	0.008
Sand	-0.491	0.028	-0.610	0.004
Silt	0.160	NS	0.513	0.021

NS = not significant at p<0.05

Table 2.5: Soil organic matter (g kg^{-1}), summary of stepwise regression 0-15 cm soil depth

Variable entered	Parameter estimate	SE parameter estimate	Partial R-Square	Model R-Square	C(p)	Pr>F
Intercept	16.17	6.16				
CEC	0.98	0.43	0.31	0.31	3.18	0.0110
Sand	-0.12	0.07	0.11	0.42	2.19	0.0941

Table 2.6: Plant dry weight at 8.5 weeks after planting, 2007/08 season

Crop	Cropping system	Dry wt/plant (g)
Pigeonpea (PP)	Sole	8.6(0.51)
	MZPP	9.0(0.47)
	GNPP	9.0(0.45)
	Mean	8.9
	Pr>F	0.714
Groundnut (GN)	Sole	17.4(1.7)
	GNPP	17.1(1.2)
	Mean	17.2 (1.5)
	Pr>F	0.799

MZ=maize; PP=pigeonpea; GN=groundnut. GNPP=groundnut intercropped with pigeonpea; MZPP=maize intercropped with pigeonpea; Number in parenthesis is standard error

Table 2.7: Groundnut grain yield and leafy biomass under sole and intercrop systems, and land equivalent ratio (LER), 2007/08 and 2008/09 crop seasons

Variable	Cropping system (CS)	2007/08	2008/09	Mean	LER 2007/08	LER 2008/09
Grain yield (kg ha^{-1})	Sole	598(63.74)bA	1101(62.56)bB	846	1.50	1.53
	GNPP	435(63.74)aA	650(62.56)aB	548		
	Mean	516	876			
Source of variation		*Pr>F*				
	CS	<0.0001				
	Season	<0.0001				
	CS*season	0.0026				
Leafy biomass (kg ha^{-1})	Sole	1895(216.36)	3156(216.36)	2526b		
	GNPP	1275(160.69)	2042(228.88)	1659a		
	Mean	1585(141.77)A	2599(169.95)B			
Source of variation		*Pr>F*				
	CS	<0.0001				
	Season	<0.0001				
	CS*season	0.2427				

Number in parenthesis is standard error; GNPP=groundnut intercropped with pigeonpea
Means within each column per variable category followed by same lower case letter are not statistically significant at p<0.05;
Means within each row per variable category followed by same upper case letter are not statistically significant at p<0.05

Table 2.8: Yield components of sole and intercropped groundnut 2007/08 and 2008/09 crop seasons

Variable	Cropping system (CS)	Season			ANOVA Source of Variation and p-value		
		2007/08	2008/09	Mean	*CS*	*Season*	*CS*Season*
Grain yield per plant(g)	Sole	14aA	26bB	20	0.0043	<0.0001	0.0141
	GNPP	14aA	20aB	17			
	Mean	14	23				
HI	Sole	0.25	0.29	0.27	0.4777	0.0621	0.4754
	GNPP	0.25	0.28	0.26			
	Mean	0.25	0.28				
100 seed weight (g)	Sole	69	56	63	0.7102	<0.0001	0.7732
	GNPP	67	56	62			
	Mean	68B	56A				
Shelling %	Sole	62	73	68	0.5795	<0.0001	0.5528
	GNPP	63	71	66			
	Mean	62A	72B				

GN=groundnut; PP=pigeonpea; GNPP=groundnut intercropped with pigeonpea; HI=Harvest Index
Means within each row per variable category followed by same upper case letter are not statistically significant at p<0.05; Means within each column per variable category followed by same lower case letter are not statistically significant at p<0.05

Table 2.9: Pigeonpea grain yield and leafy biomass under sole and intercrop systems, and land equivalent ratio (LER), 2007/08 and 2008/09 crop seasons

Variable	Cropping system (CS)	2007/08	2008/09	Mean	LER 2007/08	LER 2008/09
Grain yield (kg ha^{-1})	Sole	310(55.35)	302(55.35)	306(44.04)	1.50	1.53
	GNPP	238(57.60)	284 (57.59)	261(39.72)		
	Mean	274	293			
Source of variation		*Pr>F*				
	CS	0.7375				
	Season	0.4252				
	CS*season	0.8164				
Leafy biomass (kg ha^{-1})	Sole	3410(427.76)	4341(441.26)	3876(328.75)b		
	GNPP	1443(427.76)	2320(441.26)	1881(328.75)a		
	Mean	2426(324.26)A	3333(334.19)B			
Source of variation		*Pr>F*				
		<0.0001				
		0.03				
		0.9473				

Φbiomass includes leafy biomass plus woody stems; Number in parenthesis is standard error; GNPP=groundnut intercropped with pigeonpea
Means within each column per variable category followed by same lower case letter are not statistically significant at p<0.05;
Means within a row per variable category followed by same upper case letter are not statistically significant at p<0.05

Table 2.10: Yield components of pigeonpea from sole and intercrop system, 2007/08 and 2008/09 crop seasons

Variable	Cropping system (CS)	Season			ANOVA Source of Variation and p-value		
		2007/08	2008/09	Mean	*CS*	*Season*	*CS*Season*
Grain yield per plant(g)	Sole	11	9	10	0.2717	0.6765	0.7228
	GNPP	13	13	13			
100 seed weight (g)	Sole	18	21	20	0.1855	<0.0001	0.5927
	GNPP	19	22	21			
	Mean	19A	22B				
Shelling %	Sole	41	44	42	0.6965	0.2977	0.6488
	GNPP	38	44	41			

GN = groundnut; PP = pigeonpea; GNPP = groundnut intercropped with pigeonpea
Means within a row per variable category followed by same upper case letter are not statistically significant at $p<0.05$;

Table 2.11: Nodule number and weight for sole and intercropped legumes in 2007/08 and 2008/09 crop seasons

Crop	Cropping system (CS)	Nodule number/plantΦ		Weight/nodule (mg)	
		Season 1	Season 2	Season 1	Season 2
GN	Sole	4.5	4.1	1.9	2.9
	GNPP	4.4	3.9	1.5	2.5
	Mean	4.4B	4.0A	1.7A	2.7B
	Pr>F				
	CS	0.500		0.185	
	Season	0.0002		0.004	
	CS x season	0.653		0.965	
PP	Sole	1.8	2.1	9.4	10.5
	GNPP	2.0	2.3	9.0	9.8
	Mean	1.9A	2.2B	9.2	10.1
	Pr>F				
	CS	0.178		0.770	
	Season	0.022		0.609	
	CS x season	0.989		0.938	

Season 1= 2007/08; Season 2= 2008/09;
Φresults for nodule numbers are log transformed values; GN= groundnut; PP= pigeonpea; GNPP=groundnut intercropped with pigeonpea; For each crop and variable, means in a column followed by same letters are not statistically different at p=0.05.

Table 2.12: Nitrogen fixation rate and total amount of N fixed by groundnut and pigeonpea in sole and intercrop systems, 2007/08 season

Crop	Cropping system	Ndfa (%)	Total N fixed (kg ha^{-1})	N fixed per plant (mg)
N fixed by legume species				
Groundnut (GN)	Sole	78	50b	1006
	GNPP	79	29a	807
	Mean	78	40	906
	Pr>F	0.792	0.018	0.132
Pigeonpea (PP)	Sole	73	32b	1249b
	GNPP	79	15a	782a
	MZPP	74	13a	822a
	Mean	77	20	940
	Pr>F	0.638	0.0036	0.047
Total N fixed per unit area per cropping system				
Groundnut			50c	
Pigeonpea			31b	
GNPP			42bc	
MZPP			12a	
Mean			36	
Pr>F			<0.0002	
Difference of least square means, total N fixed per unit area				
			Pr>|t|	
GN vs GNPP			0.254	
PP vs GNPP			0.150	
MZPP vs GNPP			0.0005	
GN vs PP			0.015	

GN=groundnut; PP=pigeonpea; MZ=maize; GNPP=groundnut intercropped with pigeonpea; MZPP=maize intercropped with pigeonpea; B values obtained from lowest 15N of legume (Hansen and Vinther, 2001); B=-0.45, -0.38, -0.80, -0.73, and -1.12 for soleGN, GN intercropped with PP, sole PP, PP intercropped with GN, and PP intercropped with MZ respectively.
For each crop and variable, means followed by same letter are not statistically different at p=0.05.

Table 2.13: Correlation matrix of nitrogen fixation with plant density, Ndfa, Bray P, POM, crop N, and soil N in groundnut, 2007/08 season

	Sole GN		GNPP	
	N fixed (kg ha^{-1})	%Ndfa	N fixed (kg ha^{-1})	%Ndfa
N fixed	1.000		1.000	
%Ndfa	0.428	1.000	0.296	1.000
Plant density (ha^{-1})	**0.647** (p=0.022)	**0.745** (p=0.005)	-0.034	0.073
Bray P (mg kg^{-1})	**0.587** (p=0.044)	0.356	0.352	0.620 (p=0.056)
POM (g kg^{-1})	**0.678** (p=0.015)	0.426	0.091	0.235
N (g kg $^{-1}$)	-0.413	0.020	-0.498	0.297
pH	-0.152	-0.497	-0.123	-0.510
Crop N (kg ha^{-1})	**0.98** (p<0.0001)	0.236	**0.93** (p<0.0001)	-0.092

Values in bold are significant at p<0.05; POM= Particulate organic matter
GN = groundnut; GNPP = groundnut intercropped with pigeonpea

Table 2.14: Correlation matrix of nitrogen fixation with plant density, Ndfa, Bray P, POM, crop N, and soil N, sole and intercropped pigeonpea, 2007/08 season

	Sole		PPMZ		PPGN	
	N fixed (kg ha^{-1})	%Ndfa	N fixed (kg ha^{-1})	%Ndfa	N fixed (kg ha^{-1})	%Ndfa
N fixed	1.000		1.000		1.000	
%Ndfa	**0.731** (p=0.0164)	1.000	**0.676** (p=0.0158)	1.000	0.488	1.000
Plant density	0.504	0.165	0.407	-0.284	-0.067	-0.135
Bray P	**0.780** (p=0.008)	0.531	**0.857** (p=0.0004)	0.506 (p=0.0930)	-0.175	0.156
POM	-0.167	-0.167	-0.149	0.010	0.559 (p=0.093)	-0.123
N	-0.485	-0.103	-0.441	0.028	0.374	0.077
pH	-0.061	0.032	0.114	-0.001	0.164	0.404
Crop N (kg ha^{-1})	**0.911** (p=0.0002)	0.48	**0.599** (p=0.0397)	-0.167	**0.92** (p=0.0002)	0.172

Values in bold are significant at p<0.05; POM=particulate organic matter
PPGN = pigeonpea intercropped with groundnut; PPMZ = pigeonpea intercropped with maize

Table 2.15: Nitrogen balance of sole and intercropped groundnut, pigeonpea and maize systems, 2007/08 season

Cropping System	N inflows (kg ha^{-1})				N outflows (kg ha^{-1})				Net N balance	Net N from BNF**
	Maize stover	BNF	N fertilizerΦ	Total N inflows	Grain	Woody stems	Cores/ shells	Total N outflows	Kg ha^{-1}	Kg ha^{-1}
Maize (MZ)	3*	0	10	13	13	0	1	14	-0.94	-14
Groundnut (GN)	3	50	10	64	23	0	3	25	+39	+25
Pigeonpea (PP)	3	31	10	44	7	8	1	16	+21	+15
GNPP	3	42	10	56	22	4	3	29	+27	+13
MZPP	3	12	10	26	13	3	2	18	+8	-6

*estimated N input from residues in 2006/07 season based on stover N obtained in 2007/08;

Φ= applied as starter fertilizer to all treatments; **Net N benefit from BNF excluding N input from the 10 kg ha^{-1} inorganic fertilizer and crop residues; GNPP=groundnut intercropped with pigeonpea; MZPP=maize intercropped with pigeonpea

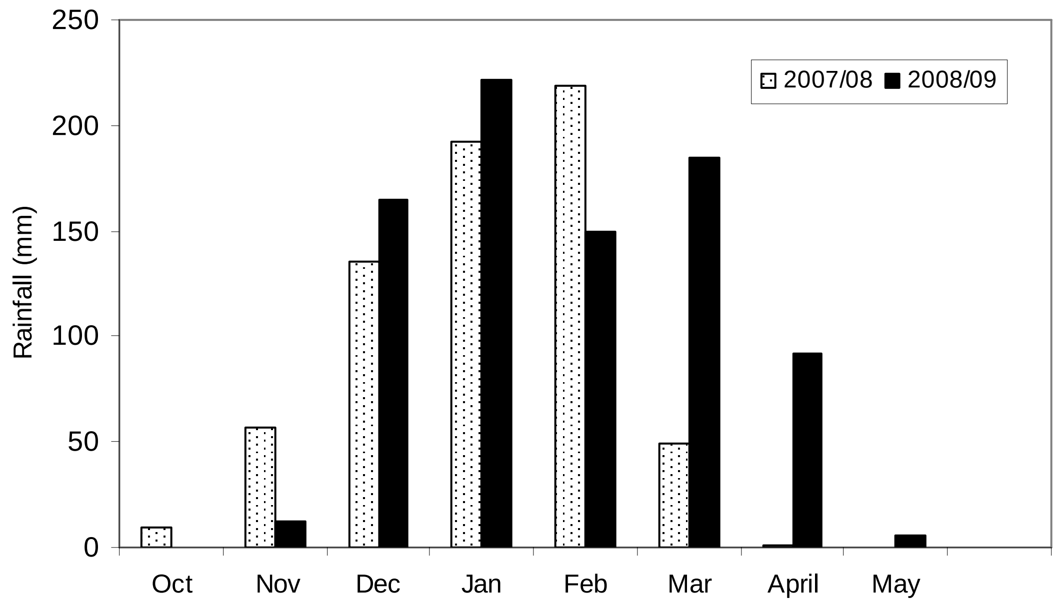

Fig 2.2: Mean monthly rainfall in Ekwendeni across sites during the 2007/08 and 2008/09 crop season

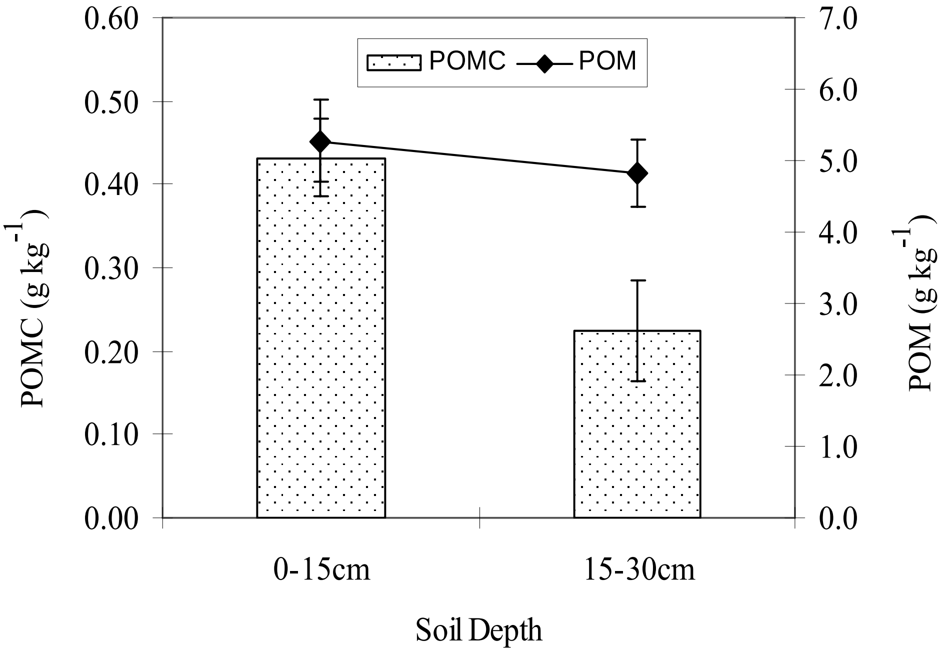

Fig 2.3a: Particulate organic matter (POM) and particulate organic matter carbon (POMC) at 0-15cm and 15-30cm soil depths.

Units of POM and POMN in g kg^{-1} soil); Error bars are standard errors

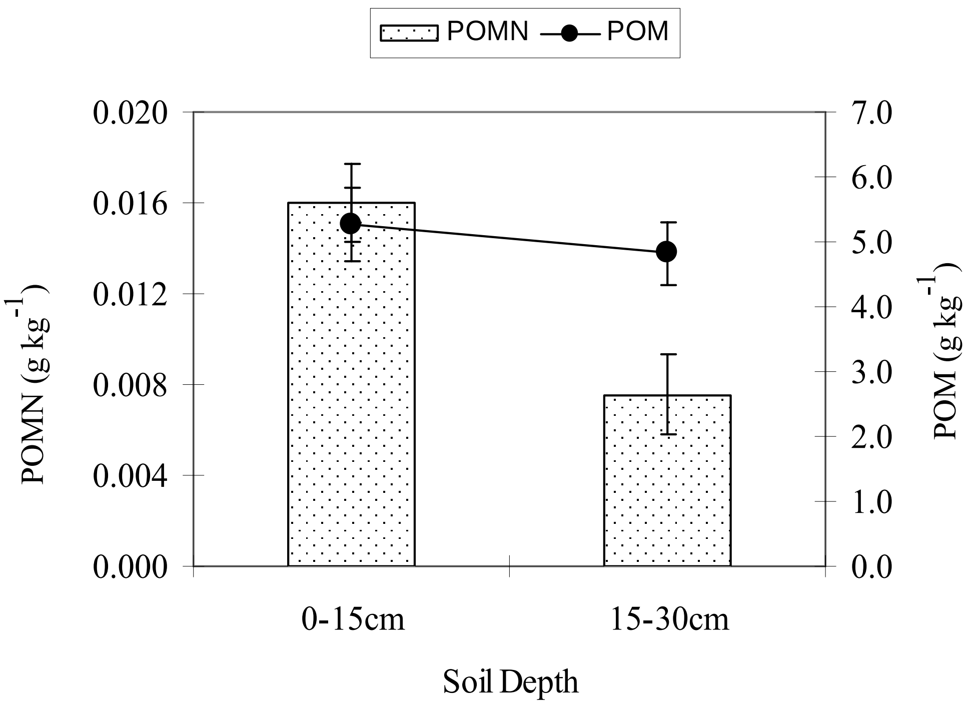

Fig 2.3b: Particulate organic matter (POM) and particulate organic matter nitrogen (POMN) at 0-15 cm and 15-30 cm soil depths.

Units of POM and POMN in g kg^{-1} soil); Error bars are standard errors

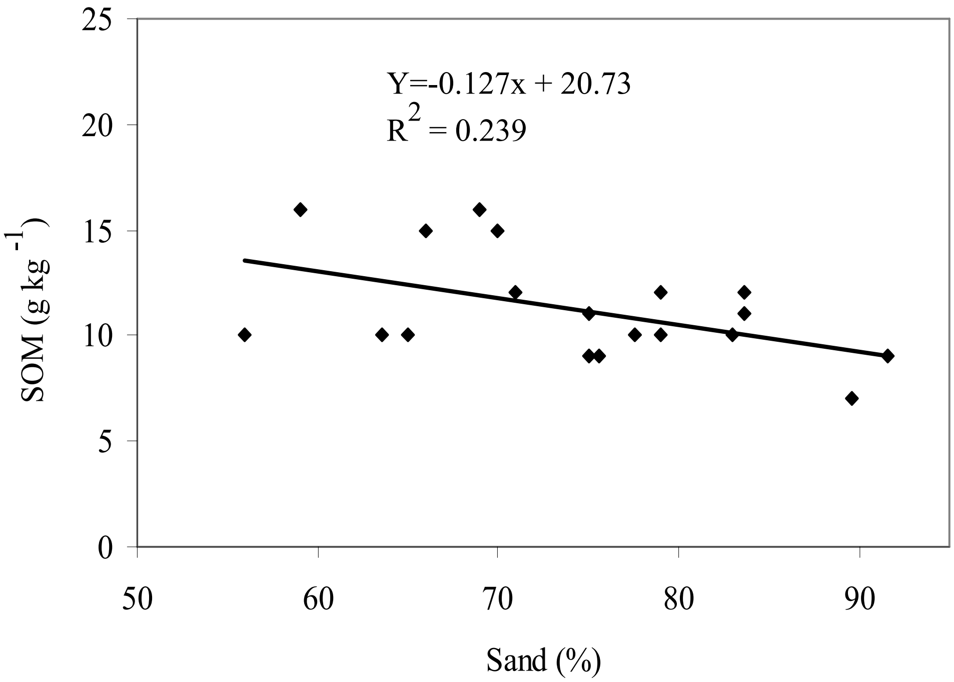

Fig 2.4: Relationship between soil organic matter (SOM) and sand content, 0-15 cm soil depth

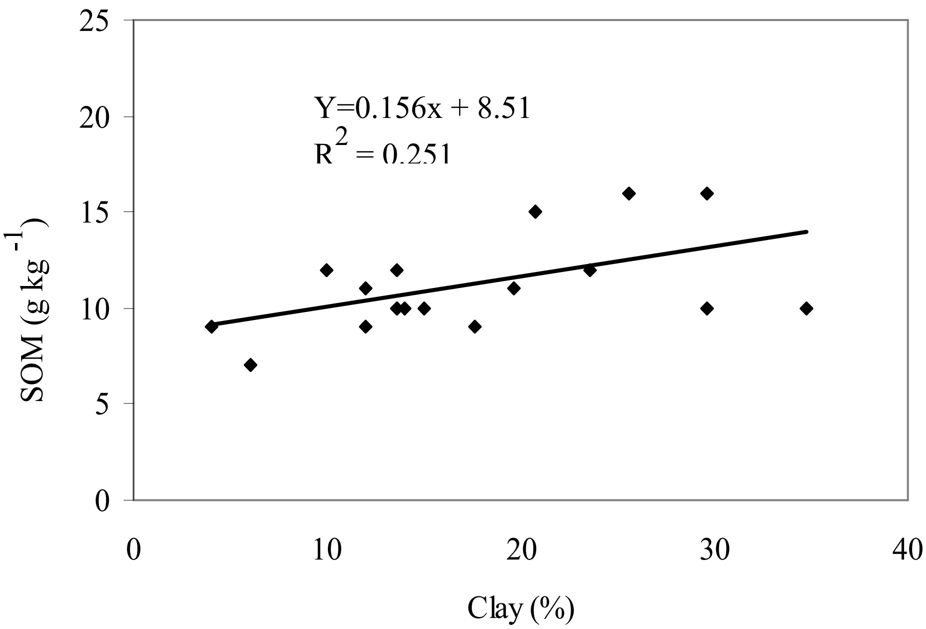

Fig 2.5: Relationship between soil organic matter (SOM) and clay content, 0-15cm soil depth

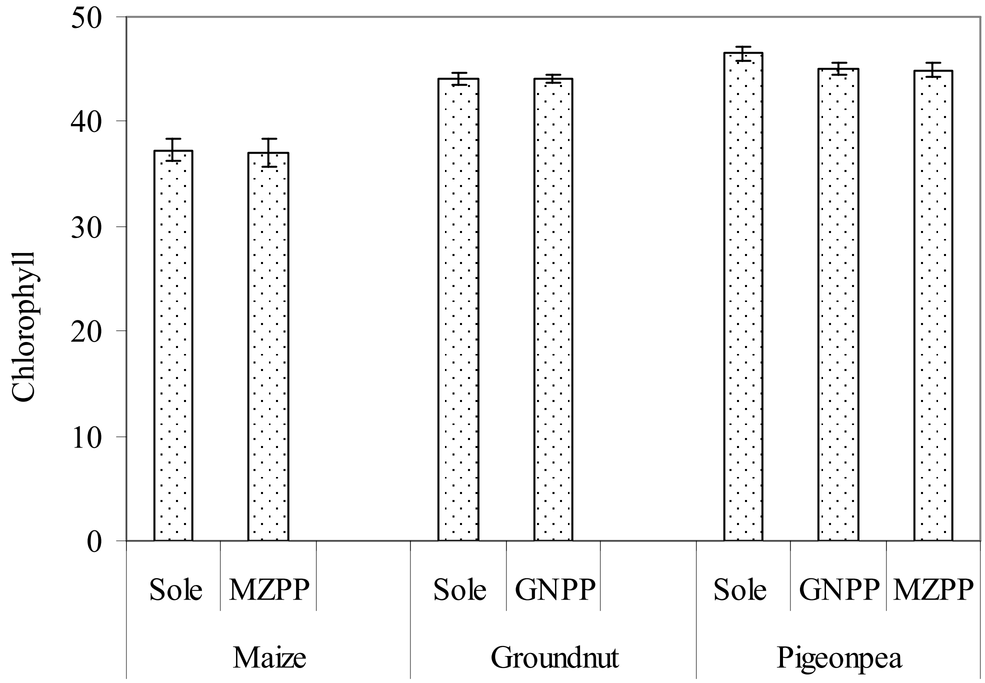

Fig 2.6: Chlorophyll in maize, sole and intercropped groundnut and pigeonpea at 8.5 weeks after planting, 2007/08 season

Error bars represent standard errors. MZ= maize; GN=groundnut; PP=pigeonpea; MZ= maize; PP= pigeonpea; GNPP=groundnut intercropped with pigeonpea; MZPP=maize intercropped with pigeonpea

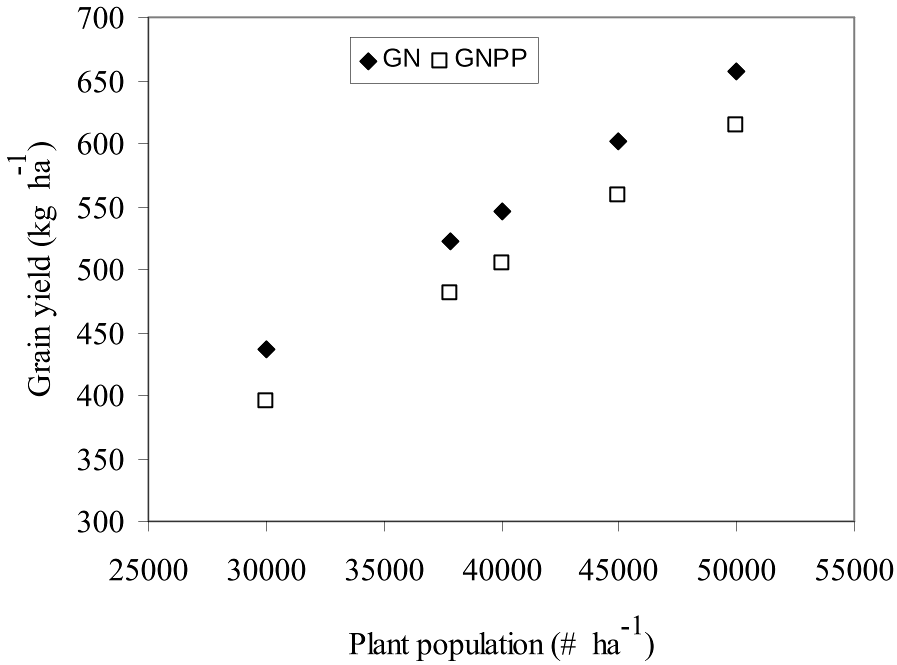

Fig 2.7: Grain yield of sole and intercropped groundnut at different densities, 2007/08 season
GN=sole groundnut; GNPP= groundnut intercropped with pigeonpea.

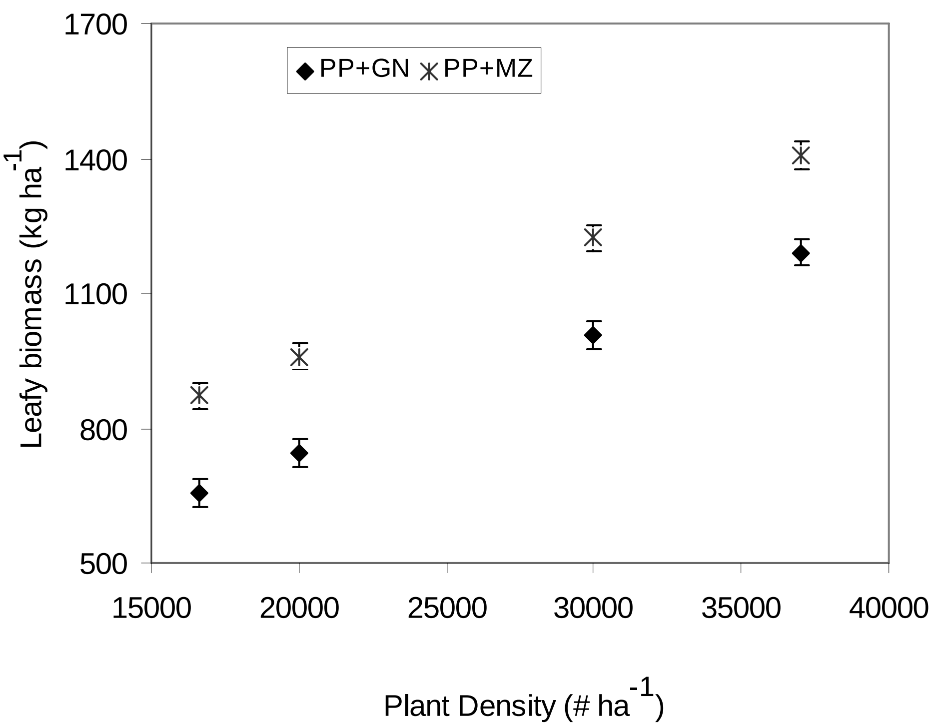

Fig 2.8: Leafy biomass of pigeonpea under maize-pigeonpea and groundnut-pigeonpea intercrops at different plant densities, 2007/08 season

PP+GN= pigeonpea intercropped with groundnut; PP+MZ= pigeonpea intercropped with maize
The error bars are standard errors

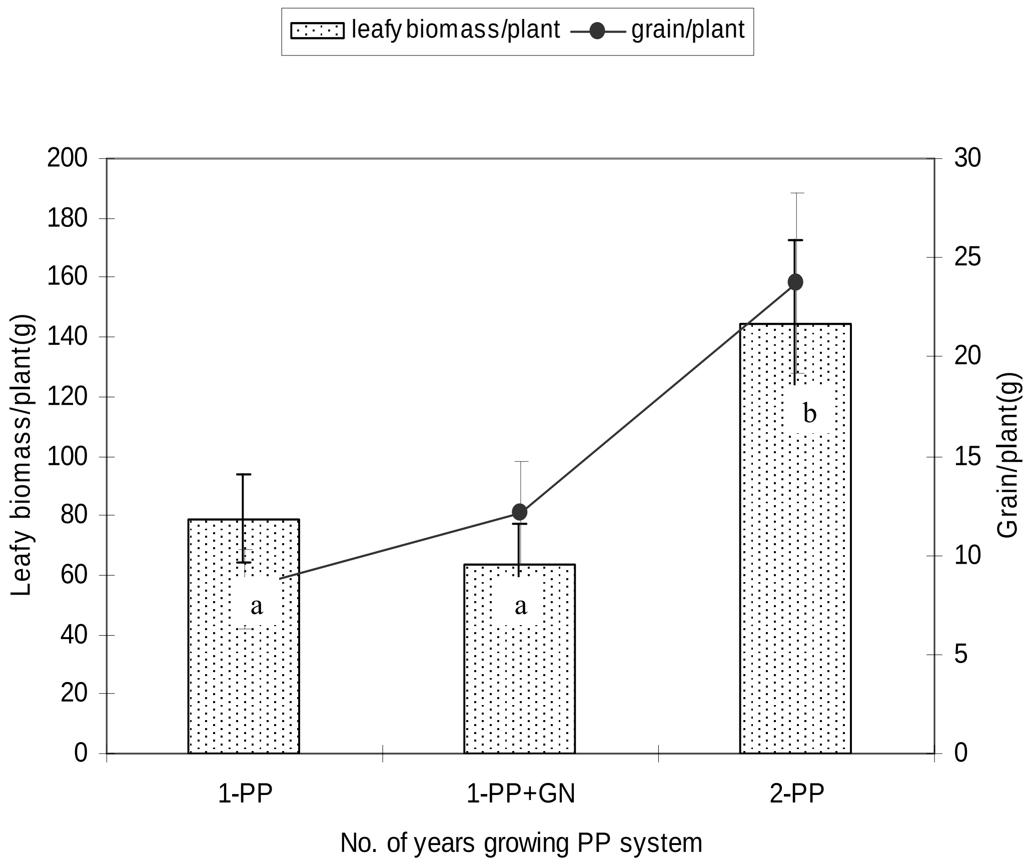

Fig 2.9: Leafy biomass and grain yield per plant of pigeonpea after one crop season or establishment from ratooning practice

PP=pigeonpea; GN=groundnut; 1-PP= One year of sole PP in 2008/09 season; 1-PP+GN= One year of PP intercropped with GN in 2008/09 season; 2-PP= PP intercropped with GN in 2007/08 season and ratooned at harvest, and then intercropped with maize in 2008/09season. Error bars indicate standard errors. Bars with same letter are not statistically significant at $p<0.05$.

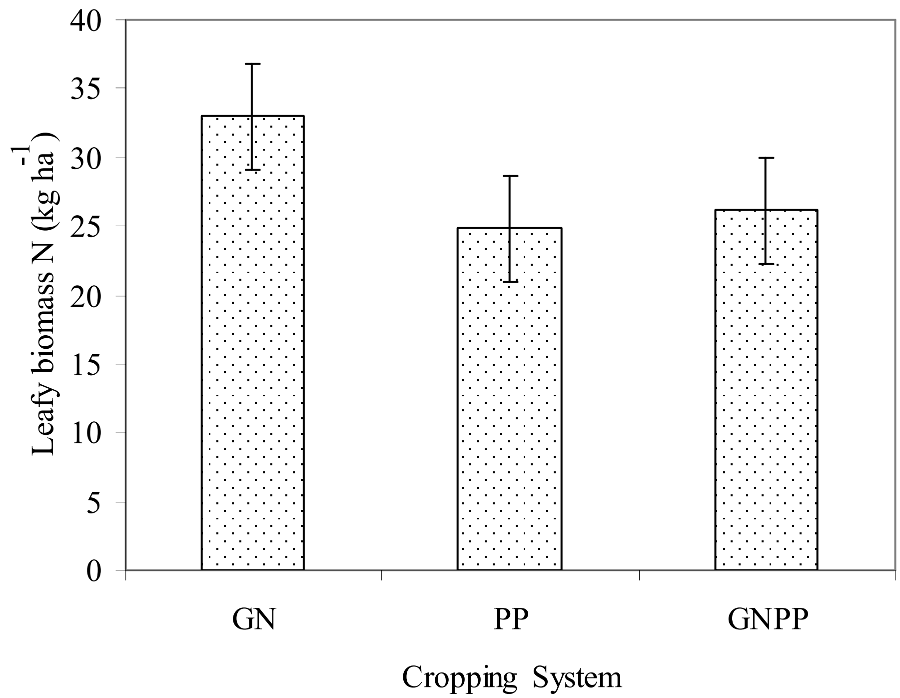

Fig 2.10: Nitrogen accumulation in leafy biomass of sole and intercropped groundnut and pigeonpea, 2007/08 season

GN=groundnut; PP=pigeonpea; groundnut intercropped with pigeonpea; Error bars are standard errors.

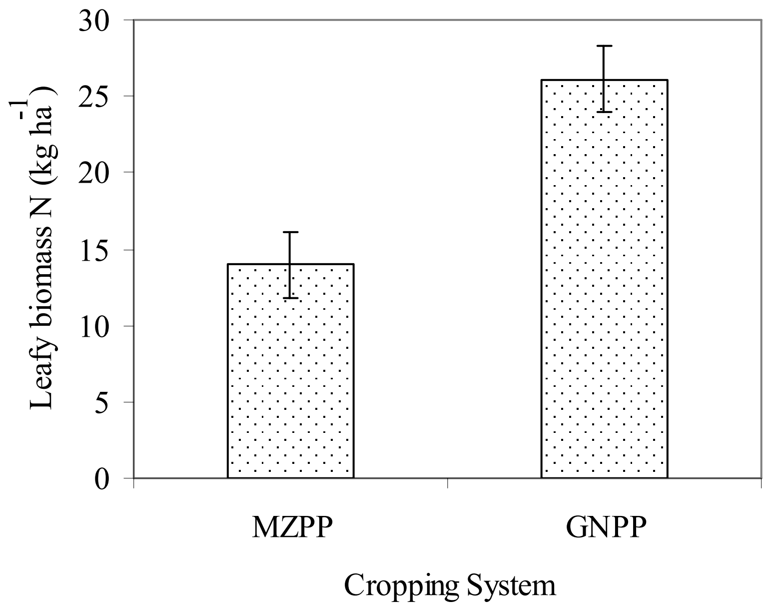

Fig 2.11: Nitrogen accumulation in leafy biomass of maize-pigeonpea and groundnut-pigeonpea intercrops, 2007/08 season

MZPP=maize intercropped with pigeonpea intercrop; GNPP=groundnut intercropped with pigeonpea; Error bars are standard errors.

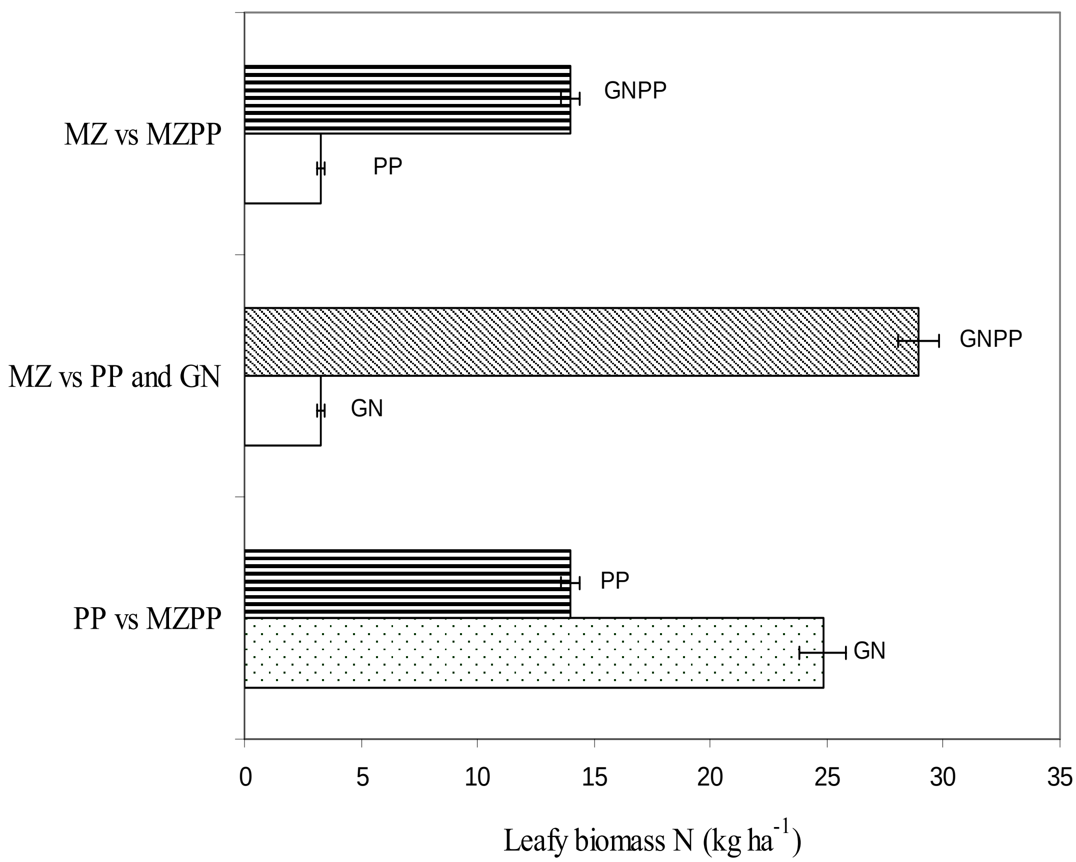

Fig 2.12: Nitrogen accumulation in leafy biomass of sole and intercropped maize, groundnut and pigeonpea, 2007/08 crop season

MZ= maize; PP=pigeonpea; GN= groundnut; MZPP=maize intercropped with pigeonpea
Horizontal error bars stand for standard error for the difference between the two cropping systems

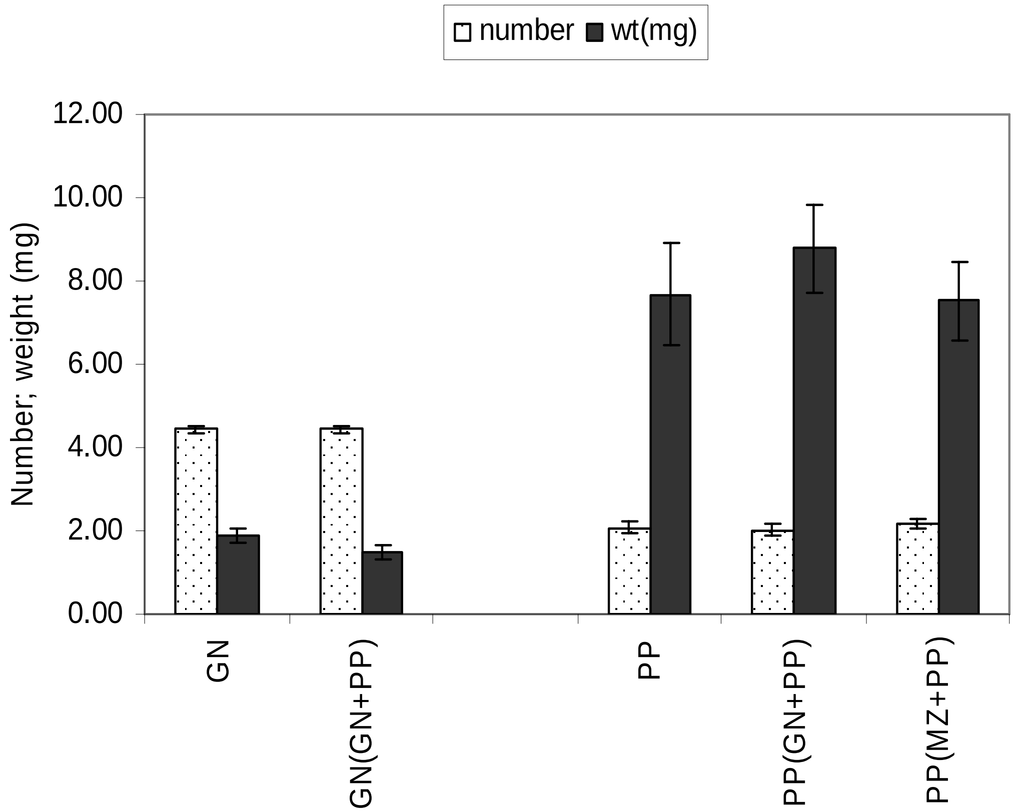

Fig 2.13: Nodule number plant^{-1} and weight nodule^{-1} of sole and intercropped groundnut and pigeonpea, 2007/08 season.

The errors bars are standard errors. GN=sole groundnut; GN(GN+PP) = groundnut intercropped with pigeonpea; PP=sole pigeonpea; PP(GN+PP)=pigeonpea intercropped with groundnut; PP(MZ+PP)= pigeonpea intercropped with maize

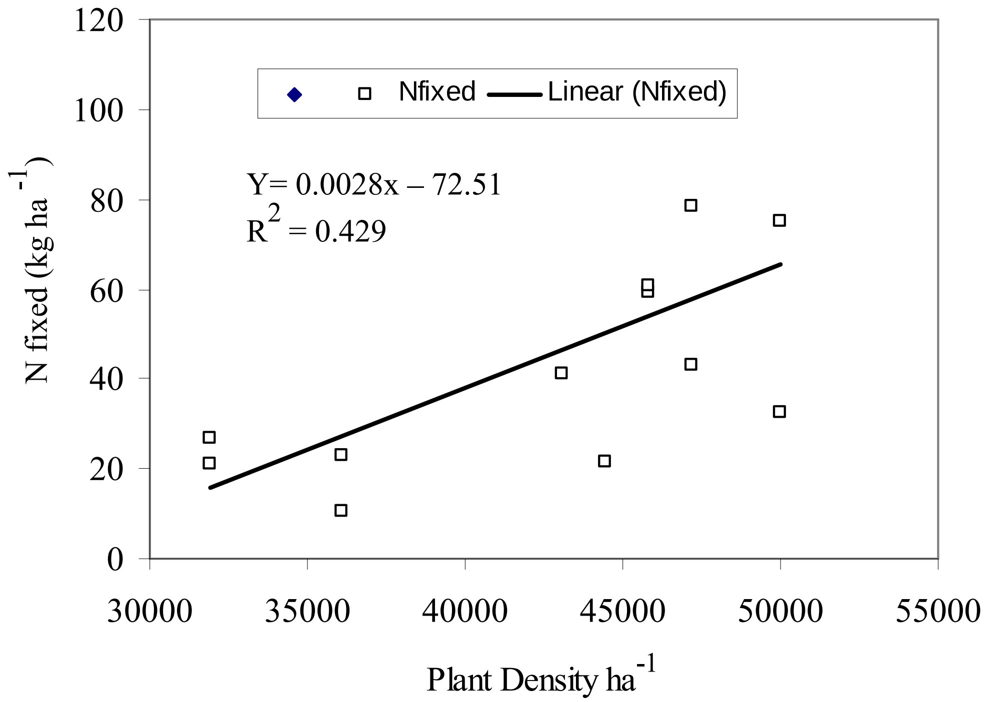

Fig 2.14: Relationship between plant density and nitrogen fixed per unit area by sole groundnut, 2007/08 season.

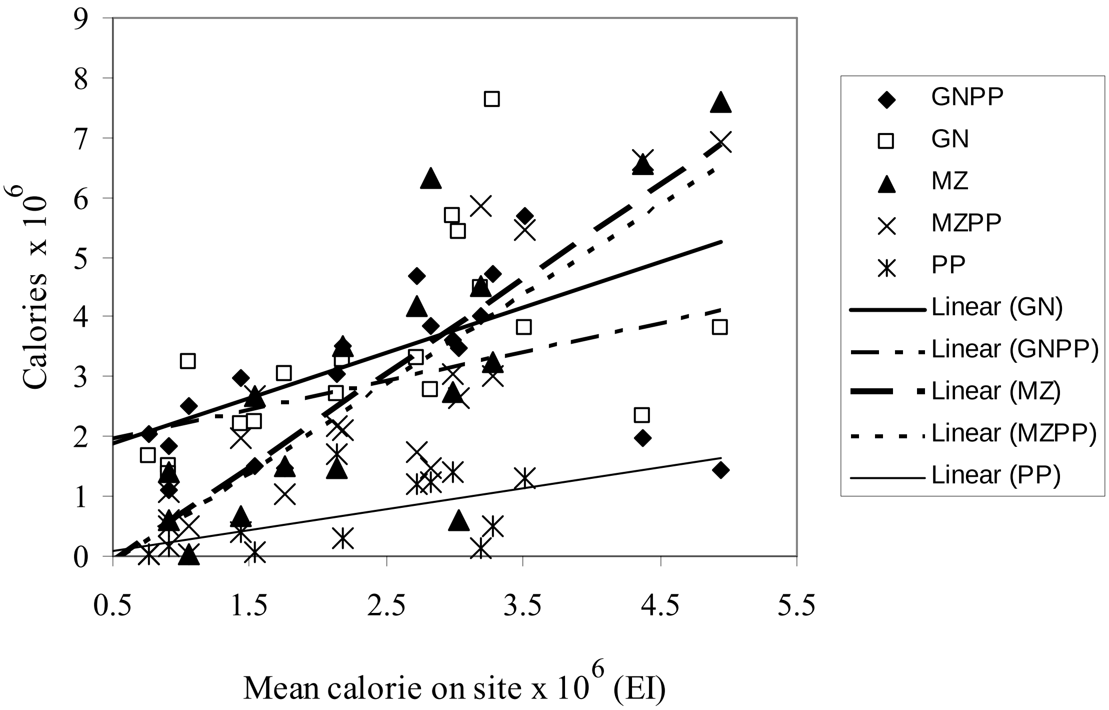

Fig 2.15: Calories per cropping system against average calories per farmer trial site (environmental index), 2007/08 season

MZ= maize; MZPP=maize intercropped with pigeonpea; PP= pigeonpea; GN=groundnut; GNPP=groundnut intercropped with pigeonpea;

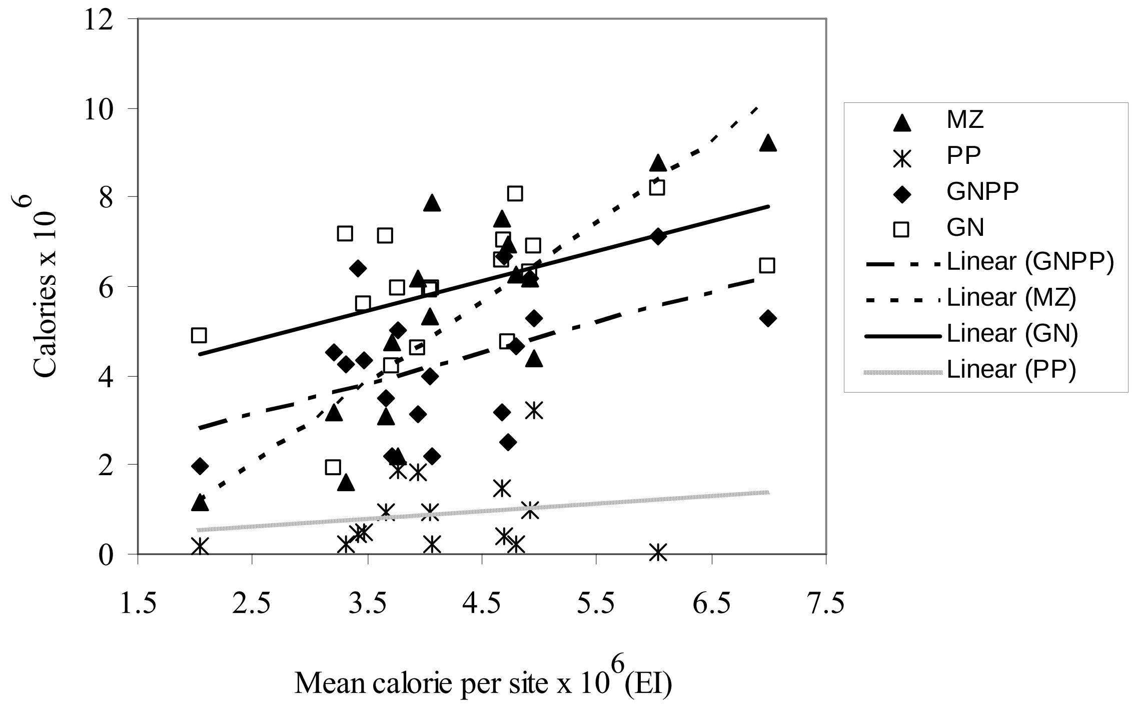

Fig 2.16: Calories per cropping system against mean calories per farmer trial site (environmental index), 2008/09 season.

MZ= maize; PP= pigeonpea; GN=groundnut; GNPP=groundnut intercropped with pigeonpea

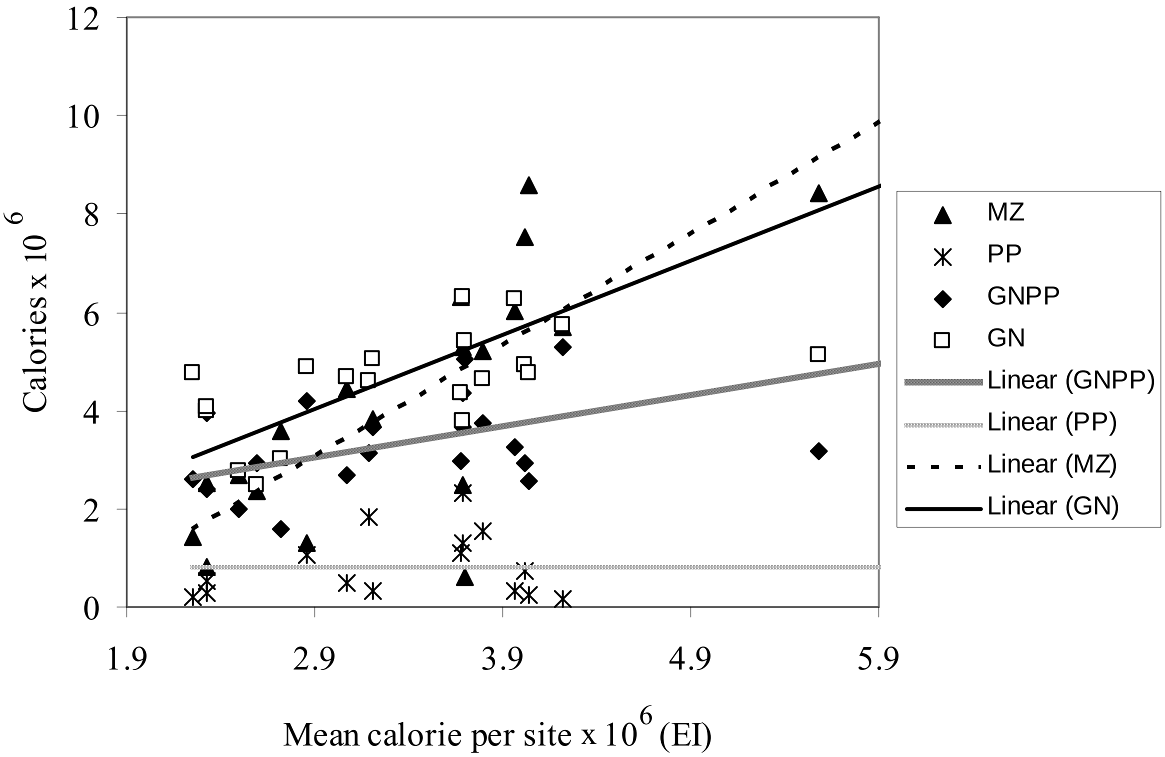

Fig 2.17: Calories per cropping system against mean calories per farmer trial site (environmental index), across two seasons, 2007/08 and 2008/09.

MZ= maize; PP= pigeonpea; GN=groundnut; GNPP=groundnut intercropped with pigeonpea;

APPENDICES

Table A2.1: Solution for Fixed effects and Type 3 tests of fixed effects, grain yield of groundnut, 2007/08 season

Effect	Treatment	Estimate	Pr>|t|
Solution of fixed effects			
Treatment	Sole groundnut	107.53	0.5627
Treatment	Groundnut+pigeonpea	65.52	0.6476
Number	0.01098	0.00405	0.0161
Type 3 Tests of Fixed Effects, Pr>F			
Treatment	0.7857		
Number	0.0161		

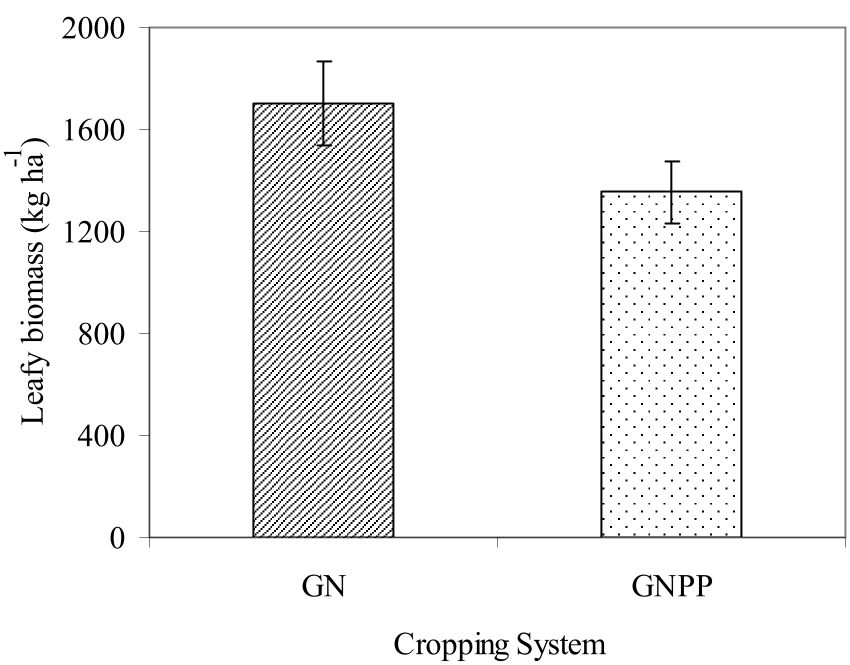

Fig A2.1: Leafy biomass of sole and intercropped groundnut at 36247 groundnut plants per hectare, 2007/08 season.

GN=sole groundnut; GNPP= groundnut intercropped with pigeonpea intercrop. Error bars are standard error

Table A2.2: Grain and stover yield, 100 seed weight and shelling % of sole pigeonpea or intercropped with maize or groundnut, 2007/08 crop season

Cropping system	BiomassΦ	Grain	LER	100 seed Weight	Shelling percent
	Kg ha^{-1}			*(g)*	*%*
Sole	3319b	294		19	41
GNPP	1352a	265		19	41
MZPP	1453a	206	1.56	20	43
Mean	2031	255		19	42
Prob	<0.0001	0.309		NS	NS

GNPP = pigeonpea intercropped with groundnut; MZPP = pigeonpea intercropped with maize;
Φ biomass includes leafy biomass plus woody stems; NS = not significant at p=0.05
Means in a column per crop category followed by same letter are not statistically significant at p=0.05

Table A2.3: Pigeonpea biomass after one season or establishment from ratoooning practice, 2008/09 season

Variable (kg ha^{-1})	Pigeonpea Cropping System (CS)			Pr>F	
	Sole	PPGN	MZ+PPrat	CS	Plant density
Total biomass Φ	2504ab	2332a	5233bc	0.006	0.017
Leafy biomassψ	1626ab	1169a	2427b	0.062	0.061
Woody stems	975a	1133a	2771b	0.015	0.016
Grain yield	331	273	365	NS	NS

Differences of least square means, leafy biomass

Label	Estimate	Std error	T value	Leafy biomass Pt>|t|
PP vs MZPPrat	-800.28	813.42	-0.98	0.3350
PPGN vs MZPPrat	-1257.98	564.83	-2.23	0.0356
PPGN vs PP	457.71	524.29	0.87	0.3913

PP = pigeonpea; GN= groundnut; MZ = maize; PPGN = pigeonpea intercropped with groundnut; MZPPrat = Maize intercropped with PP. This PP was ratooned from previous season after GNPP intercrop;
Φ total biomass includes woody stems and leafy biomass; ψ= leafy biomass exclude woody stems; NS= not statistically different; Means in a row followed by same letter are not different at p<0.05.

Table A2.4: Grain and stover yield, and yield components of sole and intercropped maize, 2007/08 season

Cropping system	Stover	Grain	LER	HI	100 seed weight	Shelling percent
	Kg ha^{-1}				*g*	*%*
Sole	1590	694	1.56	0.37	24	76
MZPP	1702	874		0.47	23	74
Mean	1646	795		0.42	24	75
Pr>F	0.6221	0.2049		NS	NS	NS

MZ=maize; MZPP= maize intercropped with pigeonpea; NS=not significant at $p<0.05$

Table A2.5: Nitrogen content (%) of stover, grain, shells, cores and woody stems of sole and intercropped maize, groundnut and pigeonpea, 2007/08 season

Crop	Cropping system	Shells N (%)	Cores N (%)	Woody stems N %	Leafy biomass N (%)	Grain N (%)
Maize (MZ)	Sole	-	0.5(0.03)	-	0.2(0.001)	1.1(0.03)a
	MZPP	-	0.5(0.02)	-	0.2(0.001)	1.3(0.04)b
	Mean	-	0.5	-	0.2	1.2
	Pr>F	-	NS	-	NS	<0.0001
Groundnut (GN)	Sole	0.6 (0.02)	-	-	1.6(0.07)b	3.8(0.13)
	GNPP	0.7 (0.05)	-	-	1.3(0.07)a	3.6(0.14)
	Mean	0.64	-	-	1.5	3.7
	Pr>F	NS	-	-	0.0029	NS
Pigeonpea (PP)	Sole	0.6(0.12)	-	0.8(0.08)b	1.3(0.01)a	3.4(0.06)b
	GNPP	0.8(0.13)	-	1.0(0.03)b	1.2(0.05)a	3.3(0.06)ab
	MZPP	0.7(0.09)	-	0.6(0.05)a	1.4(0.04)b	3.2(0.06)a
	Mean	0.8		0.8	1.28	3.3
	Pr>F	NS		0.0012	0.028	0.0209

Number in parenthesis is standard error; For each crop, means in a column followed by same upper case letter are not statistically different
MZPP = maize intercropped with pigeonpea; GNPP = groundnut intercropped with pigeonpea

Table A2.6: Nitrogen accumulation (kg N ha^{-1}) per cropping system (sole and intercropped maize, groundnut and pigeonpea), 2007/08 season

Cropping system	Leafy Biomass	Grain	Woody Stems	Shells + cores	NHI
Maize (MZ)	3(2.93)a	13(2.79)a	-	1.03a	0.52c
Groundnut (GN)	33(2.93)c	22(2.57)b	-	2.48bc	0.42b
Pigeonpea (PP)	25(2.93)c	7(3.26)a	8.25b	0.97a	0.13a
MZPP	14(2.93)b	13(2.71)a	3.25a	2.07b	0.79c
GNPP	26(2.93)c	22(2.57)b	4.06a	3.16c	0.65c
GNPPrat	24(2.93)c	24(2.57)b	3.35a	4.02d	0.77c
Mean	20.6	18.44	4.65	2.30	0.58
Pr>F	<0.0001	<0.0001	0.0001	0.0001	<0.0001

Contrasts on leafy biomass N (kg ha^{-1})

		Leafy biomass N		
Label	Estimate	SE	t value	Pr>|t|
PP vs MZPP	-10.86	3.55	-3.06	0.0031
PP vs GNPP	1.30	3.55	0.37	NS
GNPP vs MZPP	12.15	3.55	3.43	0.0010
GN vs GNPP	6.84	3.55	1.93	0.0580
GN vs PP	8.13	3.55	2.29	0.067
MZ vs GN and PP	25.63	3.07	8.34	<0.0001
MZ vs MZPP	10.70	3.55	3.02	0.0035

For ratooned pigeonpea, root biomass was not measured; Number in parenthesis is standard error; Means in a column followed by same letter are not statistically different at $p<0.05$; MZPP = maize intercropped with pigeonpea; GNPP = groundnut intercropped with pigeonpea; GNPPrat = groundnut intercropped with pigeonpea, PP ratooned at harvest in year one (2007/08) and intercropped with maize in year two (2008/09).

Table A2.7: Nitrogen accumulation (kg N ha^{-1}) in leafy biomass, grain, shells, cores and big stems of maize, groundnut, and pigeonpea, 2007/08 season

Crop	Cropping system	Total plant	Leafy biomassΦ	Grain	Woody stems	Shells	Cores
					Kg N ha^{-1}		
Maize (MZ)	Sole	12.79	3.55	11.83	-	-	1.06
	MZPP	13.74	3.63	11.57	-	-	0.97
	Mean	13.49	3.60	11.69	-	-	1.02
	Pr>F	NS	NS	NS			NS
Groundnut (GN)	Sole	55.51	31.88b	23.10b	-	2.49b	-
	GNPP	45.82	18.06a	18.52a	-	1.72a	-
	Mean	50.74	23.72	21.03	-	2.01	-
	Pr>F	NS	0.0004	0.029		0.0015	
Pigeonpea (PP)	Sole	36.45b	26.05b	7.41	8.25b	0.94	-
	GNPP	15.87a	11.90a	7.09	3.25a	1.54	-
	MZPP	17.44a	13.75a	5.80	4.07a	1.30	-
	Mean	23.25	19.96	6.93	5.28	1.28	
	Pr>F	<0.0001	0.0012	0.6041	0.0031	NS	

Φincludes all leafy shoots and roots. For ratooned pigeonpea, root biomass not measured;
Means in a column per crop category followed by same letter are not statistically different at $p<0.05$; NS=not statistically different at $p<0.05$;
MZPP = maize intercropped with pigeonpea; GNPP = groundnut intercropped with pigeonpea

Table A2.8: Mean calories from legume and maize cropping systems at different levels of environmental indices

Cropping system (CS)	Calories x 10^6 at different environmental indices					
	0.8	1.0	1.5	2.5	3.5	Mean
GN	1.51b	1.72b	2.29b	3.34b	4.41b	3.3b
GNPP	1.35b	1.54b	2.00b	2.93b	3.85b	2.9b
MZ	0.12ab	0.45ab	1.27ab	2.92b	4.56b	2.8b
MZPP	0.23ab	0.52ab	1.25ab	2.70b	4.15b	2.6b
PP	0.16a	0.22ab	0.36a	0.65a	0.93a	0.6a

Type 3 Tests of Fixed Effects, with calories as a dependent variable

Effect	Num DF	Den DF	F value	Pr>F
CS	4	62	1.45	0.2273
EI	1	62	80.8	<0.0001
CS x EI	4	62	3.65	0.0099

Means in a column followed by same letters are not statistically significant at p<0.05
EI = Environmental Index; MZ = maize; GN = groundnut; PP = pigeonpea;
MZPP = maize intercropped with pigeonpea; GNPP = groundnut intercropped with pigeonpea

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CHAPTER THREE

ECOSYSTEM SERVICES FROM LEGUME DIVERSIFICATION IN MAIZE-BASED CROPPING SYSTEMS

ABSTRACT

Technologies that optimize a wide range of services are central to developing more sustainable cropping systems. Smallholder farmers in particular urgently require environmentally friendly technologies that support short as well as long-term productivity, to address food security in a sustainable manner. On-farm experiments were conducted in Ekwendeni, northern Malawi to evaluate the impact of diversification of maize with legume crops. Intercrop and rotation systems were compared, quantifying the effects of an annual grain legume, groundnut (peanut), and a short-lived perennial grain legume, pigeonpea. Productivity in terms of grain, calories and nutrient-enriched residues was assessed along with soil fertility. Residue N production ranged from 12 kg ha^{-1} in a maize-pigeonpea intercrop (MZPP) to 33 kg ha^{-1} under sole groundnut. A nitrogen fertilizer rate experiment at 0, 24 and 92 kg N ha^{-1} with maize was conducted in year two of the rotation to assess response of maize following maize or following legume-diversified systems, in terms of agronomic N efficiency from inorganic and organic sources (fertilizer vs. legume-residues).

No effect of treatment on soil fertility was found in terms of soil inorganic nutrient status at early vegetative crop growth stage. In contrast, maize plant indicators of N status (chlorophyll and biomass) were highly responsive to cropping system treatment. In maize rotation following a sole legume treatment, maize leaf-chlorophyll at 10 weeks after planting (WAP) was positively correlated to maize yields. Further, maize following diversified legume treatments yielded 21-

62% higher than continuous maize ($p<0.05$). There was no evidence of higher maize yield following a 'doubled up' legume treatment (groundnut-pigeonpea intercrop) versus following a sole cropped legume (groundnut or pigeonpea). Fertilizer equivalency of organic N source (crop residues) was calculated and found to be highest in GN-maize rotations (31 kg N ha^{-1}) and least in maize following MZPP (10 kg N ha^{-1}). The highly diversified legume system where ratooned pigeonpea was allowed to grow a second year as an intercrop with maize showed significant competition effects, as indicated by reduced maize grain yield in year two. Overall the study found that inorganic organic N sources were markedly productive, as second year maize following a legume crop system combined with 24 kg N ha^{-1} fertilizer increased maize yield (1329 to 2444 kg ha^{-1}), 69-200% compared to sole crop, unfertilized maize.

A farmer preference survey showed that ranking of technologies suitable for wider adoption was from highest to lowest as follows: groundnut-pigeonpea intercrop maize rotation, pigeonpea-maize rotation and maize+pigeonpea intercrop-maize rotation. This was shown to differ from the maize grain yield rank order. Farmers' choices were based on labor inputs, food diversification, soil fertility benefits of legume based on seedling vigor of maize and associated yield. Constraints to broader farmer adoption identified in the survey included agronomic (pests in pigeonpea and maize), natural (unreliable rainfall), socio economic (seed, labor), and cultural issues (livestock grazing in pigeonpea).

3.1 INTRODUCTION

Maize (*Zea mays* L*)* is a staple food crop in Malawi and many countries in sub Saharan Africa. In Malawi, maize occupies >70% of arable land (Snapp et al., 2002a). Most of the farmers are smallholders producing maize for home consumption. The varieties grown include local, composite and hybrid maize with yield potential of 3000, 5000 and 6000-8000 kg ha^{-1} respectively (Malawi Government, MoAIFS 2005). The national average yield in the last 16years (1993-2008) was within 0.8-1.7 ton ha^{-1} with an exception of 2007 where high yields were obtained with the fertilizer subsidy program (Fig 3.1). However, the average maize yields under small holder farmers are <1000 kg ha^{-1} due to a number of reasons including low soil fertility, pests and diseases, unreliable rainfall pattern, inadequate labor or seed. Low soil fertility especially low N is one of the major constraints to maize production (Snapp et al., 1998; Phiri et al., 1999; Sakala and Mhango, 2003) as it is required in large amounts. In Malawi, the area specific recommended rate for low N soils is 92 kg N ha^{-1} (Malawi Government, MoAIFS, 2005). High N depletion relative to phosphorus (P) and potassium (K) has been documented (Mafongoya et al., 2007 quotes Henna and Baanante, 1999). They reported that in Malawi, annual nutrient depletion average 48 kg ha^{-1}, 7 kg ha^{-1} and 37 kg ha^{-1} for N, P and K respectively.

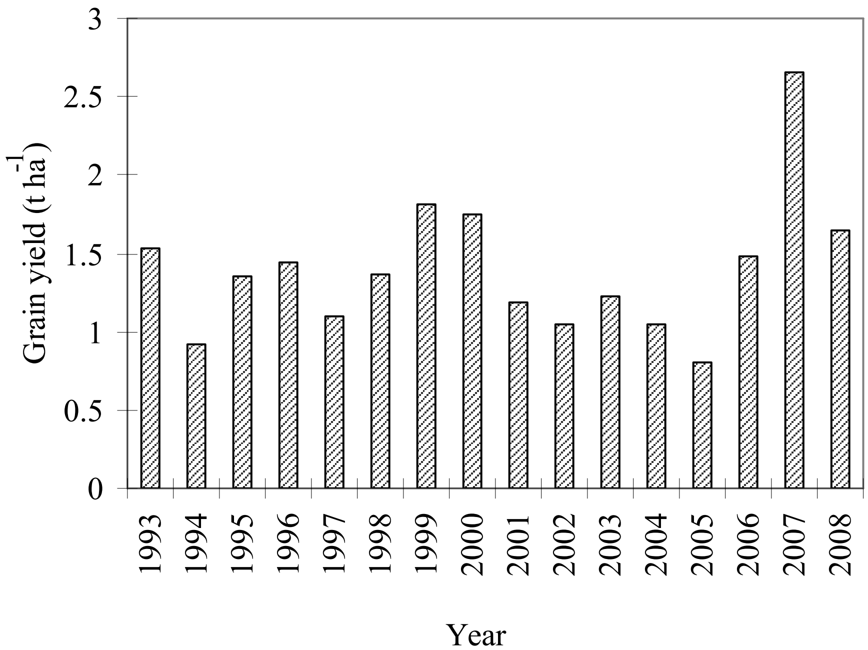

Fig 3.1: National average maize grain yields in Malawi from 1993-2008.
Source: FAO, FAOSTAT http://faostat.fao.org, Accessed on June 17, 2010

3.1.1 Maize cropping systems

In Malawi, the rainfall pattern is unimodal starting in November/December to March/April. Maize is grown in sole cropping, crop rotation, or intercropped with legumes (cowpea, groundnut, pigeonpea, common beans) and pumpkins. Legume-maize or cereal-legume/maize rotations are common traditional cropping system in Malawi (Mc Coll, 1989). A brief description of maize cropping systems in Malawi is provided in Chapter 1, section 1.1 of this dissertation. Examples of legumes planted in sole stands are dwarf varieties of common bean (*Phaseolus vulgaris*), groundnut (*Arachis hypogaea*), velvet bean (*Mucuna pruriens*), fish bean (*Tephrosia volgeli*) and improved fallows of agroforestry tree species (Mc Coll, 1989; Kwesiga and Coe, 1994; Gilbert, 2004). Legumes usually intercropped with maize are cowpea, pigeonpea, common beans (climbers), fish bean. When maize is planted after legumes, there is potential for improved crop yields and soil fertility through N inputs from BNF, crop residue incorporation, and reduced carryover of pests and diseases.

3.1.2 Legume-cereal rotations and soil fertility

Strategies to address low N include use of inorganic fertilizer, inclusion of legumes in cropping systems, application of manure or crop residue. Inorganic fertilizers provide readily available N for plant uptake and increase yield of cereal crops (Bationo and Ntare, 2000; Snapp et al., 2000). However, reliance on inorganic fertilizers may not be sustainable for small holder farmers due to high cost prices for the small holder farmers, or small quantities are applied that do not adequately support maize growth. Integration of legumes in maize based cropping systems offers a relatively cheaper alternative means of improving soil N and crop yields. Legume-cereal rotations increase soil fertility and crop yield due to BNF, NO_3^- sparing and incorporation of residues with low C:N ratio (Toomsan et al., 1995; Giller, 2001; Yusuf et al., 2009). This is particularly important in Malawi and other countries in SSA where a majority of farmers are small holders and yet few can afford inorganic fertilizers. Other benefits of incorporating legume crop residues include building soil OM, regulation of soil moisture (Shah et al., 2003), improve soil biological and physical properties. An investigation was carried by Bagayoko et al., (2000) to evaluate effect of legumes on performance of sorghum and pearl millet. They found that legumes (groundnut, cowpea) increased yield of cereals due to increase in mineral N and increase in mycorrhizal infection. Groundnut in particular reduced density of nematodes. Similarly, Yusuf (2009) reported increase in microbial biomass carbon following legume cropping systems.

The benefits of legumes on soil fertility and yield of companion and subsequent cereal crops have been documented (Bationo and Ntare, 2000; Rao and Mathuva, 2000; Snapp et al., 2000; Waddington and Karigwindi, 2001; Shah et al., 2003; Shafi et al., 2007; Yusuf et al., 2009). These cereals include maize, wheat, pearl millet and sorghum. The benefits from legumes can also be described in terms of nitrogen fertilizer equivalency (Wani et al., 1995; Giller, 2001). Shah et al., (2003) reported 36% increase in wheat yields following mungbean over continuous wheat. Increase in yield of pearl millet was reported by Bationo and Ntare (2000) in rotations involving cowpea and groundnut. Shafi et al., (2007) found higher maize yield following chickpea than wheat-maize rotations.

The effects of legumes on soil fertility and crop yields vary with legume type, BNF, biomass quality and quantity (Snapp et al., 1998a) and residue management. It has been reported that green manures have more soil fertility and yield benefits to the subsequent cereal crop than grain legumes with high N removed in grain (Giller, 2001). Earlier studies by Snapp et al., (2000) found that *Mucuna*-maize rotations yielded 18% higher than maize following groundnut-pigeonpea intercrop. Similar observations were reported by Kihara et al., (2007) on maize rotations with velvet beans and soybean. In addition, long duration and perennial legumes have longer N fixation period compared to annual legumes. A study by Rao and Mathuva (2000) found no significant differences in maize yield following sole pigeonpea and cowpea-pigeonpea intercrop under both short and long rains, however, higher maize yields were observed under cowpea-maize rotation. Similar results reported by Chirwa et al., (2003) at lower density (<37000 plants ha^{-1}) of sole pigeonpea.

Biomass quantity and BNF are influenced by availability of water, soil fertility and crop management practices. A good rainfall season (amount and distribution) coupled with good crop management practices such as timely planting, optimum plant population, weeding, management of pests and diseases, and correction of nutrient deficiencies can increase BNF and biomass production from legumes (Giller, 2001; Reddy et al., 2007). Shafi et al., (2007) reported 112% increase in maize grain yield under chickpea-maize rotations. In their study, starter N fertilizer of 25 kg ha^{-1} was applied to the legume and in addition, P and K were applied in both years to correct nutrient deficiency. Other scientists have reported location specific increase in biomass N after legumes associated with initial soil fertility status (Marschner et al., 2004), and high variation in N fertilizer equivalency from legume-maize rotations (Wani et al., 1995).

3.1.2.1 Crop residue management and soil fertility

Crop residue management is fundamental in soil fertility management. Incorporation of residues improves soil OM, moisture and crop yields (Shah et al., 2003; Mureithu et al., 2005). The quantity and quality of residues affect the amount of nutrients and timing of nutrient release for the subsequent crop. The correlation between amount of residues incorporated and maize yield vary with crop species, inherent soil fertility, and soil moisture (Giller, 2001; Phoomthaisong et al., 2003; Baijukya et al., 2006; Mhango et al., 2008). Phoomthaisong et al., (2003) observed positive linear relationship between residue N and maize grain yield under mungbean/maize or groundnut/maize rotations. Others have reported significant correlations associated with specific legume species and average annual rainfall of 2000mm (Baijukya et al., 2006).

Soil OM consists of active and recalcitrant pools. The active pool consists of particulate organic matter (POM) within 53-2000um soil particle size (Chan, 2001) and is characterized by high C:N ratio with plant residues at various stages of decomposition, high lignin, and microbial debris (Six et al., 2002). POM and POM carbon are sensitive to management practices and are therefore better indicators of changes in soil quality under different cropping systems than total organic carbon (Barrios et al., 1996; Chan, 2001; Christensen, 2001; Grandy and Robertson, 2007). Russell (2002) observed a positive relationship between recalcitrant SOM and tissue lignin content thus increasing total soil OC, while the active SOM pool decreased. This implies that most of the nitrogen was in organic form and hence not immediately available for crop uptake. Results also showed that polycultures produced higher SOM than monoculture systems. However, the authors also found that species composition had a significant effect on SOM than species richness.

SOM improve soil physical properties, chemical and biological properties (Gathumbi et al., 2002; Biederbeck et al., 2005; Leroy et al., 2008). Contribution of crop residues to SOM depend on species richness and diversity, tillage practices, soil fertility management practices, soil organisms, moisture and temperature (Schonberg et al., 1994; Sakala et al., 2000; Gathumbi et al., 2002). Crop species affect SOM because of the differences in tissue chemistry below and above ground, rooting systems, biomass production, nutrient use efficiency, and nitrogen fixation rates. Residues from legumes that have a narrow C:N ratio (<30) and therefore N mineralization is faster than cereal residues. Generally, legume residues improve soil biophysical characteristics and provide an important energy source to soil organisms thereby increasing microbial activities. Contrary, crop residues with C:N ratio >30 immobilize nitrogen hence depriving the crop of nutrients, in the short term, while building soil organic matter. In the long term, a combination of high and low quality residues can help to build up SOM (Sakala et al., 2000).

3.1.3 Doubled up legume technology and soil fertility

A number of scientists have reported on effects of legumes on cereal crops in either intercrops or crop rotations. In these studies, the focus has been on the traditional crop rotation systems where legumes are planted in sole stands or intercropped with cereals. Other scientists, for instance, Ghosh et al., (2006) reported on yield advantage of soybean/pigeonpea row intercrops in semi-arid tropics of India. Crop rotation research involving doubled up legumes (cowpea and pigeonpea) in Kenya has been reported by Rao and Mathuva (2000). They found no differences in maize yield following pigeonpea and pigeonpea-cowpea intercrops. In Malawi, earlier studies by Snapp et al., (2002) evaluated performance of maize cropping systems involving groundnut and pigeonpea intercrop and green manures in central and southern Malawi. In this research, the effects of legume-legume intercrop (doubled-up legumes), legume-cereal intercrop and sole legumes on subsequent maize and soil fertility was investigated in northern Malawi. Pigeonpea is a new legume in northern Malawi and has been promoted by the SFHC project in Ekwendeni catchment since 2000 to improve soil quality and family nutrition (Bezner-Kerr et al. 2007). A unique farmer innovation of intercropping maize and ratooned pigeonpea previously intercropped with groundnut can be viewed as cost saving technology on seed and labor for planting while improving soil fertility. It was therefore imperative to assess the effects of legume cropping systems of N cycling and crop yield.

3.1.3 Objectives

The objective was to assess maize performance and yield following legumes. Three hypotheses were tested:

a) Maize following legumes will yield higher than continuous maize
b) The yield of maize following groundnut-pigeonpea intercrop will be higher than that following pure stands of either
c) The doubled up legume system will increase particulate organic matter N in the subsequent season compared to sole legumes.

3.2 MATERIALS AND METHODS

3.2.1 Site description

This study was conducted in Ekwendeni area of Mzimba district, northern Malawi. The study site is located at $11^{0}20'S$, $33^{0}53'E$, with an elevation of 1200m (data collected during the baseline survey, chapter 1). The area receives medium to high rainfall ranging from 800-1200 mm annum^{-1}. Baseline soil tests (chapter 1 of this thesis) showed that most soils are coarse textured, slightly acid (pH=6.2), low in SOM (12±4 g kg^{-1}) and low to medium levels of inorganic P (33±26 mg kg^{-1}). The precipitation pattern is unimodal, commencing in Nov or Dec and lasting till about April.

3.2.2 Treatments and experimental design

Cropping system treatments include different types of legume diversification, where growth types varied from an annual grain legume (groundnut) to a semi-perennial grain legume (pigeonpea), grown as sole crops or as intercrops. A continuous maize system in treatments 1-3 is compared to legume-maize systems where legumes are grown in year one, and rotated with maize in year two for treatments 4-7 (Table 3.1). The year one treatments included sole crops (treatments 5 and 6), compared to a legume-maize intercrop (treatment 4) and legume-legume intercrops (treatments 7 and 8). Treatment 8 tests a more perennial form of legume diversification by evaluating a two year pigeonpea system, where pigeonpea is intercropped with groundnut in year one, then ratooned (cut back after harvest) and allowed to grow back as an intercrop with maize in year two (Table 3.1).

A maize nitrogen rate experiment was conducted along with the diversification cropping system experiment (Mc Swiney et al., 2010). This was a means to investigate a maize N response curve and calculate N fertilizer equivalency for the legume cropping systems in the preceding season (Treatments 1 to 3, Table 3.1).

The treatments were arranged laid out in a randomized complete block design (RCBD) with 20 farmers, each farm as a single replicate (Bellon and Reeves (eds.), 2002). The plot size per treatment consisted of 11 rows (aligned on a ridge following farmer practice in Malawi), 10m by 10m, spaced at 0.90m apart. The net plot used for measurements of grain and biomass consisted of the interior 8m of 7 centrally located ridges, to reduce border effects by not monitoring the external 1m of row .

3.2.3 Management

Maize, MH18 variety was planted on all plots that were previously planted to maize and diversified legume cropping systems (Table 3.1). MH18 is a hybrid semi flint maize variety with a yield potential of 5-6 ton ha^{-1} (Malawi Government-MoAIFS) and takes about 4months to reach physiological maturity.

Ridges were made at 0.90m apart with a hand hoe. Maize, MH18 variety was planted in December 2008 at 3 seeds per station, spaced at 0.75m apart (Table 3.1), for a maize population of 37,000 plants ha^{-1}. In treatment 8, pigeonpea was ratooned and intercropped with maize in year 2 in an additive design with a maize:pigeonpea ratio of 1:1 for double the plant population (Snapp et al., 2002). Residue N inputs from year 1 and cropping history are described in Chapter 2 of this thesis.

In year 2, fertilizer (Urea, 46% N) was applied at the rate of 24 kg N ha^{-1} at 4 WAP. The assumption was that early season maize growth would be provided by SOM and recently incorporated legume residues. The plot which had sole maize in year 1 was split into three, zero inorganic N fertilizer, 24 kg N ha^{-1} and 92 kg N ha^{-1}. All cultural practices were done according to smallholder farm practice, including hand hoe weeding in a timely manner. Crop performance was monitored throughout the growing season, by visits from scientists and support staff.

Table 3.1: Treatments and Planting Pattern in seasons 1 and 2

Treatment	Year 1 (2007/08)	Year 2 (2008/09)	Planting pattern Year 2	Soil fertility management, Yr 2
1	Sole MZ	MZ	3 seeds/station x 0.75m	No fertilizer
2			3 seeds/station x 0.75m	24 kg N ha^{-1}
3			3 seeds/station x 0.75m	92 kg N ha^{-1} (23 kg N ha^{-1} starter fertilizer; 69 kg N ha^{-1} at 4 WAP)
4	MZPP	MZ	3 seeds/station x 0.75m	24 kg N ha^{-1} at 4 WAP
5	Sole GN	MZ	3 seeds/station x 0.75m	
6	Sole PP	MZ	3 seeds/station x 0.75m	
7	GNPP	MZ	3 seeds/station x 0.75m	
8	GNPP	MZ + ratooned PP	Maize: 3 seeds/station x 0.75m. The ratooned PP was in the furrow	

MZ=maize; PP= pigeonpea; GN = groundnut; MZPP= maize-pigeonpea intercrop;
GNPP = groundnut-pigeonpea intercrop; WAP = weeks after planting

3.2.4 Data Collection:

3.2.4.1 Rainfall: Rain gauges were put in strategic locations in the study area, a total of two per village. During the growing season, rainfall data were recorded by selected participating farmers who were trained by the scientists

3.2.4.2 Soil sampling and analysis

Eight soil samples were collected per each plot in a random manner and composited, then were well mixed, at four weeks after planting maize, prior to application of fertilizer. The sampling depths were 0-15 cm and 15-30 cm. The soils were air dried and sieved to pass a 2 mm sieve, after a subsample was stored in the refrigerator at x temp for nitrate-N analysis. Nitrate nitrogen was extracted by adding 30ml of 2M potassium chloride to 3g of soil (Anderson and Ingram, 1993). NO_3^- was determined on a spectrophotometer using a deuterium lamp at 210nm. POM was analyzed on analyzed on ungrounded using fractionation procedures described by Cambardella and Elliot, 1992), modified as described here. Soils were mechanically separated POM was extracted by shaking with 0.5g L^{-1} sodium hexametaphosphate for 17 hours. Thereafter, soils were sieved through a 53 micron sieve and washed with deionised water until effluent run clear. POM was extracted using sodium polytungstate of density 1.85g ml^{-1}. Sodium polytungstate was recycled according to Six et al., (1999). After POM extraction, the sample was ground into powder with a clean mortar and pestle. POMC and POMN were determined using a dry combustion C and N Analyzer (Costech ECS 4010, Costech Analytical Technologies, Valencia, CA).

3.2.4.3 Chlorophyll

Chlorophyll measurements were taken using a Minolta SPAD meter at 4 WAP and 10 WAP. At 4WAP, chlorophyll readings were taken from the upper most expanded leaf (Blackmer and Schepers, 1995; Scharf et al., 2006). At 10 WAP chlorophyll readings were taken from the ear leaf. On each net plot, chlorophyll readings were taken for 30 randomly selected plants and then averaged.

3.2.4.4 Plant sampling and maize yield

Destructive sampling was done from each treatment at 4 WAP and at harvest to evaluate effect of legumes and cropping systems on biomass production. Three plants were randomly sampled from the net plot. Fresh weights were recorded, and these samples were dried in an oven at 70^0C to constant weight.

At harvest, nine plants were sampled along the diagonal line in the net plot to determine seed size, shelling percentage, and moisture content of stover and grain. To determine grain and stover yield, maize from the net plot was uprooted, total biomass and grain yield were determined. Grain yield was adjusted to 12.5% moisture content. Shelling percentage (SP) and harvest index (HI) were calculated using the formulas below.

$$SP = \frac{grainweight}{(core + grain)weight} * 100$$

$$HI = \frac{grainweight}{(grain + stover)weight} * 100$$

3.2.5 Farmer evaluation of maize response to sole and intercropped legumes

At physiological maturity, a questionnaire was administered to farmers to document feedback on technology performance, preferred technologies and constraints to scaling up (Appendix 3.1). A scale of 1-4 was used to rate each technology whereby: 1= very good technology; 2= good; 3= very poor; and 4= very poor technology. Means, frequencies and cross tabulations were computed in SPSS 17.0.

3.2.6 Data analysis

Normality of ANOVA assumptions was checked using PROC univariate procedure in SAS. There were outliers on yield from maize+ ratooned pigeonpea treatment, and therefore data from three replicates were excluded from the analysis. Residuals for plant biomass at 4 WAP were not normally distributed. Log transformation of plant biomass data was done and the AIC value was found to be lower (234) than from the analysis with untransformed data (706).

Legume cropping system effect: Maize response to legumes was analyzed with PROC MIXED procedure (SAS Institute, 2001). The replicates were considered as random effects while the treatments were fixed effects. The cropping system effect was evaluated by conducting a one way ANOVA of all treatments fertilized with the same level of N (treatments 2, 4-8, Table 3.1). Subsequently maize after legume system vs. continuous maize was tested. Differences between least square means were separated as t-tests. Planned contrasts were done to compare grain yield of maize following sole and doubled up legumes, doubled up legumes vs maize-pigeonpea intercrop, and continuous maize vs yield from all legume systems. The effects were declared significant at 5% level of significance.

Regression analysis was done to test if there was a relationship between yield of maize as the dependant variable (y) with crop residue and total residue N from year one, and chlorophyll readings. The effects were declared significant at 5% level of significance.

Nitrogen response curve: Grain yield from the 3 N levels were used to develop N response curve and calculate N fertilizer equivalency for the legume cropping systems in the preceding season (treatments 1 to 3, Table 3.1). Simple linear regression was conducted to evaluate the relationship between yield from continuous maize (Y) and three N levels as independent variable (X). Residuals were checked for normality using normal probability plots. Homogeneity of variances was assessed using plots of residuals versus predicted values. Presence of outliers was checked using Cook's D values. Stem and box plots showed presence of 2 outliers at each N rate. These were deleted from the data set and this solved normality and variance problems. Simple linear regression was used to analyze the data. Effects of N rate on grain yield were declared statistically significant at p=0.05. Data were analyzed using proc univariate and proc reg of SAS (SAS Institute, 2001). The relationship was used to construct N response curve and establish N fertilizer equivalency of legumes with or without a small amount of N fertilizer. The N fertilizer equivalency for the legumes without inorganic fertilizer inputs was calculated by subtracting 24 kg N ha^{-1} from the value on the N response curve.

Adaptability analysis: Adaptability analysis was conducted to assess two year maize rotation with diversified legume cropping systems in terms of calorie and protein yield according to Hilderbrand and Russell (1996). Grain yield were converted to calories and proteins using the following according to Gilbert (2004): calories from groundnut, 5.79/1000*grain yield; pigeonpea, 3.38/1000*grain yield; and maize, 3.63/1000*grain yield.

Protein yield was calculated by multiplying grain yield by 210/100g, 200/100g and 100/100g for groundnut, pigeonpea and maize respectively. Calorie or protein yield for each season was calculated separately by crop species and thereafter values were summed up for the intercrop systems before calculation of environmental index (EI). The EI was the average protein or calories at site. Simple linear regression was done on calories or protein as a dependent variable on environmental index. Analysis of variance was done with EI as the covariate, treatment as fixed effect and site as random factor. Where the EI and cropping system were significant, analysis of protein yield under different levels of EI was done. Statistical analysis was done in SAS proc mixed procedures. Effects were declared significant at p=0.05.

3.3 RESULTS

3.3.1 Rainfall

In the 2007/08 season (October/November 2007 to March 2008), rainfall was considerably below average at 669mm. This was much less than 800-1200mm, the expected range for this agroecological zone. A dry spell occurred in second half of February 2008, when maize and groundnut were at reproductive stage whilst pigeonpea was at vegetative growth stage. In 2008/09crop season, Ekwendeni received well distributed rainfall (total of 826mm) for production of most arable crops (Fig 3.2) starting in November, and ending in April. This is within the expected range of 800-1200mm for this area. In January 2009, an intense period of high rainfall occurred at some farm sites which led to visible sheet erosion, and may have leached nutrients as well. Another challenge in the 2008/09 season was a high growth rate of ratooned pigeonpea in maize-pigeonpea treatment 8, which appeared to be highly competitive with maize. Farmers were unwilling to prune pigeonpea as they were interested in harvesting pigeonpea grain along with maize grain, and maximizing pigeonpea residue production for soil fertility benefits (personal communication).

3.3.2 Effect of sole and intercropped legumes on soil nitrate, POM, POMC and POMN at four weeks after planting

3.3.2.1 Soil Nitrate at 4 WAP

Fig 3.3 shows mean values of nitrate-N on maize plots following legume cropping systems. NO_3^- in the top 0-15 cm soil layer ranged from 11±1.0 mg kg^{-1} on plots which had MZPP to

14±2.6 mg kg^{-1} on sole PP plots. Similar trend was observed in the 15-30 cm soil depth. These values fall within the medium range of 10-20 mg kg^{-1}. There was high variation of NO_3^- between farms and this could be related to differences in management among farmers and edaphic factors. Soil NO_3^- is variable under on-farm conditions so it was not surprising that cropping system treatment and legume type grown in the previous year did not influence soil N status.

3.3.2.2 Particulate organic matter (POM), POM carbon (POMC) and POM nitrogen (POMN) at 4 WAP, 0-15 cm soil depth

Soil organic matter fractionation was conducted, and POM, POMC and POMN results are shown in Table 3.2. POM ranged from 3±1.0 g kg^{-1} following sole PP or MZPP to 4±0.61g kg^{-1} on fields previously planted to GNPP. On-farm variability of soil organic matter pools was high, with a coefficient of variation of 35% for POMC and 40% for POMN. The cropping system present in 2007/08 did not influence the total amount of POM, POMC and POMN in the soil but significantly affected the concentration of POMC, p=0.0

379. The overall means were 3.7 g kg^{-1} soil, 825 mg kg^{-1} soil and 36 mg kg^{-1} soil for POM, POMC, and POMN respectively. A planned contrast was carried out comparing soil organic matter pools of treatment 1, continuous sole maize with treatment 8, GNPP rotated with maize. A trend was observed in POMC and POMN, with less in treatment 1 sole maize (POMC 710 ± 270 mg kg^{-1}) than in treatment 8 planted previously to doubled up legumes (920 ± 440 mg kg^{-1}).

Similarly, smaller POMN values were observed in sole maize (29 ±15 mg kg^{-1}) than in doubled legumes (43 ±20 mg kg^{-1}).

The concentration of POMC was significantly different among cropping systems, p=0.038, however, no differences observed in concentration of POMN (Table 3.2). GNPP increased POMC concentration by 12% over sole groundnut (p=0.0532) and maize (p=0.045) cropping systems but not different from MZPP and sole PP. Similarly, POMC concentration was found to be higher following sole PP than GN, p=0.0087. The C:N ratio in POM did not differ between cropping systems and ranged from 22-24, mean equal to 23. Linear regression analysis on POM and sand or clay content showed no relationship between POM and texture.

3.3.3 Plant growth

Maize growth was influenced by cropping system (Figure 3.7; p-value = 0.03), as shown by aboveground biomass accumulated at 4 WAP. Unfertilized continuous maize had the lowest biomass accumulation. Evaluating all systems fertilized at 24 kg N ha^{-1} (treatments 2, 5-8), maize biomass was enhanced by 19 to 27% when grown subsequent to legume (s), compared to continuous maize (Fig 3.7). There were no differences in biomass between sole and doubled up legumes. However, GNPP and GNPPrat increased biomass of maize than MZPP/MZ rotation, p=0.031 and 0.06 for treatments GNPPrat and GNPP respectively.

Chlorophyll was monitored at 4 and 10 WAP (Table 3.3), and was consistent with growth data. The treatment which supported limited growth (unfertilized continuous, sole maize) also had the lowest chlorophyll rating at 4 WAP, 32. In comparison, application of 23 kg N ha^{-1} starter fertilizer increased chlorophyll rating to 39. Maize chlorophyll status was enhanced by the presence of legumes in the previous year, but no consistent pattern was observed in terms of legume growth type (annual vs semi-perennial) or cropping pattern (sole vs intercrop) and maize chlorophyll response. There was a decrease in chlorophyll level at 10 WAP for all treatments except the one with the highest N fertilizer input (92 kg N ha^{-1}). Continuous sole maize with no fertilizer input had the lowest chlorophyll levels and these plants looked stunted compared to other treatments (personal observations). Sole or doubled up legumes increased chlorophyll by 14% over continuous maize fertilized with 24 kg N ha^{-1}. Ratooned pigeonpea was associated with vigorous growth that may have competed for resources with intercropped maize in treatment 8, probably due to heavy rainfall in 2009 that enhanced growth rate of pigeonpea in the second year of the cropping system.

3.3.4 Grain and stover yield of maize

Maize grain yield following legume diversified cropping systems and different N fertilizer rates are shown in Table 3.4. The yield varied from 0.8 ton ha^{-1} for continuous sole maize with zero N input to 2.4 ton ha^{-1} for rotations with sole and doubled-up legumes, and 3.8ton ha^{-1} with application of 92 kg N ha^{-1}. There were significant differences in grain yield between the cropping system, p=0.0001 (Table 3.4). Maize following sole and doubled up legumes yielded higher than continuous maize. As expected, maize with 92 kg N ha^{-1} yielded highest (3.7 ton ha^{-1} grain) and 4.5 ton ha^{-1} stover. When legumes were complimented with 24 kg N ha^{-1}, there was an increase of 69%-200% in grain yield of maize, $p<0.0001$ (Table A3.1).

There were no differences in stover yield between continuous maize with zero N input and maize rotated with legume cropping systems. Maize with highest N input accumulated largest amount of stover among the other cropping systems.

Harvest index (HI) differed significantly with cropping system (p=0.0003) (Table 3.4). The values ranged from 0.41 under continuous maize without fertilizer to 0.71 for maize with 92 kg N ha^{-1} input, with mean equal to 0.51. Maize following sole legume and GNPP had higher HI (0.56-0.59) than continuous maize (0.45) or MZPP/MZ rotation (0.50). The 100 seed weight ranged from 26g to 31g with a mean=28g. Seed size of maize was the same for rotations with GN, GNPP and MZPP and continuous maize fertilized with 92 kg N ha^{-1}.

Shelling percent ranged from 76±6.6% under continuous maize to 82±3.5% in GN/MZ rotations with a grand mean of 78 % (Table 3.4). Cropping system effects were highly significant on shelling percent (p=0.0003) with higher values obtained from maize following legume cropping systems than continuous maize except when PP was ratooned.

Effect of diversified legume systems on yield of maize: Maize rotation with sole and GNPP yielded 51-62% higher compared to continuous sole cropped maize or MZPP/MZ rotation. The increase in grain yield were statistically significant for GN/MZ, PP/MZ and GNPP/MZ rotations, p= 0.0001, 0.0043, 0.0072 respectively (Fig 3.5). However, when pigeonpea was ratooned, the higher relative growth rate of pigeonpea resulted into shading of maize during vegetative growth stage. Contrary to the hypothesis, maize yields after sole and GNPP were not statistically different. Similarly, GNPP/MZ did not increase maize grain yield over than the traditional MZPP/MZ rotation.

Effect of residue N and stover inputs from year 1 (2007/08 season) on maize yield: Under GN/MZ rotation, results from multiple regression with stover and residue N inputs as factors, and maize yield as a dependent variable showed that the model was significant only if both factors were included (p=0.009). The R^2 was = 0.646, thus, residue N and stover quantity explained 65% of the variation in maize grain yield. The relationship between maize grain yield (Y) and stover characteristics from sole groundnut was described by the following regression model:

$$Y = 1965 - 4.9 \text{ stover yield (kg ha}^{-1}) + 322 \text{residue N (kg ha}^{-1})$$

The root MSE was equal to 672. Standard error for parameter estimates were 408 for intercept; and 1.40 and 82.7 for slope estimates for stover yield and residue N inputs respectively. However, for the rest of the cropping systems, there was no were no significant relationship between stover quantity and residue N input with maize grain yield in year 2.

When chlorophyll at 10 WAP and residue N input from sole groundnut were included in the model to predict maize yield, the model was significant, (p=<0.0001), R^2 = 0.878. The parameter estimates for intercept, chlorophyll and residue N were all significant, p= 0.003, <0.0001 and 0.018 respectively. The relationship between maize grain yield (Y) and chlorophyll (x1) and residue N (x2) from sole groundnut was described by the following regression model:

$$Y = -2511 + 123 \text{Chlorophyll} + 31.8 \text{ residue N (kg ha}^{-1}).$$

Relationship between chlorophyll and maize grain yield: Chlorophyll levels at 4 WAP and grain yield were linearly related in all crop cropping systems except for PP/MZ rotation ($p<0.05$). However there was a weak correlation between the variables (R^2 = 0.19-0.49) (Table 3.5). Under

GNPP/MZ and MZPP/MZ systems, chlorophyll levels explained 50% of the variations in maize grain yield. At 10 WAP, chlorophyll levels were positively correlated with yield particularly under GN/MZ and PP/MZ crop rotation systems. Linear regression between chlorophyll reading and maize yield under GN/MZ indicated significant effects of model with F value=59.13 and Pr>F=0.008. The standard errors for estimates of the intercept and slope parameters were equal to 458 and 14.6, respectively. The R^2 was equal to 0.79, that is, chlorophyll explained 79% of variations in grain yield of maize, and RMSE was equal to 497. The relationship between chlorophyll readings at 10 WAP for GN/MZ rotations was described by following fitted regression models:

$$\textit{Maize yield (kg ha}^{-1}\textit{)} = 106.84(\textit{chlorophyll}) - 1462.92.$$

Similar results were observed under PP/MZ rotation in which chlorophyll readings explained 69% of the variation in maize yield. The relationship was described by the following equation: *Maize yield (kg ha^{-1}) = 116.74(chlorophyll) -1759.99*. The RMSE = 583.98, and standard error for intercept and slope were equal to 708.8 and 20.97 respectively.

3.3.5 Effect of nitrogen fertilizer on grain yield of maize

Maize grain yield differed significantly with N rates, p<0.0001. Application of 24 and 92 kg N ha^{-1} increased grain yield by 92 and 383% over continuous maize with zero N input (Fig A3.1). Linear regression analysis between N rates and maize yield indicated significant effects of model with F value=115.30 and Pr>F=<0.0001 (Fig 3.6). The standard errors for estimates of the intercept and slope parameters were equal to 156.31 and 2.97, respectively. The R^2 was equal to 0.71, that is, N rate explained 71% of variations in grain yield of maize, and RMSE was equal to

799. Grain yield at three N levels was used to construct N response curve. The relationship between maize grain yield (kg ha^{-1}) and N rate (kg ha^{-1}) was described by following fitted regression model:

Yield=764.43 + 31.84N

3.3.6 Nitrogen fertilizer equivalency of legumes

Nitrogen fertilizer equivalency (NFE) from diversified legume cropping systems ranged from 10 kg N ha^{-1} in MZPP/MZ to 31 kg N ha^{-1} under GN/MZ rotation (Table 3.6). This is equivalent to one to two-50kg bags of UREA fertilizer (cost price in 2009= ~US$70/50 kg bag). With ISFM (legumes plus 24 kg N ha^{-1}), N equivalency increased to 18-55 kg N ha^{-1}.

3.3.7 Calories and protein yield for the two year legume/maize rotations

Total calories ranged from 7.36×10^6 under PP/MZ rotation to 10.21×10^6 for GN/MZ rotation (Table 3.7). There was a positive linear relationship between calories and mean calories at site as the environmental index (EI) for all cropping systems (Fig 3.7). The R^2 was equal to 0.78, 0.77, 0.83, 0.88, and 0.94 for maize rotation with GN, PP, GNPP, MZPP and MZ respectively. The cropping system*EI interaction was not significant on calorie production. However, effects of cropping system and EI were significant, p= 0.0014 and <0.0001 respectively. Therefore, model with EI was used to evaluate effects of cropping system on calories yield. There were no significant differences in calories between GN/MZ and GNPP/MZ rotations but produced more calories than MZ/MZ. Similar observations were made on rotations with the two intercrop systems (GNPP/MZ and MZPP/MZ). PP/MZ gave less calories compared to GNPP/MZ (p=0.0005) and GN/MZ, p=<0.0001.

Protein yield by cropping system for combined years 1 and 2 are shown in Table 3.7. Protein yield was variable among farms ranging from 210 ± 109.21 kg ha^{-1} under PP/MZ to 315 ± 143.57 kg ha^{-1} for GN/MZ rotation. There were significant differences between cropping systems, p=0.0144. GN/MZ produced more proteins than the rest of the cropping systems but not different from the GNPP/MZ. The GNPP/MZ increased protein yield than PP/MZ system (p=0.0097). There were no differences in protein yield between GNPP/MZ and MZPP/MZ system.

Adaptability analysis on protein yield showed a linear relationship between protein yield mean site protein (EI) with R^2 equal to 0.64, 0.71, 0.79, and 0.74 for maize rotations with GN, PP, GNPP and MZPP respectively (Fig 3.8).

Analysis of variance indicated that the EI was highly significant (p<0.0001) and a trend on EI x cropping system interaction (p=0.0994) (Table A3.2). Analysis of protein yield at different levels of EI indicated that under less productive environments with mean protein yield of <180 kg ha^{-1}, PP/MZ gave less proteins compared to GNPP/MZ system (p=0.035) and continuous maize (p=0.037). In addition, there was a trend of higher protein yield under GN/MZ than PP/MZ (p=0.0493) and MZPP/MZ (p=0.092). For sites with a mean protein yield of 268 kg ha^{-1}, GNPP/MZ significantly increased protein yield over PP/MZ but same protein as GN/MZ. Similarly, GNPP/MZ produced 20% more proteins than MZPP/MZ, p=0.0661. In highly productive sites with mean protein yield >360 ≤ 450 kg ha^{-1}, GN/MZ, GNPP/MZ, and MZPP/MZ systems produced more proteins than MZ/MZ and PP/MZ.

3.3.8 Farmer evaluation of performance of maize and diversified legume cropping systems over two seasons, and preferred technologies to scale up

In 2007/08 season, results from farmer assessment of technologies based on a scale of 1 to 4 (1=very good, 2=good, 3=poor, 4=very poor) showed that GNPP and sole GN were rated as the best technologies with a mean of 1.55. This was mainly due to expectation of high yield and soil fertility benefits (65%). Farmers indicated that the GNPP has additional benefits over sole legumes including labor saving, food diversification, and soil moisture conservation. Sole pigeonpea was rated second with a mean rank of 1.65, then MZPP (2.80) and lastly sole maize (3.35). The top three technologies to be scaled up in order of preference were GNPP, MZPP and sole PP. the MZPP was chosen because it provides the staple food crop “maize” while improving soil fertility.

In 2008/09 season, a survey was conducted when maize was at physiological maturity stage to get feedback from participating farmers on performance of each crop rotation system. Results on overall rating of technology and reasons are shown in Table 3.8. Farmers’ ratings were based on seedling vigor, soil fertility benefits, yield and food (related to yield). The mean rating of each technology differed significantly depending on the previous cropping systems. Continuous maize with 92 kg N ha^{-1} was ranked as the best technology with a rating of 1.2 due to seedling vigor and high yield. All legume systems were ranked # 2 with mean rating of 2.1 (rotations with sole GN or PP) to 2.4 (MZPP). At the bottom was continuous maize with or without a small amount of N fertilizer.

Surprisingly, the top three technologies for scaling up by the farmers were different from the ratings on technology performance. Even though continuous maize with 92 kg N ha^{-1} was rated as the best technology due to high yield, farmers indicated that the high cost of inorganic fertilizers is a major constraint. The top three technologies for potential adoption in order of preference were GNPP/maize rotation, sole pigeonpea/maize rotation and MZPP/maize rotation. Farmers' choices were based on multiple factors such as food security and cost of inputs. They indicated that the doubled up legume offer multiple benefits to the farmers such as food diversification, income from groundnut and high crop yields due to improved soil fertility. In addition, farmers indicated that doubled legumes can provide enough starter N to support maize establishment and thereby saving money on inorganic fertilizer. Lastly, crop management practices are labor intensive and intercropping helps to maximize labor and land use.

Surprisingly, sole pigeonpea-maize rotation was ranked second. The main reasons cited were high maize yield after pigeonpea and also a source of relish. On the third position was MZPP/MZ rotation. This cropping system provides maize, the staple food every year while the pigeonpea improves soil fertility. The GNPP with pigeonpea ratooned can be cost saving in terms of seed and labor for planting. However, in this season, high rainfall increased growth rate of pigeonpea resulting into competition for light with the intercropped maize. Farmers were advised to prune pigeonpea but they did not comply because they expected to harvest grain earlier.

The main production constraints are unreliable rainfall, socio economic (seed availability for groundnut and pigeonpea, high labor inputs), agronomic (pests in maize in particular termites and a soil dwelling pest locally known as *"nkhwali"*), low grain yield of pigeonpea, beetles and weevils in pigeonpea) and livestock grazing in pigeonpea (Table 3.8). Livestock grazing was cited as by 20% of participating farmers in this on farm study.

3.3.9 Evaluation of legume-maize rotations based on agronomic benefits and farmer preference

Fig 3.9 shows a radar chart on technology performance based on residue N inputs in year 1 (2007/08 season), maize yield in year 2 (2008/09 season), nutritional benefits (protein and calorie) across two seasons and farmer preference of technology. All cropping systems received 24 kg N ha^{-1} in year 2 and variables on radar chart are presented relative to GN/MZ system. The GN/MZ rotation provided the most benefits in terms of residue N, maize yield, calories and proteins. However, this crop rotation system was the least preferred along with continuous maize. In terms of calories and proteins, all cropping systems were superior to continuous maize except for PP/MZ system. GNPP/MZ was ranked as the best technology followed by pigeonpea-maize rotations. Combining agronomic benefits and farmers' preference, GNPP/MZ was the best technology. The MZPP/MZ did not optimize yield of maize and calories but was fairly ranked among the top three technologies for wider adoption.

3.4 DISCUSSION

3.4.1 Effects of legume cropping systems on soil NO_3^-, POM, POMC and POMN

Legume diversified cropping systems improved inorganic N as evidenced by higher chlorophyll content compared to continuous maize at 4 WAP (Table 3.3). Similar results were reported by Chabi-Olaye et al., (2005) in which legume-maize rotations increased leaf N at 5 and 9 WAP. The higher levels on inorganic N on plots previously planted to doubled up legumes than MZPP is probably due to rhizodeposition from ratooned pigeonpea (Wichen et al., 2008) and also low residue N input from maize-pigeonpea intercrop in season 1 (2007/08) resulting into slow mineralization of mixed cereal-legume residues (Sakala et al., 2000). High variation of soil NO_3^- N between farms has been previously reported (Phiri et al., 1999) and this could be related to differences soil fertility and field management practices among farmers. These values fall within the medium range of 10-20 mg kg^{-1} and cannot support maize growth to physiological maturity. The results are contrary to findings by Rao and Mathuva (2003) and Bagayoko et al., (2000) of higher inorganic N (NO_3^- and NH_4^+) at planting time following legume-cereal rotations. This may be attributed to plant uptake as shown by higher chlorophyll content legume-maize rotation than continuous maize. In another study involving *Sesbania sesban*, Phiri et al., (1999) found that NO_3^- levels increased 2 to 3 fold in legume plots later in the season (12 WAP and 49 WAP) suggesting slow mineralization. Contrary to the hypothesis, doubled up legumes did not increase inorganic soil N over sole legume systems and this concurs with Rao and Mathuva (2003) probably due to same quantity of residue N and BNF rate per area basis in year 1 (2007/08 season).

POM pool is the labile fraction of OM and is sensitive to changes in cropping systems (Six et al., 2002). The levels of POM, POMN and POMC in this area (Table 3.2) are lower than values reported by Beedy et al., (2010) of 9-18 g kg^{-1}, 60-150 mg kg^{-1} and 800-2500 mg kg^{-1} for POM, POMN and POMC respectively, on fields under maize-Gliricidia-N fertilizer cropping systems in southern Malawi. This could be attributed to differences in cropping systems and soil texture. The soils in this study area have lower clay content compared to sites reported by Beedy et al., (2010). One cropping season of diversified legumes did not affect total POM, POMN and POMC in the soil but influenced the concentration of POMC. There was a trend of higher POMN content on plots previously planted to GNPP with PP ratooned at harvest compared to MZPP or sole maize can be attributed to N additions from rhizodeposition by the ratooned pigeonpea (Wichen et al., 2008). This study has also shown that the concentration of POMC is sensitive to changes in cropping system as reported by Six et al., (2002). Cropping systems with semi-perennial grain legumes such as pigeonpea or intercrops with short season grain legumes (e.g GNPP) have potential to increase POMC and contribute to total SOM pool in the long term than sole cropping of maize or annual grain legumes (groundnut). In another long term field study of 14 years, Beedy et al., (2010) reported positive effects of intercropping *Gliricidia sepium* with maize on concentration of POMC.

3.4.2 Effect of legume cropping systems on subsequent maize

Legume based cropping systems have potential to improve maize yield through improved soil N to support seedling growth and yield. The mechanisms through which legumes improve soil fertility and growth of subsequent maize are complex. This study has shown that legumes increased inorganic N at the start of the season as evidenced by higher chlorophyll levels and biomass of maize at 4 WAP compared to continuous sole maize. Significant linear relationship between chlorophyll content at 10 WAP and maize grain yield may suggest that chlorophyll measurements at early reproductive stage can be a useful predictor of maize yield (Blacker and Schepers, 1995). Maize following sole pigeonpea and doubled up legumes accumulating ~27% more biomass compared to continuous maize and maize-pigeonpea/maize rotations at 4 WAP and this agrees with Bagayoko et al., (2000). In another study, Marschner et al., (2004) who evaluated effects of legumes on growth and soil properties found that at 5 WAP, legumes increased root and shoot dry matter of sorghum 2-6 times over continuous sorghum. The lower plant biomass under MZPP/MZ is probably due to two reasons, firstly, lower residue N input (15 kg ha^{-1}) in season1 as compared to sole and doubled up legumes (24-27 kg N ha^{-1}); secondly, immobilization of available soil N by the maize stover (Sakala et al., 2000).

Low maize grain yield of <1000 kg ha^{-1} under continuous sole maize with incorporation of maize stover only are consistent with values reported under smallholder farms in Malawi (Snapp et al., 2002). This study has shown the importance of inclusion of legumes to increase crop yields and food security under smallholder farming systems. This finding support the hypothesis of legume-cereal rotations increasing yields than continuous maize and are consistent with earlier reports by Bagayoko et al., 2000; Rao and Mathuva, 2000; and Yusuf et al, 2009. The benefits are even more with ISFM (legumes plus 24 kg N ha^{-1}) in which maize yields can be increased by 69-200%. This rate of N is a ¼ of the recommenced rate of the area specific N fertilizer rates for maize on low N soils (Malawi Government MoAIFS, 2005). Yusuf et al., (2009) found that cowpea and soybean increased maize yields by 49-68% when P and K fertilizer were applied. The savings on inorganic fertilizer are quite substantial for resource poor farmers while building up soil fertility. The NFE values are 2-5 times higher compared to those reported by Carsky et al., (1999) for velvet bean, lablab, crotalaria and cowpea. Under ISFM, NFE values (18-55 kg N ha^{-1}) are comparable to findings by Kihara et al., (2007) of 40 kg N ha^{-1} NFE for soybean, and 18-27 kg N ha^{-1} for *Mucuna* and *Tephrosia candida* (Baijukya et al., 2006) with P and K inorganic fertilizer applied to the legume and/or maize. The HI for continuous maize with zero input or maize following diversified legume cropping systems (0.41-0.59) is comparable to 0.41-0.54, a range of values reported by Moser et al., (2006). Shelling percent for maize are not different from earlier studies by Betran et al., (2003) and Esechie et al., (2004).

The non significant difference of maize yield following sole and GNPP is contrary to the hypothesis but consistent with same N inputs through residues and BNF per area basis in year 1. This could be related to the effects of drought in year 1 (2007/08 season) that reduced biomass production, residue N inputs and BNF of intercropped legumes (Giller, 2001). Rao and Mathuva (2000) reported similar results of no yield difference in maize rotated with cowpea-pigeonpea intercrop or sole stands of either. Under MZPP/MZ rotations, inter-specific competition for limited water, and incorporation of high and low quality residues might have immobilized N during the early stages of maize growth thereby reducing plant biomass (Sakala et al., 2000).

Biomass quantity and residue N are important in predicting the yield of subsequent maize. However, results indicate variability between cropping systems on relationships between stover characteristics and maize yield. The amount of biomass incorporated and total residue N were significant in groundnut-maize rotations only. The findings on groundnut are similar to observations by Phoomthaising et al. (2003) and could be attributed to C:N ratio of residues.

The R^2 value (0.65) may suggest other multiple benefits from legumes of soil quality other than N inputs only, for example, enhancing mycorrhizal infections important in P limited soil, microbial biomass carbon, suppress soil pests and pathogens (Bagayoko et al., 2000; Yusuf et al., 2009). Baijukya et al., (2006) found no correlation between maize yield and residue N or amount of legume residues incorporated except for *Tephrosia candida* and *Crotalaria grahamiana* in zones receiving annual rainfall of 2100 mm.

3.4.3 Agronomic and farmer evaluation of maize rotation with diversified legume systems

Cropping systems that provide high grain yield are likely to be adopted by smallholder farmers for food security. Farmer assessment of performance of technology was based on crop responses in terms of seedling vigor, food value and yield. However, the criteria for choice of technology for potential adoption were based on multiple benefits such as yield, food value, input costs (seed, labor, land, inorganic fertilizers). Maize with 92 kg N ha^{-1} was ranked as the best technology because it gave highest yield. However, this is not affordable for most smallholder farmers due to high cost of inorganic fertilizer (Table 3.8). Based on agronomic performance and nutritional benefits, crop rotation with sole groundnut was the best technology for building soil N and increasing food availability. Even though the doubled-up legumes did not increase maize yield over sole legumes, this was farmers' number one ranked technology due to multiple benefits such maximizing labor and land use (Snapp et al., 2002), and food diversification while improving soil fertility.

The PP/MZ was ranked second followed by MZPP/MZ rotation. One feature worth noting is that pigeonpea features in all the top three technologies despite associated constraints (low yield, pests in field and storage). This implies that the farmers are aware of and value soil fertility benefits from this legume. These farmers have been trained in soil fertility and recipes by the SFHC project. However, future on research should incorporate integrated pest management of pigeonpea pests. There are socio-economic and biophysical constraints to adoption of legume based cropping systems. Almost all the constraints except unpredictable weather were also reported by Snapp et al., (2002) in Central and Southern Malawi.

CONCLUSION

This study investigated effect of sole and intercropped legumes on yield of subsequent maize. Legume diversified cropping systems increased inorganic soil N as evidenced by higher chlorophyll and biomass over continuous maize at early vegetative stage. Doubled up legumes (groundnut-pigeonpea intercrop) can contribute to N cycling and building POMN pool than cereal-legume intercrops. Smallholder farmers can increase maize yields by up to 62% through incorporation of groundnut and pigeonpea in maize based cropping systems, and by 200% with ISFM. There was no evidence of yield benefits on maize grown in rotation with doubled-up legumes over sole stands of either. However, multiple benefits of doubled-up legumes such as food diversification, savings on labor, maximizing land use and combined calories and proteins for the two seasons surpass the sole legume/maize rotations. Further studies are recommended on the potential of doubled-up legumes under unlimited soil moisture conditions. Secondly, interspecific competition in ratooned pigeonpea-maize intercrops should be investigated.

Small holder farmers are interested in technologies that are relatively cheaper in terms of inputs; provide reasonable yield and ecological benefits such as build soil fertility, crop diversity.

Table 3.2: Particulate organic matter (POM), POM nitrogen (POMN) and POM carbon (POMC) following diversified legume cropping systems

Cropping System year 1	POM (g kg^{-1} soil)	POMC (g kg^{-1} POM)	POMN (g kg^{-1} POM)	POMC (mg kg^{-1} soil)	POMN (mg kg^{-1} soil)	POM C:N ratio
Maize (MZ)	4(0.34)	214(10.14)a	10(0.48)	713 (92.31)	30 (3.66)	23 (0.91)
Groundnut (GN)	4 (0.34)	215(10.14)a	10(0.48)	848 (90.14)	38 (4.08)	23 (0.91)
Pigeonpea (PP)	3 (0.34)	247(10.14)b	11(0.48)	841 (90.14)	36 (4.08)	23 (0.91)
MZPP	3 (0.34)	224(10.14)ab	10(0.48)	724 (90.14)	31 (4.08)	24 (0.91)
GNPP	4 (0.35)	239(10.59)b	10(0.51)	865 (92.66)	37 (4.19)	24 (0.93)
GNPPrat	4 (0.34)	223(10.14)ab	10(0.48)	925 (90.14)	42 (4.08)	22 (0.91)
Mean	4	226	10	825	36	23
Pr>F						
Cropping system	0.614	0.037	0.123	0.380	0.303	0.244
Planned contrast:						
GNPP vs GN		0.0532				
GNPP vs PP		0.5229				
GN vs PP		0.0087				

Number in parenthesis is standard error; year 1= 2008/09 crop season; MZPP=maize intercropped with pigeonpea; GNPP=groundnut intercropped with pigeonpea; GNPPrat=groundnut intercropped with pigeonpea, pigeonpea cut 45 cm above groundnut at harvest in 2007/08 season and intercropped with maize in 2008/09 season; C:N= carbon to nitrogen ratio

Means in a column followed by same letter are not significantly different at p=0.05

Table 3.3: Chlorophyll in maize following sole and intercropped legumes

Cropping system Year 1$^{\Phi}$	Cropping system Year 2$^{\Phi}$	Chlorophyll Year 2	
		4 WAP	10 WAP
Maize (MZ)	MZ	32a	22a
MZ	MZ+24N	-	28b
MZ	MZ+92N$^{\Phi\Phi}$	39c	42d
Groundnut(GN)	MZ*	36b	32c
Pigeonpea (PP)	MZ	36b	33c
GNPP	MZ	36b	32c
GNPPrat	MZPP	36b	31b
MZPP	MZ	34b	31b
Mean		35	31
Pr>F (cropping system)		<0.0001	0.0113

Label at 4WAP	SE	Pr>|t|
GN vs PP	0.718	0.661
PP vs GNPP	0.679	0.607
GN vs GNPP	0.461	0.940
GNPP vs MZPP	0.855	0.127
Maize vs legume based systems	0.655	0.002

Note: $^{\Phi}$Year 1=2007/08 crop season, year 2 = 2008/09 crop season; WAP = weeks after planting; $^{\Phi\Phi}$at 4 WAP, only 23 kg N ha^{-1} was applied; *all plots that had legumes received 24 kg N ha^{-1} as top dressing fertilizer i.e. after collecting chlorophyll readings at 4 WAP;
GNPP = groundnut intercropped with pigeonpea; GNPPrat = groundnut intercropped with pigeonpea, pigeonpea cut at harvest in 2007/08 season and intercropped with maize in 2008/09 season; Means in a column followed by same letter are not significantly different at p<0.05

Table 3.4: Maize grain, stover yield, harvest index, shelling percent and 100 seed weight following legume cropping systems, 2008/09 crop season

Cropping system Year 1	Cropping system Year 2	Grain yield *(kg ha^{-1})*	Stover yield *(kg ha^{-1})*	HI	Shelling %	100 seed weight (g)
MZ	MZ+ 0N	814a	2174a	0.41a	76a	26ab
MZ	MZ+24N	1510b	3103b	0.47ab	75a	26ab
MZ	MZ+92N	3667d	4471c	0.71d	79b	31c
GN	MZ+24N	2444c	3286b	0.57c	82b	28abc
PP	MZ+24N	2392c	3249b	0.56bc	79b	28b
GNPP	MZ+24N	2286	3289b	0.59c	81b	29bc
GNPPrat	MZPP+24N	1377b	2944ab	0.45a	74a	27b
MZPP	MZ+24N	1830b	2609ab	0.50ab	80b	29bc
Mean		2038	3152	0.51	78	28
P value		<0.0001)	<0.0001)	0.0003	0.0003	0.003

Note: N rate in kg ha^{-1}; Year 1=2007/08 crop season; Year 2= 2008/2009 crop season
MZ = maize; MZPP = maize intercropped with pigeonpea; GN = groundnut; PP = pigeonpea; GNPP = groundnut intercropped with pigeonpea; GNPPrat = groundnut intercropped with pigeonpea, pigeonpea cut at harvest in 2007/08 season and intercropped with maize in 2008/09 season
Means within a column followed by same letter are not significantly different at p<0.05

Table 3.5: Linear regression parameter estimates between chlorophyll reading (x) and maize grain yield (Y)

Cropping system[a]	4 WAP				10 WAP			
	Intercept	Slope	R^2	Pr>F	Intercept	Slope	R^2	Pr>F
MZ/MZ	-999.9	54.4	0.28	*	-652.9	65.4	0.56	***
GN/MZ	-3334.4	150.2	0.31	*	-1461.9	101.8	0.79	***
PP/MZ	-3188.5	155.7	0.19	NS	-1760.0	116.7	0.69	***
GNPP/MZ	-2354.5	121.7	0.47	**	-1490.5	109.0	0.56	**
MZPP/MZ	-4047.5	163.1	0.49	**	-614.8	72.9	0.44	**
GNPPrat/MZPP[b]	-2638.7	108.2	0.23	NS	-53.3	33.3	0.17	NS

Note: [a]Cropping system in 2007/08 and 2008/09 seasons; WAP=weeks after planting; [b]Groundnut intercropped with pigeonpea in 2007/08, pigeonpea cut at harvest and intercropped with maize in year 2; MZ=Maize; GN=groundnut; PP=pigeonpea, MZ/MZ =continuous maize; GN/MZ = groundnut/maize rotation. Significance level: *at p<0.05; ** at p<0.01; *** at P<0.001; NS = not significant

Table 3.6: Nitrogen equivalency of diversified legume cropping systems

Legume cropping system year 1	N equivalency of legume cropping system+ 24 kg N ha^{-1} (ISFM) Kg ha^{-1}	N equivalency of legume cropping system only Kg ha^{-1}
Groundnut (GN)	55	31
Pigeonpea (PP)	49	25
GNPP	46	22
GNPPrat	18	0
MZPP	34	10

ISFM=Integrated soil fertility management; ratooned= pigeonpea cut at 45cm above ground at harvest in year 1; MZPP=maize intercropped with pigeonpea; GNPP=groundnut intercropped with pigeonpea; GNPPrat= groundnut intercropped with pigeonpea ratooned, pigeonpea ratooned at harvest and intercropped with maize in 2008/09 season

Table 3.7: Calories and proteins for a two year maize rotation with diversified legume cropping system

Cropping system in 2007/08 season	Cropping system in 2008/09 season	Caloriesx10^6	Proteins (Kg ha^{-1})
GN	MZ	10 (0.48)c	316 (28.69)c
PP	MZ	7 (0.51)a	211 (31.35)a
GNPP	MZ	10(0.48)c	295 (31.35)bc
MZPP	MZ	9 (0.51)bc	247 (31.35)ab
MZ	MZ	8 (0.48)ab	264 (31.35)ab
Mean		9	268
Pr>F		<0.0001	0.0144

Number in parenthesis is standard error

Means in a column followed by same letter are not statistically different at $p< 0.05$

MZ = maize; MZPP = maize intercropped with pigeonpea; PP = pigeonpea; GN = groundnut; GNPP = groundnut intercropped with pigeonpea

Table 3.8: Farmer evaluation of maize rotation with diversified legume based cropping systems

Technology year 1/year 2	Rating			Reasons for rating	Constraints	Benefits of technology
	Female N=11	Male N=8	Overall N=19			
MZ/MZ+ 0 N	3.6	3.8	3.8	Very poor maize yield (almost zero yield)	termites and pests locally known as Nkhwali; unreliable rainfall	Staple Food
MZ/MZ + 24N	2.6	3.1	2.9	Low maize yield	Same as above	Staple Food
MZ/MZ + 92N	1.4	1.1	1.2	Good establishment and high maize yield	High cost of inorganic fertilizer; termites and pests locally known as Nkhwali; ; unreliable rainfall	Staple Food
MZPP/MZ+ 24N	2.5	2.4	2.4	Medium maize yield; soil fertility from pigeonpea, food from maize;	Unreliable rainfall Maize: pests (termites and Nkhwali) PP: low yield, labor; seed, beetles and storage pests in PP; low yield; livestock grazing	Staple food Relish and soil fertility benefits from pigeonpea
GN/MZ + 24N	2.3	2.1	2.1	Good maize establish -ment, good maize yield with little inorganic fertilizer input	Labor, Seed unreliable rainfall	1. Improved soil fertility increase maize yield and food security; 2. Food (e.g. season relish) 3. Income
PP/MZ + 24N	2.4	1.9	2.1	Good maize establishment, high yield with little inorganic fertilizer input	Unreliable rainfall; yield, labor; seed, Pests (beetles and weevils in storage); Low grain yield; livestock grazing	1. Improved soil fertility, therefore high yield of subsequent maize and food security; 2. Food

Table 3.8 cont'd

Technology year 1/year 2	Rating			Reasons for rating	Constraints	Benefits of technology
	Female N=11	Male N=8	Overall N=19			
GNPP/ MZ+24N	2.4	2.1	2.2	Good maize establishment, high maize yield with little inorganic fertilizer input	Seed availability for both legumes; livestock grazing in pigeonpea; field and storage pests in pigeonpea	1. Improved soil fertility increase yield and food security; 2. Food diversification (e.g. relish from both legumes); 3. Intercropping maximize labor and land use; pigeonpea help to conserve soil moisture; 4. income from groundnut
GNPPrat/ MZPP + 24N	2.5	2.1	2.3	Maize yield reduced due to shading. Pigeonpea improve soil fertility	Low maize yield because ratooned pigeonpea shade maize; unreliable rainfall; livestock grazing; beetles on pigeonpea	1. Improved soil fertility for >2 years; 2. Food (e.g. relish from both legumes); 3. Intercropping maximize labor and land use; pigeonpea help to conserve soil moisture

year 1= 2007/08 season; year 2 = 2008/09; Rate of N in kg ha^{-1}; Maize grown on all plots in 2008/09 season; MZ=maize; GN= groundnut; PP= pigeonpea

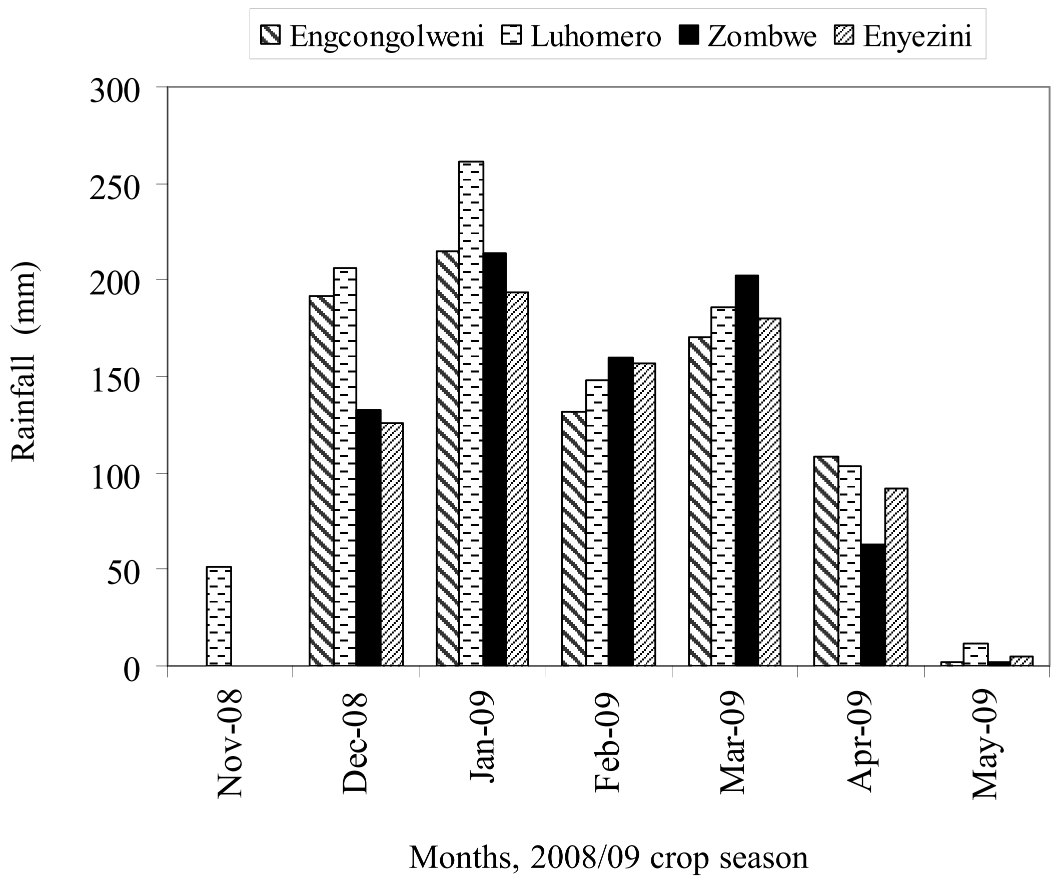

Fig 3.2: Average monthly rainfall for the study sites in Ekwendeni, 2008/09 crop season

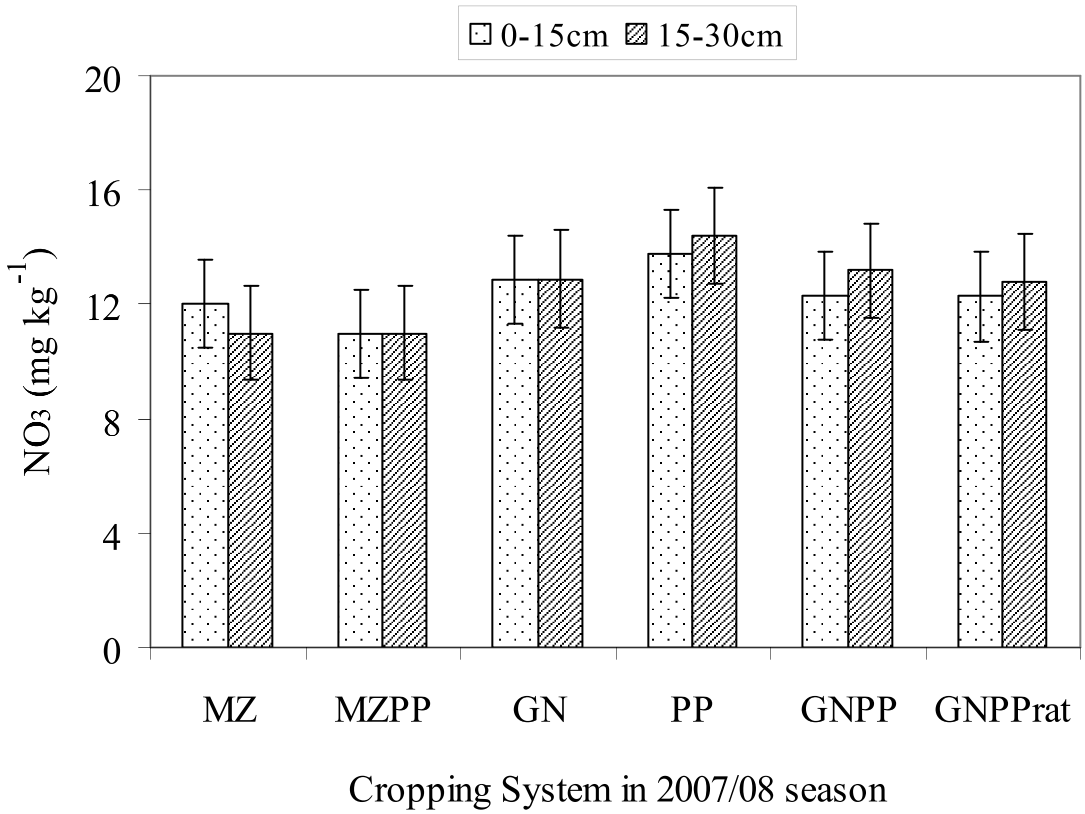

Fig 3.3: Soil nitrate levels on fields previously planted to maize, sole and intercropped legumes at four weeks after planting
MZ = maize; MZPP = maize intercropped with pigeonpea; GN = groundnut; PP = pigeonpea; GNPP = groundnut intercropped with pigeonpea; GNPPrat = groundnut intercropped with pigeonpea ratooned, pigeonpea ratooned at harvest and intercropped with maize in 2008/09 season
Error bars are standard errors;

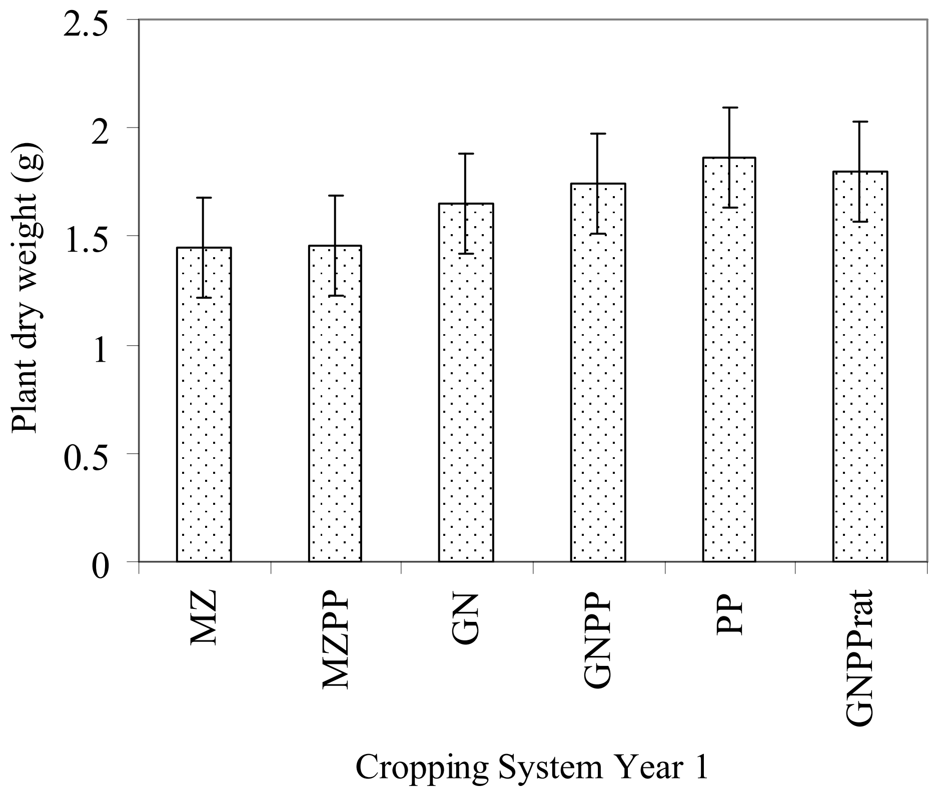

Fig 3.4: Maize dry matter/plant following legume cropping systems at four weeks after planting

Plant dry weight is based on log transformed values.

MZ = Maize; MZPP = maize intercropped with pigeonpea; GN = groundnut;
GNPP = groundnut intercropped with pigeonpea; PP = pigeonpea; GNPPrat = groundnut intercropped with pigeonpea, pigeonpea cut at harvest in 2007/08 season and intercropped with maize in 2008/09 season; Error bars are standard errors.

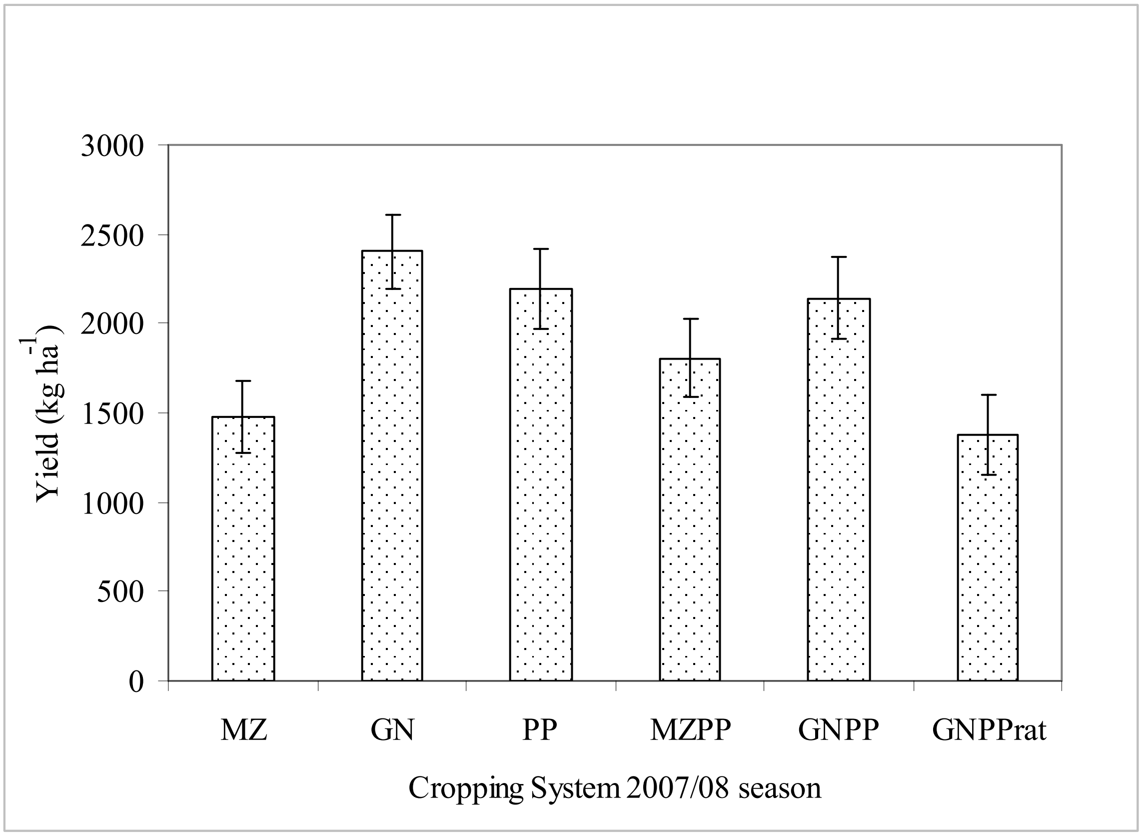

Fig 3.5: Effect of diversified legume cropping system on subsequent maize grain yield, all fertilized with 24 kg N ha^{-1}, 2008/09 season

Error bars are standard errors. MZ = maize; GN = groundnut; PP = pigeonpea; MZPP = maize-pigeonpea intercrop; GNPP = groundnut intercropped with pigeonpea; GNPPrat = groundnut intercropped with pigeonpea, pigeonpea ratooned at harvest and intercropped with maize in 2008/09 season

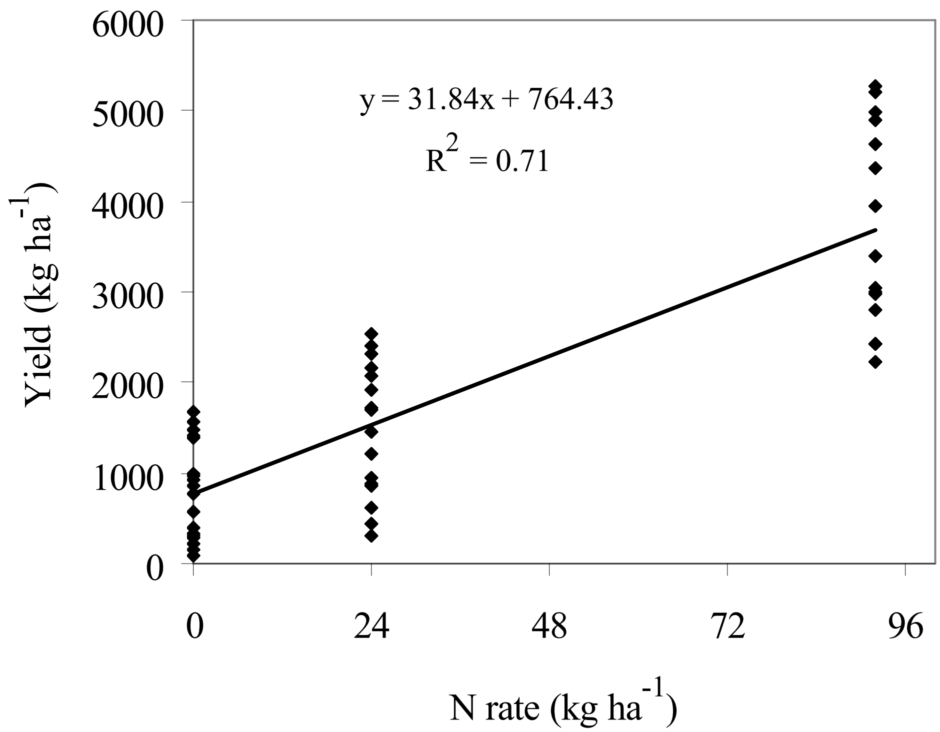

Fig 3.6: Effect of nitrogen fertilizer rate on grain yield of maize, 2008/09 season

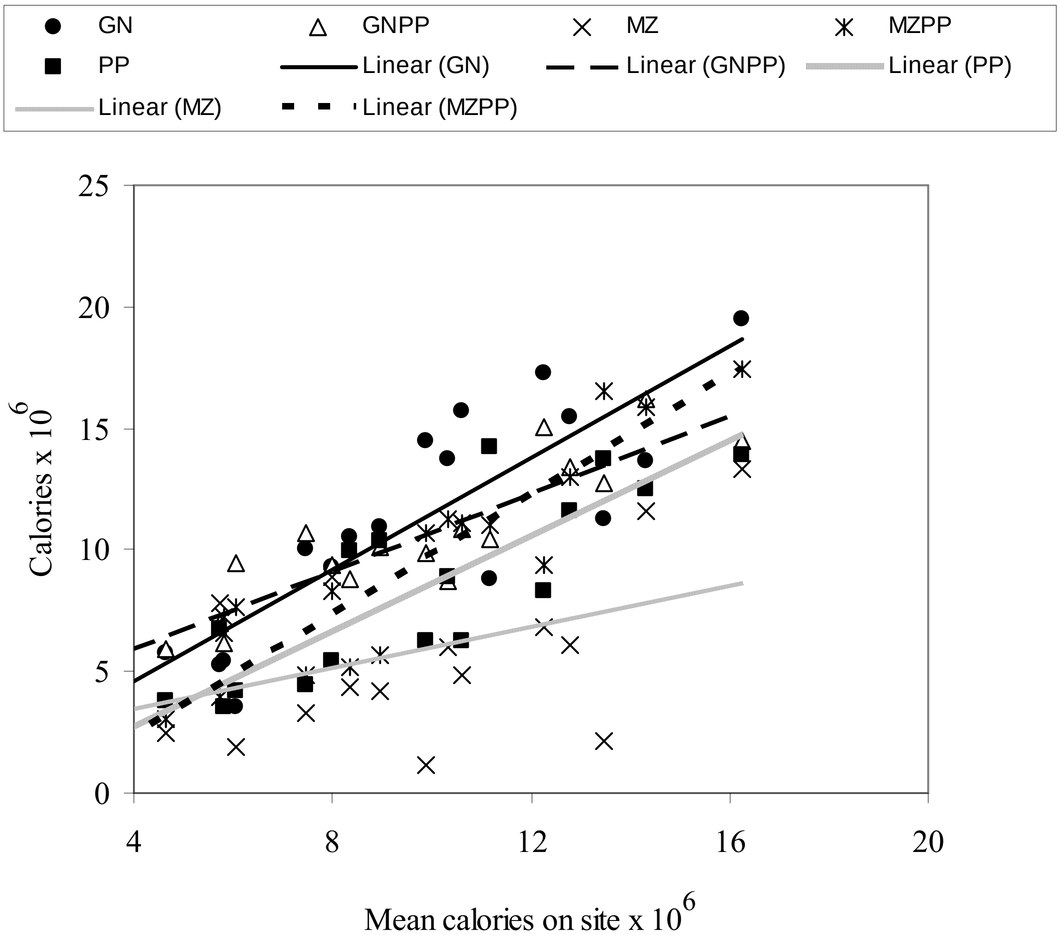

Fig 3.7: Relationship between calories yield and average calories per trial site following a two year maize rotation with diversified legume cropping systems, 2007/08 to 2008/09 seasons.
MZ = maize; GN = groundnut; PP = pigeonpea; MZPP = maize-pigeonpea intercrop; GNPP = groundnut intercropped with pigeonpea. These treatments were planted in year 1 (2007/08) followed by maize in year 2 (2008/09)

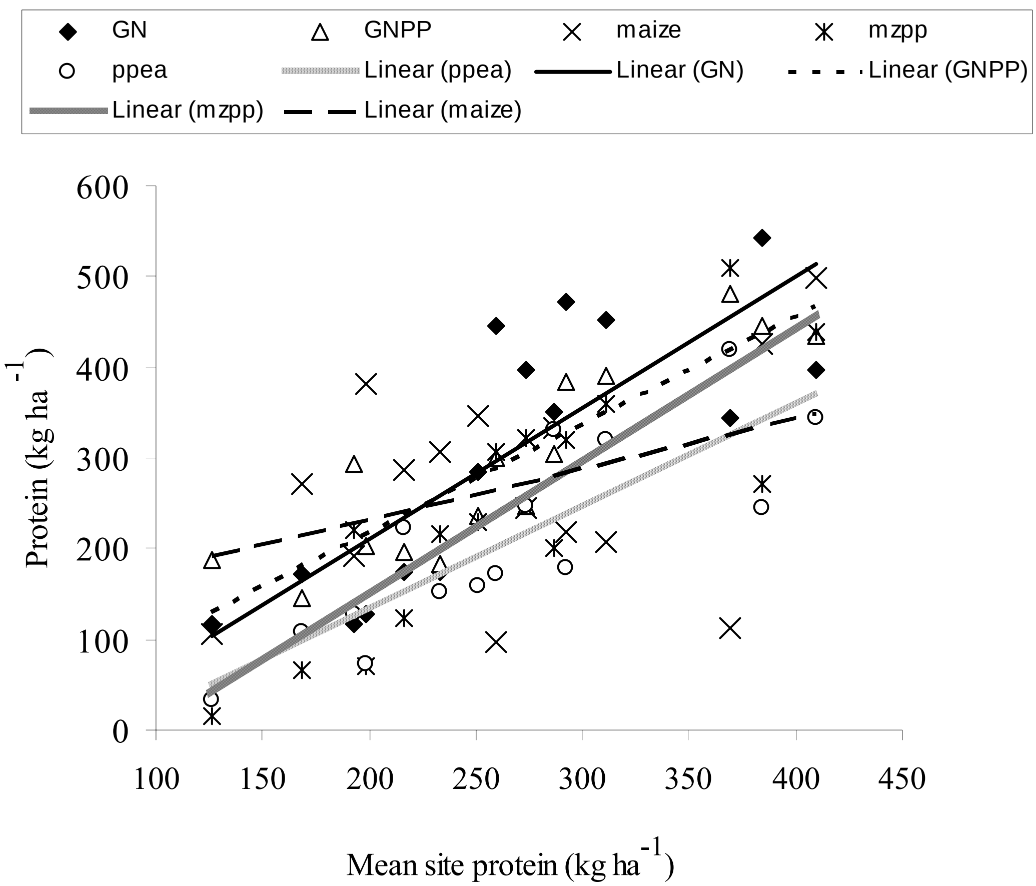

Fig 3.8: Relationship between protein production and average protein per trial site following a two year maize rotation with diversified legume cropping systems, 2007/08-2008/09 seasons

MZ = maize; GN = groundnut; PP = pigeonpea; MZPP = maize-pigeonpea intercrop;
GNPP = groundnut - pigeonpea intercrop. These treatments were planted in year 1 (2007/08 crop season) followed by maize in year 2 (2008/09 crop season)

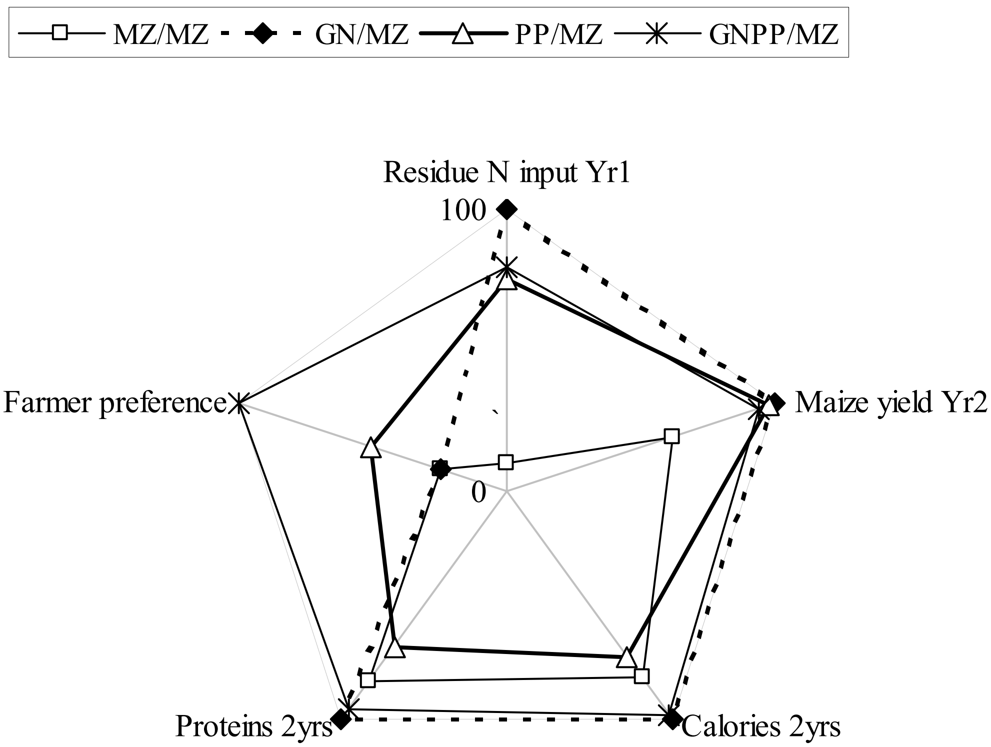

Fig 3.9: Technology performance based on residue N input, yield, grain quality and farmer preference.

MZ = maize; GN = groundnut; PP = pigeonpea; Yr = year; yrs = years;

GNPP = groundnut-pigeonpea intercrop. All cropping systems received 24 kg N ha^{-1} in year 2 (2008/09 season). Results presented relative to GN/MZ rotation. Absolute values are as follows: residue N input year 1 = 33 kg ha^{-1}; Maize yield year 2, 2444 kg ha^{-1}; Calories, 10 x 10^{6}; proteins, 312 kg ha^{-1}; farmer preference of technology, 4.

APPENDICES

Appendix 3.1: Farmer evaluation of maize response to sole and doubled up legume cropping systems, Ekwendeni 2008/2009 field experiments

Name of farmer:______________________________ Field ID #: ____________
Date: ____________ Interviewer: __________________

1). Ask the farmer to rate the response of maize to sole and doubled up legume technologies starting with "1" as a very good technology, 2 as a good technology, 3 as a poor technology and 4 as a very poor technology.

Plot	Yr 1 Treatment	Yr 2 Treatment	Rating	Comments
1	Sole groundnut (GN)	Maize+ 24N kg N/ha		
2	Sole pigeonpea (PP)	Maize +24N kg N/ha		
3	GNPP intercrop	Maize +24N kg N/ha		
4	GNPP, PP ratooned in year 2	Maize +24N kg N/ha		
5	Maize + PP	Maize +24N kg N/ha		
6	Sole maize	Maize + 0 kg N/ha		
	Sole maize	Maize+24 kg N/ha		
	Sole maize	Maize + 92 kg N/ha		

2) List the top 3 technologies which the farmer wants to grow more of, where #1 is the best. Ask the farmer if she or he plans to grow this technology next year, not just in a trial, but on a larger area.

List top technologies:	Will the farmers grow this technology next year, yes or no? Describe why or why not.
#1	
#2	
#3	

3) In the opinion of this farmer, what are the two most important CONSTRAINTS to growing more of these technologies?
1.

2.

4) In the opinion of this farmer, what are the two most valuable BENEFITS of growing more of these technologies?
1.

2.

Table A3.1: Contrasts on maize grain yield following diversified legume cropping systems and maize, 2008/09 season

Label (cropping system in 2007/08 season)	Estimate	Standard Error	t value	Pr>|t|
All legume systems vs MZ+0N	1252.66	179.85	6.96	<0.0001
MZPP vs GNPP	456.26	241.20	1.89	0.0614
GN vs GNPP	158.40	252.09	0.63	0.5312
PP vs GNPP	-105.72	248.64	-0.43	0.6716

MZ=maize; MZ+0N= continouos maize without inorganic fertilizer input; GN=groundnut; PP=pigeonpea

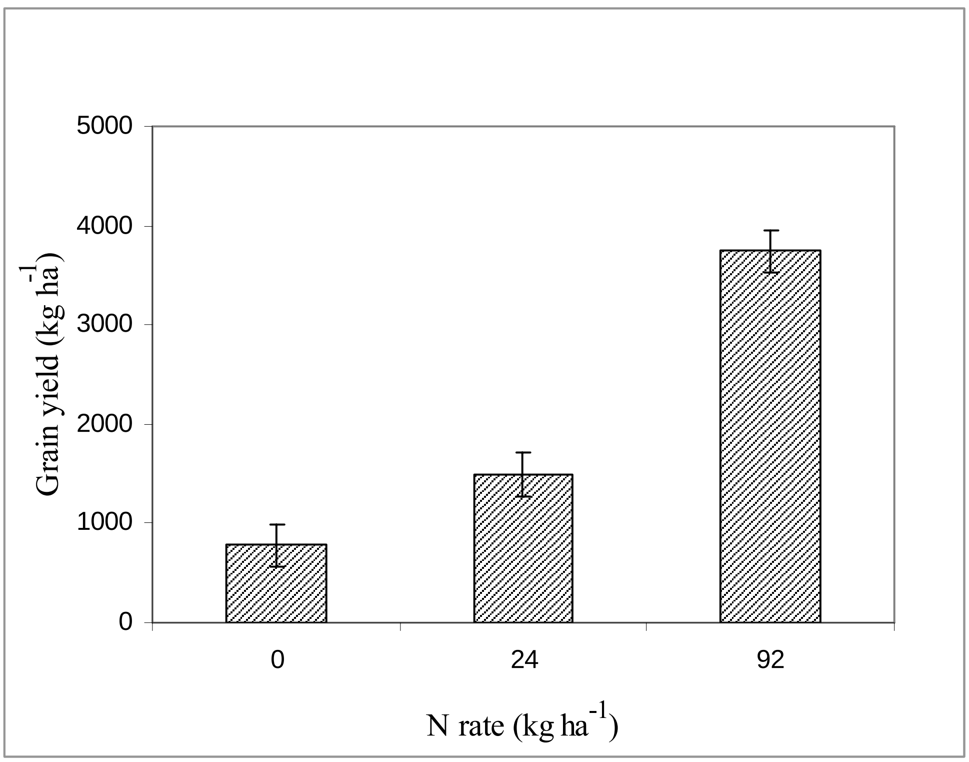

Fig A3.1: Maize yield at different rates of nitrogen fertilizer, 2008/09 season.
Error bars represent standard errors

Table A3.2: Total proteins for maize rotation with diversified legume cropping systems under different environments, 2007/08 -2008/09 season

Crop rotation system, 2008/2009Φ	Site protein mean (EI) (kg ha^{-1})			
	180	268	360	450
MZ/MZ	206b	258ab	313a	364a
GN/MZ	200ab	312c	428b	542c
PP/MZ	125a	213a	303a	392ab
GNPP/MZ	209b	299bc	392b	484bc
MZPP/MZ	136ab	250a	367ab	483bc
Mean	174	266	361	453
Test of fixed effects				
Effect	Pr>F			
EI (A)	0.2592			
Cropping system(B)	<0.0001			
A*B	0.0994			

Φ2008= 2007/08 crop season; 2009 = 2008/09 crop season. All cropping systems received 24 kg N ha^{-1} in 2008/09 season.
EI = Environmental index. This is the mean protein yield per site; MZ = Maize; GN = groundnut; PP = pigeonpea; MZ/MZ = maize/maize rotation; GN/MZ = groundnut maize rotation; PP/MZ = pigeonpea maize rotation; GNPP/MZ = groundnut intercropped with pigeonpea in 2007/08 season and rotated with maize in 2008/09 season; MZPP/MZ = maize intercropped with pigeonpea in 2007/08 season and rotated with maize in 2008/09 season; Means in a column followed by same letter are not significantly different at $p<0.05$

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CHAPTER FOUR: SUMMARY

4.1 INTRODUCTION

Smallholder farmers in SSA operate under stressed environments characterized by low soil fertility, pests and diseases, and unpredictable weather. Nitrogen and phosphorus are widely deficient in these woodland savannah soils, primarily course textured and low in organic matter. Fertilizer sources are unaffordable to the vast majority of resource-limited farmers in the region, yet nutrient requirements are high in order to boost crop productivity. Sustainable cropping system practices that maximize nutrient efficiency and ensure sufficient grain production are urgently required, as population density is increasing and food insecurity is an on-going challenge.

This study focused on the small, land locked country of Malawi. As is typical of southern Africa, cropping systems are dominated by maize, the staple food crop for a majority of Malawians occupying 70-80% of arable land (Alwang and Siegel, 1999; Snapp et al., 2002; Malawi Government MoAIFS, 2005). About 85% of the farmers are smallholders cultivating on 0.5-0.75 ha of arable land. The major maize based cropping systems include continuous monoculture of maize, maize-legume intercrop, maize rotation with sole and cereal-legume intercrops, and agroforestry (Mc Coll, 1989; Kwesiga and Coe, 1994; Snapp et al., 2002; Gilbert, 2004). The growing season is unimodal with precipitation commencing in November or December to April.

Maize grain yield under smallholder farms average less than 1000 kg ha^{-1} partly due to low soil N. Most farmers cannot afford to buy inorganic N fertilizers due to high cost prices. Legumes offer an alternative strategy to improve soil N because of their ability to fix N through BNF and incorporation of high quality crop residues (Toomsan et al., 1995; Phiri et al., 1999;

Giller, 2001; Werner, 2005). Groundnut and pigeonpea can fix 32-206 and 20-118 kg N per ha respectively depending on varieties, soil properties, cropping system, field management practices (Giller et al., 1987; Rao et al., 1987; Werner, 2005; Adu- Gyamfi et al., 2007).

Soil fertility benefits from legumes vary with species and variety (Kumar et al., 1987; Maskey et al., 2001; Unkovich and Pate, 2005); soil chemical properties, soil moisture, and population of *Rhizobium* species ((Fujita et al., 1992; Giller, 2001). There is a tradeoff between high grain yield and soil fertility in that grain legumes have high nitrogen harvest index (NHI) and subsequently nitrogen is removed and fertility benefits limited, compared to legume green manures. Negative N balances have been reported in cropping systems with soybean due to high NHI (Ojiem et al., 2007). In addition, perennial legumes with indeterminate growth such as velvet bean and long duration pigeonpea varieties have longer N fixation period than annual legumes with determinate growth (Maskey et al., 2001). Soil chemical properties affect BNF. Optimum levels of nutrients including inorganic N and P are required to boost root development, legume growth and enhance BNF. Research has shown that application of inorganic P fertilizer to legumes increase biomass production and BNF (Hoa et al., 2002; Jemo et al., 2006).

The net N input from legumes in cropping systems partly depend on total N fixed through BNF less N exports through grain harvest or residues if not returned to the field. Determination of N budget can help to improve sustainability of cropping systems through: identification and promotion of legume based cropping systems with more positive N balances for improvement of soil N while optimizing grain yields; and second, strategies to maximize N inputs in different cropping systems and environmental conditions. There is an information gap on performance and BNF of groundnut and doubled up legumes under smallholder farm conditions. Literature reviews indicate a tremendous range of BNF rate is possible, ranging from as little as 0 or 10 kg of N fixed to several hundred kg of N per hectare (Giller, 2001), but there is very limited knowledge of actual levels that occur within tropical cropping systems. In this study, the overall objective was to establish nitrogen budget for maize rotation with sole and intercropped grain legumes (maize-legume and legume-legume intercrops); and identify farmers' preferred legume cropping system.

4.2 STUDY SITE AND EXPERIMENTAL PROCEDURES

On-farm participatory trials were conducted in Ekwendeni area of northern Malawi in 2007/08 and 2008/09 cropping seasons to evaluate BNF and performance of sole and intercropped groundnut (*Arachis hypogaea*) and pigeonpea (*Cajanus cajan*), effects on particulate organic matter (POM), POM nitrogen (POMN) and subsequent maize. Ekwendeni is located at $11^{0}20'$S, $33^{0}53'$E, with an elevation of 1200 m, and annual rainfall of 800-1200 mm. Since 2000, the Soils Food and Healthy Communities (SFHC) project of Ekwendeni Mission Hospital has been promoting legume production among the small holder farmers to improve family nutrition, and educating farmers on residue management and legume utilization (Bezner-Kerr, 2005). Prior to implementation of field trials, household and farm field surveys were conducted in selected villages of Ekwendeni catchment working with the SFHC project. The objective was to characterize farming systems, farmer's perception of soil fertility and preferred legume characteristics. Through a farmer survey, paired fields were selected at each farm, one with a history of legume crops grown in combination with the staple maize crop, designated the 'legume field', the other a continuous maize-dominated cropping sequence with no legumes ('maize field'). Field specific data on cropping history for the previous three seasons and soil fertility management. Composite soil samples were collected from legume and maize fields from the 0-15 cm and 15-30 cm soil depths for chemical and physical analyses.

4.3 RESULTS AND DISCUSSION

4.3.1 Soil status

This onfarm study evaluated soil characteristics of fields previously dominated by either maize or legume cropping systems. The soils were shown to be largely light textured, sandy or sandy loam; with low organic matter (12±3.7 g kg^{-1}), and low to medium inorganic P (33±26 mg kg^{-1}). Exchangeable cations were adequate for production of most crops (calcium= 447 mg kg^{-1}; magnesium=112 mg kg^{-1}; and potassium=117 mg kg^{-1}. The CEC was 4.3±1.4 cmol kg^{-1}. No differences were observed between the legume and maize diversified field, except extractable inorganic P was lower in the legume field (26±18 mg kg^{-1}) than in the maize field (35±20 mg kg^{-1}) ($p=0.012$). Other studies have shown that farmers target soil fertility management practices and allocate portions with better soil fertility to maize rather than legume production (Tittonel et al., 2006). SOM levels are lower than 18-33 g kg^{-1}, range of values reported in earlier studies by Snapp et al., (1998) and Beedy (2008). Inorganic P status was highly variable among farms and the low levels cannot sustain production of most arable crops. In Malawi, the critical value of inorganic Bray P for maize production is 20 mg kg^{-1} (Chilimba et al., 1999).

4.3.2 Traditional knowledge of soil fertility

Farmer assessment of soil fertility status and indigenous terms used to describe soil types are documented using indigenous terms. Indicators of soil fertility included overall crop performance, yield, soil color and texture. This observation confirms earlier findings by Murage et al., (2000) and Mairura et al., (2007) but differ in that farmers did not mention indicators such as presence of specific weed species and invertebrate animals. Fertile soils were described as dongo lifipa "black soils," usually clays (chigandasi) or with mixed texture. Sandy soils locally known as "chichenga" were associated with low soil fertility and poor yield of maize and soybean. Farmers' description of sandy soils and black soils is similar to an earlier study in some parts of Malawi (Kamanga, 2002). According to Malawi soil classification, sandy soils are described as sandy ferrallitic soils with low organic and water holding capacity (Kamanga, 2002 quotes Lowole, 1995; and Young and Brown, 1962).

4.3.3 Cropping systems overview

There is a broad diversity of legume species among farmers ranging from food legumes to green manures. The main legumes grown in order of decreasing frequency are groundnut, soybean, pigeonpea, common bean, cowpea, velvet bean, bambara groundnut and fish bean. In literature, food legumes have been widely adopted than green manures Bezner-Kerr et al., (2007) and Mafongoya et al., (2007) except for species with multipurpose uses such as velvet bean for soil fertility and weed management (Schultz et al, 2003). Grain legumes were grown in sole and intercrop systems (legume-legume intercrop "doubled up legumes" or legume-maize intercrop). Doubled up legumes were of pigeonpea-groundnut or pigeonpea-soybean. Field primarily grown to maize was twice as much compared to fields primarily used to grow legume-diversified cropping systems (0.35 vs 0.15 ha). This indicates that there is a potential for building soil fertility through BNF but there is a challenge to increase total N fixed per area due to small hectarage allocated to legumes (Giller, 2001).

Preferred legume characteristics included high yield, nutritional value, food value, early maturity, good grain storage characteristics, high market potential, pest resistance and positive effect on soil fertility. Pigeonpea was the only grain legume that was primarily grown for soil fertility improvement. High yield was the number one criterion for evaluating groundnut and common bean, while nutritional benefits of soybean on children were highly valued. This poses a challenge on use of grain legumes to improve soil fertility in that there is a tradeoff between high yield and net soil N benefits due to NHI (Toomsan et al., 1995; Giller, 2001).

As farmers are interested in extension advice on recommended agronomic practices to optimize legume production and soil fertility, on-farm participatory demonstrations can help to build the capacity of farmers (Norton et al., 1999). Other demand driven extension advice include marketing, post harvest handling of grain, and utilization of legumes specifically value adding activities such as oil extraction from groundnut and soybean milk or meat.

The cropping system diversity at this site has changed over time, with more legume species being grown now than 12 years ago. Groundnut, common bean, cowpea and bambara groundnut have been grown for decades and in addition three new species are now being grown: pigeonpea, soybean, and velvet beans. About 50% of the farmers indicated fish bean was not a new legume even though it was adopted by only 22% of project farmers. Project farmers were designated as those who are actively involved in SFHC activities and have received training from this project; they were found to have adopted more legumes than control farmers. Twenty six percent and 38% more pigeonpea and soybean respectively were grown by project farmers than control farmers. About 40% of farmers surveyed grew velvet bean whether or not they worked with the SFHC project. High diversity of legumes among project farmers demonstrates the impact of the SFHC project in this area. Project farmers are trained in production and utilization of legumes using participatory approaches (Bezner-Kerr et al., 2007).

Constraints to legume production: There are biophysical (soil fertility, pests, non preferred varieties), socio-economic (seed availability, labor) and natural (unpredictable weather) challenges to sustainability of legume based cropping systems. Cross cutting issues for all legume species were mainly socio-economic at household (no money) or policy issue (lack of markets, seed not locally available). Specific constraints to producing legumes as perceived by farmers are discussed in detail in chapter 1. Seed shortage and marketing issues have been previously been reported (Snapp et al., 2002; Kabambe et al, 2008). Certified legume seed is expensive and hence not affordable for a majority of small holder farmers. There is need for the government and non governmental organizations to find strategies for increasing seed availability to smallholder farmers. This might include investments in infrastructures to facilitate seed distribution and support local seed banks.

Generally, cropping systems are optimized for maize production as evidenced by less hectarage allocated to legumes compared to maize, higher inorganic P on maize diversified fields than legume diversified fields, and wide ridge spacing do not maximize plant population of legumes. Another constraint to legume production is low inorganic soil P (Giller, 2001; Hoa et al., 2002). In the onfarm trials, we found that BNF of both groundnut and pigeonpea was negatively correlated with inorganic soil P. There is need to identify strategies for increasing smallholder farmer access to phosphate fertilizer in order to improve legume productivity and associated ecosystem services.

4.3.4 Biological nitrogen fixation and yield of diversified legume cropping systems

Legumes can help to improve soil N through biological nitrogen fixation. Studies on BNF and yield of legumes have been reported. However, not much is known about BNF and growth of legumes under smallholder farmer environment and diversified legume cropping systems. On-farm trials were conducted in Ekwendeni, northern Malawi in 2007/08 (season 1) and 2008/09 (season 2) crop seasons to evaluate BNF by sole and intercropped groundnut (annual grain legume) and pigeonpea (semi-perennial legume). It was hypothesized that N fixation per area basis would be higher under legume-legume intercrop than sole stands of either but lower on per plant basis. The treatments consisted of sole system of groundnut (GN), pigeonpea (PP) and maize (MZ); and intercrops of groundnut-pigeonpea (doubled up legumes) (GNPP) and maize-pigeonpea (MZPP). BNF of sole and intercropped legumes was determined by $^{15/14}N$ natural abundance method (Shearer and Khol, 1986; Peoples et al., 1989). The experiments were researcher designed but managed by farmers. In 2007/08 season, the area experienced a dry spell when GN and MZ were at reproductive stage (pod formation and grain filling) and pigeonpea was in vegetative growth stage.

Adaptability analysis (AA) is a method used to evaluate performance and adaptation of cropping systems to specific environments (Hildebrand and Russell, 1996). The environment includes both the socioeconomic and biophysical factors that influence crop performance. AA on calories showed that under low productive environments, sole groundnut and doubled up legumes produced more calories than the other cropping systems. In contrast, in high yielding environments, sole cropped MZ produced more calories than legume diversified cropping system. Pigeonpea showed wide adaptation across the environments making it a suitable candidate for soil fertility management under the highly variable smallholder farming systems in SSA. A study by Hogh-Jensen et al., (2007) showed differences in adaptation of pigeonpea varieties to the environment using grain yield as a response variable and mean yield per trial site as an environmental index.

Biomass production of groundnut was not optimized in a season with insufficient rainfall and this may have negative implications for crop residue N accumulation and BNF. Cropping system had no effect on nodule numbers per plant for both legumes, and BNF per plant basis of groundnut. However, pigeonpea grain yields were not affected by season. Doubled up legumes did not increase BNF rate per area over sole stands of GN or PP. In a drought season, on area basis, sole groundnut fixed 63% more N than sole pigeonpea. Even though maize, pigeonpea and groundnut have complementarities and redundancy characteristics in-terms of initial growth rates, N fixation, and photosynthetic pathways (C3 vs C4), interspecific competition decreased vegetative growth and BNF of pigeonpea. Assessment of intercrop productivity indicated that intercropped species were more efficient at utilizing resources than sole stands as shown by LERs greater than 1: 1.56 and 1.50 for MZPP and GNPP.

4.3.5 Effect of diversified legume systems on performance of maize and ecosystem services

Legume based cropping systems are one of the strategies to improve soil N and maize productivity. Smallholder farmers require technologies that are affordable, adapted to varied agroecologies, and provide a wide range of services in the short and long term. Ecosystem services and performance of maize following diversified legume cropping systems were evaluated in 2008/09 season. Participatory on-farm experiments were established on fields previously planted to sole and intercropped annual grain legume (groundnut) and semi-perennial grain legume (pigeonpea). Cropping system productivity was assessed in terms of grain yield of maize, calories for the two year rotation, POMN and POMC. In year one (2007/08), crop residue N production ranged from 12 kg ha^{-1} in a MZPP to 33 kg ha^{-1} under sole GN. A maize nitrogen rate experiment at 0, 24 and 92 kg N ha^{-1} was conducted along with the legume diversification system trials in year two of the rotation to assess maize N response curve and determine N equivalency of diversified legume systems.

Plant indicators of N status (chlorophyll and biomass) showed that maize growth in year two was influenced by cropping system. Legume cropping systems increased maize growth ($p=0.03$) and chlorophyll ($p<0.0001$) at early vegetative crop stage over continuous maize. However, no effect observed in terms of legume growth type (annual vs semi-perennial) or cropping pattern (sole vs doubled up legumes). These observations are similar to findings by Bakayoko et al., (2000) and Maschner et al., (2004) in which legume cropping systems increased biomass of maize and sorghum than continuous cereal system. In contrast, soil indicators of inorganic N were not responsive to cropping systems probably due to the dynamic nature on nitrate N and we only did one time measurement.

Diversified legume cropping systems increased the subsequent maize grain yield by 21-65% over continuous maize, $p<0.05$. Maize grain yield of <1000 kg ha^{-1} under continuous unfertilized maize are consistent with values obtained on small holder farms in Malawi (Snapp et al., 2002). Benefits of legume cropping systems on soil fertility and yield of cereals have been previously documented (Katayama et al., 1995; Rao and Mathuva, 2000). With integrated soil fertility management (ISFM) (legumes cropping system + 24 kg N ha^{-1}), grain yields were 69-200% higher than continuous unfertilized maize (1329 to 2444 kg ha^{-1}). Contrary to the hypothesis, GNPP did not optimize subsequent yield of maize over GN/MZ or PP/MZ rotation. Nitrogen fertilizer equivalency (NFE) of organic N sources (crop residues) was found to be highest in GN/MZ rotations (31 kg N ha^{-1}) and least in MZPP/MZ system (10 kg N ha^{-1}). NFE with ISFM varied from 18 to 55 kg N ha^{-1}. NFE ranging from 5-40 kg ha^{-1} have been reported depending on soil chemical properties, soil moisture, legume species, residue management and inorganic N and P fertilizer applied to legume (Carsky et al., 1999; Baijukya et al., 2006; and Kihara et al., 2007). The NFE values in this study are 2-5 times higher than those reported by Carsky et al., (1999) probably due to residue incorporation. Others studies have reported NFE values of 40 kg N ha^{-1} for soybean/maize rotation (Kihara et al., 2007), and 18-27 kg ha^{-1} for *Mucuna* and *Tephrosia candida* with application of inorganic P and K fertilizer to the legumes. The doubled up legume system where ratooned pigeonpea was allowed to grow a second year as an intercrop with maize was highly competitive resulting in significant reduction in maze grain yield in year two.

Adaptability analysis over two seasons showed higher calorie production from GN/MZ and GNPP/MZ rotations than the other crop rotation systems. Other studies have used AA to compare adaptation of different varieties across environments using grain yield as an environmental index and specific recommendations have been made according to environments (Hogh-Jensen et al., 2007). Similarly, maize rotation with diversified legume cropping systems improved protein yield than continuous maize except for PP/MZ rotation. This implies that farmers can improve calories and protein yield by inclusion of legumes in maize based cropping systems probably due to improved inorganic soil N and yield of subsequent maize (Bationo and Ntare, 2000; Ncube et al., 2007) and grain quality (Liu, 1999; Ncube et al., 2007). Protein yield was positively related to productive potential of site. Under low to medium yielding environments with average protein of ≤268 kg ha^{-1}, GN/MZ produced higher protein yield than MZPP/MZ, PP/MZ and MZ/MZ but similar to GNPP/MZ system. However, under high productive domains with mean protein yield of ≤450, crop rotation systems with diversified legumes were highly responsive producing 32-49% more protein than MZ/MZ except for PP/MZ that gave minimal increase (8%). Therefore, farmers can take advantage of the favorable production environments (both biophysical and socio economic) to scale up legume/cereal rotations with either annual or semi-perennial grain legumes in order to optimize grain and protein yield.

Technologies that provide multiple ecosystem services are likely to be adopted by smallholder farmers. A farmer preference survey showed that technologies suitable for wider adoption ranked from highest to lowest as follows: GNPP/MZ rotation, PP/MZ rotation and MZPP/MZ rotation. This was shown to differ from the maize grain yield rank order in which continuous sole maize (MZ/MZ) fertilized with 92 kg N ha^{-1} was ranked as the best, followed by maize rotation with sole and GNPP. Continuous maize with or without a small dose of inorganic N fertilizer was ranked as the least. Farmers' choice of technologies were based on input costs (inorganic fertilizer, labor), food diversification, soil fertility benefits of legume cropping system as indicated by seedling vigor of maize grown after legume and the associated grain yield. Constraints to broader farmer adoption of legume cropping systems identified during the survey include: agronomic (low grain yield of pigeonpea, pests in pigeonpea and maize), natural (unreliable rainfall), socio economic (seed availability, labor inputs for farming activities), and cultural issues (livestock grazing in pigeonpea). Even though pigeon pea was mentioned repeatedly as a grain legume primarily grown for soil fertility, farmers are also interested in harvesting reasonable grain yield. This has been noted before, that farmers need immediate returns even from soil improving technologies (Snapp, 2008), and this is a challenge for agronomists and breeders to come up with varieties that with multiple preferred traits preferred by farmers. Policy makers need to take note that farmers may require support and incentives in the short term in order to adopt crops that have sustainable, resource building properties.

4.4 Implications

Promotion of legume based cropping systems

Legume based cropping systems can contribute to sustainable cropping systems under the degraded smallholder farms as evidenced by higher calorie and protein production, maize grain yields and N inputs compared to continuous sole maize systems which currently are relatively widely adopted across the country. A number of legume based technologies have been promoted for decades including intercrops or crop rotations of maize with grain legumes, green manures and agroforestry species (Mc Coll, 1989; Kwesiga and Coe, 1994; Kamanga et al., 1999; Snapp et al., 2002). However, adoption of these technologies has been variable depending on socio-economic and biophysical constraints (Snapp et al., 2003; Mafongoya et al., 2007). At the same time, in the 1990s, Sasakawa planting pattern of maize (1 seed x 25cm within row spacing) was promoted along with high inorganic fertilizer inputs. This system does not support intercropping (Malawi Government, MoAIFS 2005) thereby reducing the total density of legumes that could be intercropped with maize. This system has negative implications on N inputs into cropping systems by legume species, biodiversity and overall sustainability of cropping systems. In addition, smallholder farmers who cannot afford inorganic fertilizers for maize production do not optimize grain yield.

In Malawi and other countries in SSA, adoption and disadoption of legume technologies have occurred over years depending on household characteristics, cost and availability of farm inputs, performance and benefits of legumes, short term vs long term benefits, environmental conditions (Snapp and Silim, 2002; Shultz et al., 2003; Kiptot et., al 2007; Mafongoya et al., 2007). Snapp et al., (2003) reported that institutional support is important for building capacity of farmers to manage and adapt cropping technologies. This study had shown that investment in capacity building of farmers on legume production and utilization can help to increase adoption. A majority of project farmers are aware of the nutritional benefits of legume-based diets and have been educated by the SFHC project in production and utilization of legumes, and crop residue management. In this study area, there is scope for wider adoption of diversified legume cropping systems because farmers are already growing a diversity of legume species, farmer interest in education about agronomy and utilization of legumes. Development of extension materials on recommended agronomic practices for specific legumes can help to build farmers' capacity to manage legume cropping systems and optimize yields.

Cropping systems for the future

Understanding farmers' characteristics and needs is key to developing cropping technologies that would be widely adopted. Farmers' preference was for cropping systems that offer multiple benefits rather than optimizing yield or soil fertility alone. For example, intercropping of legumes with cereals or doubled up legumes has help to address labor, land and soil fertility constraints while providing diverse food sources and increase crop yields. Farmers' choice of technology has implications on cropping systems for the future in that technologies with high potential for building soil fertility and increasing crop productivity might not necessarily be adopted. Therefore, research on sustainable cropping systems would require participatory approaches to ensure development of technologies likely to be adopted by farmers.

Climate change is one of the challenges for sustainable cropping systems. Some of the effects of climate change are short or poor rainfall distribution, increasing temperatures and changes in resilience of ecosystems (IPCC, 2007). Increasing temperatures holding other factors constant may favor growth of C4 crops like maize because they are adapted to high temperatures. However, interactions of high temperatures and limited soil moisture can negatively affect crop growth. This study has shown that inclusion of both annual and semi perennial legumes in cropping systems can be an insurance against weather risks. Under short rainfall season, vegetative biomass of long duration legumes such as pigeonpea is not supported and this has negative implications on BNF.

Time of planting the cereal crop following legume cropping system is important to ensure early root development and synchrony between nitrogen release from legume residues with crop demand. In this study, we found that plant indicators of N (chlorophyll and plant growth) were responsive to cropping systems during early vegetative growth stage of maize but no effect on inorganic soil N. This could be related to nitrate release from legume residues early in the season "birch effect." With global warming and unpredictable weather patterns (IPCC, 2007), the challenge for farmers would be to determine the appropriate planting time for the cereal crop following legume cropping system. This might require comprehensive research on crop modeling to develop models for predicting weather and planting time.

4.5 CONCLUSION

This study evaluated N budget of diversified legume cropping systems and the effect on performance of subsequent maize. The soils were highly degraded with low OM, N and P. There is a diversity of legumes with grain legumes being more preferred to green manures. Intercropping was advantageous for both legume-legume and cereal-legume systems over sole cropping as evidenced by LER>1. The drivers of BNF were inorganic P, plant density and interspecific competition.

Legume cropping systems increased subsequent maize grain yield compared to continuous sole maize. Overall, ISFM increased maize grain yield by 69-200%. Under low productive domains, legume based cropping systems produced more calories that continuous maize system.

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