EFFECTS OF INORGANIC AND ORGANIC FERTILIZERS ON NUTRIENT UPTAKE, SOIL CHEMICAL PROPERTIES AND CROP PERFORMANCE IN MAIZE BASED CROPPING SYSTEMS IN EASTERN PROVINCE OF RWANDA

BY

NDAYISABA PIERRE CELESTIN, AGRIC. ENG.

N50EA/12339/2009

A THESIS SUBMITTED IN PARTIAL FULFILLMENT FOR THE DEGREE OF MASTER OF ENVIRONMENTAL STUDIES (AGROFORESTRY AND RURAL DEVELOPMENT) IN THE SCHOOL OF ENVIRONMENTAL STUDIES OF KENYATTA UNIVERSITY

DECEMBER, 2013

DECLARATION

CANDIDATE DECLARATION

This thesis is my original work and has not been presented for a degree in any other University or any other award.

Signed______________________ Date ___________________

Pierre Celestin Ndayisaba (Agric. Eng.)

Department of Environmental Sciences

DECLARATION BY SUPERVISORS

We confirm that the candidate under our supervision carried out the work reported in this thesis.

Signed ______________________ Date__________________

Dr. Monicah Mucheru-Muna

Kenyatta University, Department of Environmental Sciences

School of Environmental Studies

Signed ______________________ Date__________________

Prof. Daniel Mugendi

Kenyatta University, Department of Environmental Sciences

School of Environmental Studies

Signed ______________________ Date__________________

Dr. Bernard Vanlauwe
International Institute of Tropical Agriculture, IITA/Nairobi-Kenya.

DEDICATION

This work is dedicated to my beloved wife Mrs Alice Umuhire Ndayisaba, to my wonderful sons and daughter, Gold Munyaneza Irera Ntwari, Heavenly-Glory Munyaneza Mugabe Mbaraga, and Lily Giramata Akarabo Munyaneza, to my mother Mukandutiye Godelieve and Abanyaneza family, to my father and mother in law Mr Etienne Kamanzi and Mrs Césarie Kabagwira, to my uncle Isai Niyonzima, to the family of Mugendi Martin, and to Juliet Ogola.

ACKNOWLEDGEMENT

Special thanks to Dr Bernard Vanlauwe for having given me this great opportunity to undergo post graduate education and to have willingly accepted to support and supervise this work, to Prof Daniel Mugendi to have helped me through the application process despite other heavy responsibilities he then had and to have supervised this work, and to Dr Monicah Mucheru–Muna to have supervised this work. I hereby acknowledge their input, guidance, understanding and encouragement throughout this study.

I would like to recognize the advice, input and technical support I got from Dr Pieter Pypers. My heartfelt gratitude is hereby expressed to him. I sincerely thank the Tropical Soil Biology and Fertility Institute of the Centre Internationale de Agricultura Tropicale (TSBF-CIAT) to have financially supported me throughout my studies (all costs included).

I am thankful to Mrs Evonne Oyugi from ICRAF laboratory for her assistance in preparation of samples and subsequent laboratory analysis. I would also like to thank Mr Martin Kimenyi, Severin Ntivuguruzwa, and members of cooperatives partnering with CIALCA-TSBF in Rwanda (the Eastern province) for their cooperation and assistance in trial management and sample collection.

I thank CIAT – TSBF Nairobi, and CIAT Kigali staff for their good cooperation and facilitation all along this study. Let my thanks also go to ICRAF - Nairobi library staff, Mr Humphrey Keah and Mrs Caroline Mbogo for facilitating me to access several publications otherwise not accessible.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ACRONYMS AND ABBREVIATIONS

BCR	Benefit-cost ratio
BNF	Biological nitrogen fixation
DAP	Diammonium phosphate
DNA	Deoxyribonucleic acid
g:	Gram
ISFM:	Integrated soil fertility management
K:	Potassium
Kg:	Kilogram
LER:	Land equivalent ratio
mals:	meters above sea level
MINAGRI:	Ministry of agriculture
MRR	Marginal rate of return
N:	Nitrogen
N_2:	Dinitrogen
P:	Phosphorus
SOM:	Soil organic matter
TSP:	Triple super phosphate
%Ndfa:	Percentage of Nitrogen derived from atmosphere

DEFINITION OF TERMS

ISFM - According to Vanlauwe *et al.* (2010), Integrated Soil Fertility Management (ISFM) is defined as a set of soil fertility management practices that necessarily include the use of fertilizer, organic inputs and improved germplasm, combined with the knowledge of how to adapt these practices to local conditions, aimed at maximizing agronomic use efficiency of the applied nutrients and improving crop productivity.

Biological Nitrogen fixation *BNF* - According to Mulongoy (2005), biological nitrogen fixation is the process whereby atmospheric nitrogen N≡N is reduced to ammonia NH_3 in the presence of nitrogenase.

Nitrogen balance - According to Ogoke *et al.* (2003), the N balance is calculated as the difference between the N derived from the atmosphere (Ndfa) and N removed at harvesting legumes through grain and residues (when residues are removed from the system).

B- Values - According to Okito *et al.* (2004), B – *value* is defined as the difference between the ^{15}N abundance of the whole legume plant grown entirely on BNF and that of the air.

Fertilizer agronomic efficiency - The fertilizer use efficiency refers to the quantity of yields obtained from the application of 1 kg of fertilizer. It can be calculated per kg of fertilizer or an element of interest (for example N, P, K, etc) (derived from Yusuf *et al.*, 2009a).

N and P physiological efficiency - N and P physiological efficiency refer to quantities of yields obtained per kg of N or P taken up due to the applied fertilizer (derived from Yusuf *et al.*, 2009a).

N and P recovery efficiency - N and P recovery refer to the percent*age of* N and P taken up by the plant following the N and P applied through fertilizer inputs (derived from Yusuf *et al.*, 2009a).

Benefit to cost ratio BCR - The benefit to cost ratio is a measure at*tempti*ng to identify the relationship between the cost and benefits of a proposed intervention (CIMMTY, 1988). It is a measure of present value per dollar invested and is given by the benefit divided by the cost. For beneficial interventions, benefit-cost ratio is greater than 1.

Marginal rate of return - The marginal rate of return is a measure of just how the net benefit from an investment increase as the amount invested increases (CIMMTY, 1988). It is calculated as the marginal net benefit (change in net benefit) divided by the marginal cost (change in costs). It is expressed in percentage or just as a ratio.

Land equivalent ratio LER - The Land Equivalent Ratio (LER) is considered to be one of the most appropriate indices to evaluate the efficiency of intercropping system in producing better yields as compared with yields in sole cropping (Prasad and Brook, 2005; Morgado and Willey, 2008). LER indicates the total land area required under mono cropping to give yields obtained from intercropping system (Clément *et al.,* 1992; Tsubo *et al.*, 2003; Addo –Quaye *et al.,* 2011).

ABSTRACT

The Eastern province of Rwanda is highly populated. This has led to continuous cropping systems without addition of external fertilizers to compensate losses due to removal of grains and residues through harvesting. In such conditions, soil fertility decline is a major factor limiting per capita crop production in the area. It is quite difficult for smallholder farmers to afford to buy and apply adequate quantities of mineral fertilizers and organic sources, making it difficult for them to replenish the soil fertility. In order to address this problem, experiments were laid out in farmer fields in the Eastern province of Rwanda in an incomplete randomised block design with 14 treatments. The objectives were to evaluate the response of maize, common bean and soybean to combined application of mineral fertilizers and FYM on yields, BNF, N balance, and soil chemical properties; their rotational effect on the subsequent maize; and to economically analyse their fitness to adoption by means of the BCR and MRR analyses. Fertilization treatments were 5 t of FYM ha^{-1}, 200 kg of DAP ha^{-1}, and 2.5 t of FYM + 100 kg of DAP ha^{-1} (½ DAP + ½ FYM). Two intercropping systems, MBILI (2:2 common bean: maize) and 2:1 (common bean: maize) were compared ½ DAP + ½ FYM significantly ($P = 0.05$) increased the yield of common bean, soybean, and maize and improved their fertilizer agronomic efficiency of DAP both in short and long rains. Intercrops had the LER > 1.0. The BNF was significantly higher ($P = 0.05$) in common bean plots than in soybean plot. N balances were more negative in soybean than in common bean treatments ($P < 0.001$). Yields were higher in common bean and soybean–maize rotations than from the continuous maize. The N and P uptake was significantly ($P = 0.05$) affected by DAP and ½ DAP + ½ FYM. Changes in N and Olsen P in soils were not significant but higher concentrations were found in the DAP treatment. Common bean–maize and soybean–maize rotations (without fertilization), and maize–maize but with ½ DAP + ½ FYM were economically acceptable to farmers. The 2:1 intercrop had a MRR > 1.18. Farmers' evaluation was positively correlated between male and female farmers (r = 0.671 at $P < 0.001$ in short rains, and r = 1 at $P < 0.001$ in long rains) and was negatively correlated to the BCR and MRR. From this study, mineral fertilizers should not be applied to common bean and soybean in rotation because they do not improve their BNF and yet, these crops are not responsive to them, hence a loss of investment. FYM or ½ DAP + ½ FYM should be applied to maize planted in rotation (responsive and economically acceptable). Intercropping common bean and maize in 2:1 rows arrangement is also economically feasible. Rotation of common bean or soybean with maize is recommended.

CHAPTER ONE

1.0 INTRODUCTION

1.1 Background to the problem

Around 90% of active Rwandese people are engaged in agricultural activities and earn their living on agriculture (MINECOFIN, 2003; Nabahungu and Visser, 2011). The total population of Rwanda was estimated to be 9,058,392 in 2006 (MINECOFIN, 2008), and 10,042,578 in 2010 (Governing Body of Jehovah's Witnesses, 2011) whereas its agricultural land is only 1 940 000 ha (FAO STAT, 2009). This has led to a tremendous pressure on agricultural land where the mean landholding per family is as low as 0.5 ha (Nabahungu *et al.*, 2011). Consequently, soil fertility conserving cropping techniques such as fallowing (Nair, 1993; Amede and Kirkby, 2004) are no longer feasible, which has resulted in a negative trend of crop yields across the country over years.

The gradual soil fertility depletion is the main cause of crop yield decline in most lands of Africa including Rwanda (Nair, 1993; Vanlauwe *et al.,* 2006; Bationo *et al.,* 2007; Mapfumo *et al.,* 2007). Lack of soil fertility restoring resources, unbalanced nutrient mining, soil erosion, and unequal soil fertility management within family fields have been reported to contribute to soil fertility depletion by several researchers (Amede *et al.,* 2001; Vanlauwe and Giller, 2006; Bationo *et al.,* 2007; Mugendi *et al.,* 2007; Nabahungu and Visser, 2011). The dynamism of soil fertility depletion is enormous in Rwanda. The annual rate is estimated to exceed 40 kg N ha^{-1}, 6.6 kg P ha^{-1}, and 33.2 kg K ha^{-1} (Smaling *et al.*, 1997).

Long-term strategies to replenish soil fertility have been developed, including the proper management of organic and mineral fertilizers, and building up the soil organic matter (SOM) (Vanlauwe, 2004). However, high prices at the farm gate, and lack of credit facilities limit the farmers' access to mineral fertilizers (Sanchez and Jama, 2002; Nziguheba *et al.*, 2004). The fact that most of organic resources are labour intensive, necessitates additional land, are of low quality, compete with crops when grown together, and are required in large amounts to meet moderate yield increases (Nziguheba *et al.*, 2004; Vanlauwe, 2004) restrict their use. Mostly, crop residues are used as firewood and fodder rather than being returned to the soil.

Therefore, neither organic nor mineral fertilizers can stand on their own to overcome soil fertility depletion problems in Rwanda. They should be used together to meet sustainability in soil fertility (Vanlauwe, 2004; Marenya and Barrett, 2007; Mugwe *et al.*, 2009). The legume-cereal cropping systems (rotation and intercropping) are also believed to have the ability to contribute to the soil fertility improvement (Sanginga and Woomer, 2009). Dual purpose legume crops add organic nitrogen (N) to soils through the biomass production and biological nitrogen fixation. They add diversity to the food options for farmers, and are environmentally sound (Kamanga *et al.*, 2003; Gwata *et al.*, 2004; Muneer *et al.*, 2004; Vanlauwe, 2004; Wang *et al.*, 2008; Hauggaard-Nielsen *et al.*, 2009).

1.2 Problem statement and justification

The declining crop yields consequent to high population pressure has been a major problem experienced by smallholder farmers in the eastern province of Rwanda. The major factor contributing to reduced productivity is soil fertility depletion caused by continuous cropping without addition of adequate mineral fertilizers and manures, and nutrient loss through soil erosion and leaching. The average use of mineral fertilizers is 5 to 10 kg ha^{-1} $year^{-1}$ (Bationo *et al.*, 2012). The amount is incomparable to losses estimated to 40 kg N, 6.6 kg P, and 33.2 kg K ha^{-1} $year^{-1}$ (Smaling *et al.*, 1997). Though farmers are aware of the scenario, their farming practices reveal that they do not know how to resolve the problem. Prices of mineral fertilizers are unaffordable to smallholder farmers. Organic manures are not used as required due to their availability in small amounts, and high labour requirement. This called for exposing the farmers to integrated soil fertility management (ISFM) technologies so as to meet the need for adequate food production. The purpose of this study was therefore to address the constraints of declining soil fertility, using affordable fertilizer rates, and beneficial effects of grain legumes.

1.3 Research questions

This study sought to answer the following questions:

1. To what extent do various ISFM components (fertilizer use, organic matter application, legume rotation and legume intercropping) either sole or in combination, increase crop productivity in the Eastern province of Rwanda?

2. How are bean and soybean different in N balances under different fertilization and cropping techniques in the eastern province of Rwanda?
3. How do improved bean–maize intercrops, legume–maize rotation, and sole and combined use of manure and mineral fertilizers affect chemical properties of soils and plant nutrient uptake in legume–maize systems in the eastern province of Rwanda?
4. How are the proposed ISFM components profitable to farmers?
5. How acceptable are the proposed ISFM components to male and female farmers from the Eastern province of Rwanda?

1.4 Objectives

The main objective of the study was to assess ISFM technologies that are capable of improving soil fertility properties and food production in smallholder farming systems in the eastern province of Rwanda. To achieve this objective the following specific objectives were addressed:

1. To quantify the effects of different ISFM components on the productivity of maize–based systems in the Eastern Province of Rwanda

2. To assess the N balance of soybean and common bean, plant nutrient uptake and effects on soil chemical properties following the application of different ISFM components

3. To evaluate the economic implications of different proposed ISFM components

4. To evaluate the acceptability of the different ISFM components by male and female farmers

1.5 Hypotheses

The study sought to test the following hypotheses:

1. The proposed ISFM technologies have a positive effect on crop yields.
2. The integration of beans and soybean in ISFM technologies leads to a positive N balance, improvement of soil chemical properties, and higher plant nutrient uptake.
3. There are significant differences in the benefit to cost ratio of different proposed ISFM technologies.
4. There is a significant relationships between farmers' perceptions and benefit to cost ratio of proposed ISFM technologies among male and female farmers.

1.6 Significance and anticipated output

In Rwanda as well as in most Sub–Saharan Africa countries, soil fertility has been in the decline (Rayar, 2000). To deal with this decline, the heads of states of African nations committed to increase fertilizer use by 2015 from 8 to 50 kg of nutrients per hectare (Abuja Fertilizer Summit, 2006). Since then, Rwanda has moved ahead and is actively supporting farmers through fertilizer schemes (voucher system) where fertilizers are 50% subsidized. This program known as crop intensification is going hand in hand with land consolidation and is specifically targeting crops such as maize, wheat, rice, and Irish potatoes (monocultures). Findings from this research will provide knowledge to agricultural extension workers on maize, common bean and soybean responses to fertilizers in the Eastern province of Rwanda. This knowledge would serve as a tool to decide whether embarking on subsidizing fertilizers for common bean and soybean is a green venture. Additionally, this study will generate knowledge on effects of crop rotation on maize production, and maize–grain legume intercropping across the Eastern province of Rwanda, which will help agricultural extension workers to advice farmers backed by locally generated knowledge. Policy makers in the Ministry of Agriculture of Rwanda may use findings of this research to design food production policies that are sustainable across generations and specific to the study area (the Eastern province of Rwanda). Recommendations from the study will be tailored to farmers cropping conditions with financial evidences. Finally, scholars would use findings of this research to design further research.

1.7 Conceptual framework

To break the existing scenario (Figure 1.1), smallholder farmers would start by applying to their farms affordable quantities of both mineral and organic sources of nutrient coupled with grain legume integration in cropping systems either in crop rotation or in intercrops.

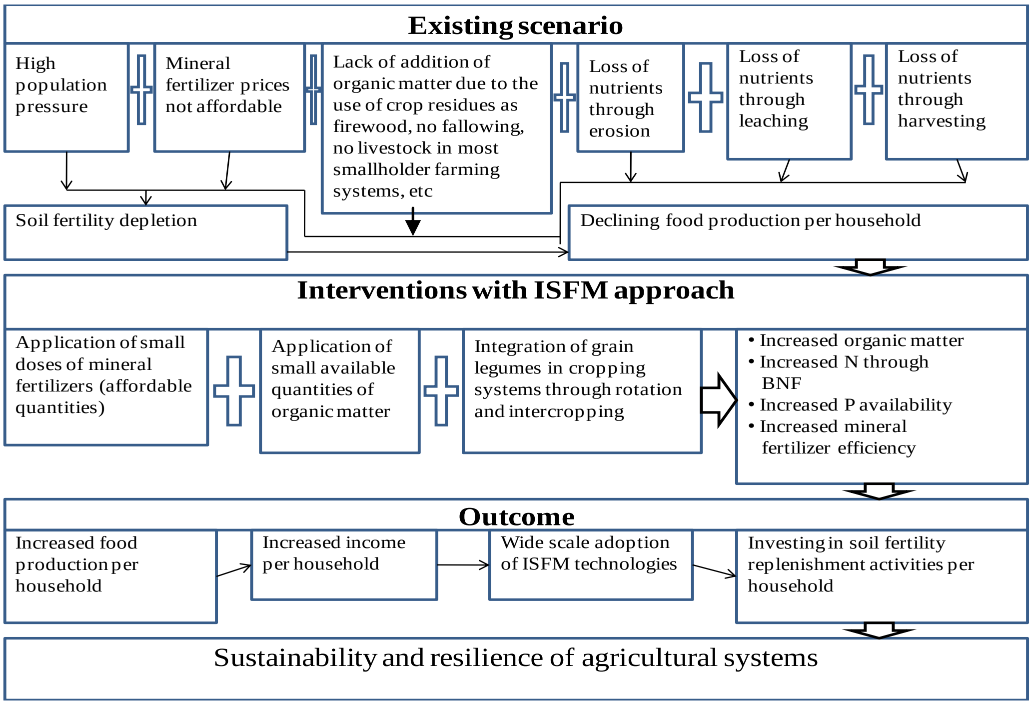

Figure 1.1 Reversing the existing soil fertility depletion

Such ways of production will foster the insitu biomass production to build up the SOM, hence an increased efficiency of the applied mineral fertilizer. Henceforth, one may expect to have increased crop yields leading to increased income with possibility to invest the part of income in to soil fertility management activities. The overall outcome then will be the system sustainability and resilience.

1.8 Limitations of the study

The study did not take into account farm variability which may be potential drivers in deciding what type, how much, and when to apply both inorganic and organic amendments. Findings of this research are bound to varieties of crops tested under this study. These are ZM 607 (maize), BRB 194, and RWR 2245 (common bean), and Peka – 6 (soybean). The use of other varieties may lead to totally different findings due to variability in genetic endowment of a variety compared to another.

CHAPTER TWO

2.0 LITERATURE REVIEW

2.1 Integrated soil fertility management for sustainable agriculture in Rwanda – Overview

Soil fertility is referred to as the ability of the soil to sustain plants through the steady supply of nutrients required by the plant to complete its life cycle (Donovan and Casey, 1998; Rayar, 2000; Ştefanic and Gheorghiţă, 2006; Bationo *et al.*, 2012). This ability results from physical, chemical and biological properties of the soil. Soil fertility is closely linked to land productivity and is a function of individual soil variables (inherent and influenced) such as climate, management and slope (Donovan and Casey, 1998; Rayar, 2000; Bationo *et al.*, 2012). Soil fertility declines when its nutrient content diminishes, and/or when its physical, chemical and biological makeup changes in ways that lower its ability to support plants (Donovan and Casey, 1998).

It has been widely reported by several soil fertility scholars that soil fertility depletion is taking place across African countries at an alarming rate, and is the root cause for gradual per capita food production decline in East Africa, including Rwanda (Dudal, 2002; Sanchez and Jama, 2002; Bationo and Waswa, 2011). It is considered as the core problem to be tackled for the green revolution in Africa to take off (Sanchez and Jama, 2002). For example, Bationo and Waswa (2011) mentioned a loss equivalent to 660 kg N ha^{-1}, 75 kg of P ha^{-1}, and 450 kg of K ha^{-1} from about 200 million ha of cultivated land in 37 countries during the last 30 years, and an annual net depletion of nutrients of 54 kg of N, 9 kg of P, and 47 kg of K ha^{-1} $year^{-1}$ in

Rwanda. They also observed that nutrient balances are negative for many cropping systems indicating that farmers are mining their soils of nutrient reserves.

Major causes of soil fertility decline are intensification of crop production under continuous cropping systems as fallowing practices have been rendered impossible by high population pressure on land, resulting in high nutrient removal season after season, lack of farmers to replenish removed nutrients through the application of inorganic and/or organic sources of nutrients, due to limited use of fertilizers, the labour intensive aspect of most of organic sources, and collection of crop residues for uses other than soil fertility replenishment (fire wood, animal fodder, construction material, etc) (Vanlauwe, 2004; Bationo and Waswa, 2011). Other causes include nutrient leaching, volatilization, losses through water erosion, denitrification, etc (Dudal, 2002).

In Rwanda, high pressure on agricultural land is the root cause of tremendous soil fertility decline. For example, in 1960s the population was as low as 3 millions. Later in 1990s, it had already doubled (Dudal, 2002). Rwandan population is more than 10 millions (Governing Body of Jehovah's Witnesses, 2011). The mean landholding per family dropped from around 1 hectares in 2003 to 0.5 ha (Dudal, 2002; Rutunga and Neel, 2006; Musoni, *et al.*, 2010; Nabahungu *et al.*, 2011). This brought about a shift in soil fertility management from shifting cultivation to sedentary and intensive cropping systems. Though research on soil fertility management, recommendations, and extension interventions were deployed since 1970 (Dudal, 2002), adoption of technologies by farmers did not take place due to the lack of incentives such as markets and attractive prices of agricultural commodities at the farm gate (Dudal, 2002).

Looking back across the farming history in Rwanda, fertilizer application by farmers is not a problem when the activity is remunerative. For examples, farmers eagerly buy fertilizers for vegetables, rice, sugarcane, tea, Irish potatoes, pyrethrum, and other easily marketable agricultural products even prior to the present fertilizer scheme (subsidies of fertilizers). The same was observed by Vanlauve and Giller (2006) about the popular myth saying that African farmers do not apply mineral fertilizers because they are too expensive. Moreover, they (Rwandan farmers) are used to buy chemicals to spray the above said easily marketable crops. But they never attempted to do so for food crop production (maize, bean, sorghum, soybean, cassava, etc). This behaviour of farmers was recognised by Dudal (2002). When cost: benefit ratios are unfavourable, technical assistance to promote new technologies is in vain.

When crop prices are such that external inputs do not pay, efforts deployed to enhance the use of mineral fertilizers are often discouraged or discredited. On the contrary, such crops (food crops); occupy most of the agricultural land of Rwanda similar to the whole African continent where farming systems are dominated by root and tuber crops, sorghum, millet, maize and pulses (Bationo and Waswa, 2011). Furthermore, they are depletive. For example, a yield of 2 t of common bean grain ha^{-1} year^{-1} is likely to remove almost 100 kg of N and about 10 kg of P from a system where seeds are only removed and residues maintained (Jansa *et al.*, 2011). Without fertilizer application, 200 kg of N, and 30 kg of P ha^{-1} $year^{-1}$ may be removed by maize production in a bimodal cropping system (Chikowo *et al.*, 2010; Sugihara *et al.*, 2010) in soils able to support 2.7 t of maize grain yield ha^{-1}.

Though the application of organic sources of nutrients such as *Tithonia diversifolia, Senna spectabilis, Calliandra calothyrsus, Sesbania sesban, Tephrosia vogelii,* etc, or herbaceous legumes such as *Mucuna pruriens, Desmodium intortum, Desmodium uncinatum,* etc, would be recommended (Murwira *et al.,* 2002), this exercise of cut-and-carry is reported to be labour intensive and might need huge quantities to meet fertilizer requirements for a comprehensive soil fertility management practice. They should also be located in the direct surrounding of the farm in enough quantities to be applied in an economically acceptable way. Dudal (2002) observed that relying on such technologies in semi – arid areas where biomass production is severely limited by water deficit is unrealistic because they may not suffice to sustain soil fertility.

The application of manure is in such conditions a most feasible technology to rebuild soil fertility but was found to be slow while farmers need quick action interventions (Rutunga and Neel, 2006). On the other hand, it has been found not sufficient to sustain crop production by itself. For example, it is said that the application of 5 t of high quality manure is able to sustain moderate yields of maize as low as 2 t ha^{-1} (Bationo and Waswa, 2011) and meet N requirement for such production, but cannot meet P requirement especially in P deficient areas. Manure quality is on the other hand a problem. Murwira *et al.* (2002) worked on organic sources of nutrients including manure across Kenya, Tanzania, Madagascar, Zambia, Malawi, and

Zimbabwe. However, N content reported in their work varied between 0.5 and 1% in most sites whereas the threshold of good N mineralization from an organic source is 2.5%. Quantities of manure might be also a great challenge. For example, to supply 5 t of manure ha^{-1} $year^{-1}$, one needs to have at least 5 livestock units of unimproved local cattle breed in maize – livestock systems in semi – arid parts of eastern Kenya (Bationo and Waswa, 2011), which is not possible for smallholder farmers of Rwanda.

Consequently, the combined application of mineral and organic fertilizers was advocated and promoted under ISFM research undergoing shifts in paradigms (Bationo and Waswa, 2011) especially because neither of these sources is applied by farmers in required quantities and proved themselves to be beneficial compared to their separate applications (Murwira *et al.,* 2002; Vanlauwe, 2004). Additionally, ISFM principle application is recognised to be efficient if only it is accompanied by good cropping systems (intercropping and crop rotation) which integrate dual purpose grain legume as sources of additional N through BNF. For example, the intercropping of groundnut and sorghum in Senegal was reported to increase yields by 75 to 195%, while the soybean/maize rotation system including the use of mineral fertilizers (15 kg P ha^{-1} supplied to soybean and 45 kg N ha^{-1} supplied to maize) gave soybean yield of 2.5 t ha^{-1} and, supplied 50 kg of N ha^{-1} to maize through BNF, and increase maize yields by 75% compared to maize following maize (Bationo and Waswa, 2011).

Under the expending use of mineral fertilizers in Rwanda under the crop intensification program of MINAGRI especially in maize based systems of the Eastern province of Rwanda, efforts should be made to increase fertilizer use efficiency and develop farmers habit to supply to the system the little manure their can afford to have, and explore possible benefits offered by dual purpose grain legumes such as BNF for a sustainable crop production. This is urgent as far as the achievement of the first millennium development goal is concerned which is about the eradication of poverty and hunger among populations. In the following section, the above said soil fertility replenishment options have been discussed.

2.2 Inorganic and organic fertilizer management and soil fertility management in cereal based cropping systems

2.2.1 Inorganic fertilizers and soil fertility management

Generally, mineral fertilizers containing N, P, K and S not only increase crop yield but also improve nutritional quality of crop yields, such as protein, oil, starch, essential amino acids and vitamins in pulses, oil seeds, tubers, and vegetables respectively (Wang *et al.,* 2008). This is because nutrients in mineral fertilizers are immediately available for plant uptake (Nyamangara *et al.,* 2003). However, their intensive use (especially N fertilizer) can result in undesirable changes in foods, and negative effects on atmospheric and aquatic environments (Wang *et al.,* 2008, Hauggaard-Nielsen *et al.,* 2009). That is the result of their susceptibility to losses in gaseous forms or by leaching if added at a wrong time or in excess of plant demand, and surface overflow (runoff) (Nyamangara *et al.,* 2003).

Empirical data proved that sole application of mineral fertilizers does not provide sustainable soil fertility management. However, they can serve an entry point for a comprehensive sustainable soil fertility management (Sanginga and Woomer, 2009; Vanlauwe *et al.,* 2010). Their high cost in contrast with low purchasing power of smallholder farmers and restricted access to credit limit their use in improving soil fertility (Nziguheba *et al.,* 2004). Delays in delivery, poor transport and marketing infrastructure are other factors restricting the use of mineral fertilizers (Nair, 1993, Mugwe *et al.*, 2009). Fortunately, African Heads of states committed themselves to work on fertilizer use hindrances in their respective countries and raise the current mean fertilizer use of 8 kg ha^{-1} to 50 kg of fertilizer ha^{-1} by 2015 (African Fertilizer Summit, 2006). This is good information to African farmers.

Since then, the Rwandan government is working hard to attain the target in fertilizer application rates. In fact, a fertilizer scheme bringing many actors on board was established through which farmers get fertilizers at a 50% subsidized price plus the improved germplasm seeds. Quantities of fertilizers and seeds are issued on farm size basis. The scheme is called “voucher system” and involves the Ministry of Agriculture through its Rwanda Agriculture Board institution, fertilizer service providers which are local NGOs subcontracting to facilitate the seed and fertilizer distribution to farmers, and the Ministry of Local Government through its decentralized entities to supervise the implementation of the program by farmers. This is a positive action taken and is likely to result into abrupt increases of crop yields across the country.

In this regard, the use of mineral fertilizers may be an entry point for integrated soil fertility management (Sanginga and Woomer, 2009) in Rwanda in a way that it will not only increase grain yields of crops, but also will be a way to increase insitu organic matter production through increased crop residues which will be used as animal feed and/or added to the soil. If this happens in a proper way, the needed high fertilizer use efficiency, a prerequisite for farmers to benefit from mineral fertilizers, will be achieved as it is widely known that organic source application along with mineral fertilizers improves its agronomic use efficiency (Sanginga and Woomer, 2009). Tittonell *et al.* (2008) recognised the ability of mineral fertilizers when coupled with manures in rehabilitating degraded soils, a service which could not be offered by 12 year sole application of locally available manures (low quality) in smallholder farming systems of Kenya.

Therefore, with the Rwanda background in mind, interventions are needed to create awareness among farmers about the need to apply organic matter in an easily available form in their surrounding area. Additionally, according to Dudal (2002), the Government of Rwanda needs to make extra steps to reinforce this program for farmers to fully benefit from this new venture. Interventions needed include the provision of markets to farmers through which they will sale their production instead of keeping quantities in stores waiting for the production of the following season and finally spoilage due to long periods of stock and pests. Additionally, the price of commodities should be such that farmers are able to get their investment plus a return to it. Again, there is a need to look at how the expanding use of fertilizers will be to farmers in terms of economic issues.

2.2.2. Organic resources and soil fertility management

Organic fertilizers also referred to as organic sources are described as those organic materials that are used in agriculture as external or recycled inputs to produce crops either for subsistence or for commercial purposes (Lekasi, 2003). These include fresh, dried or composted livestock and poultry manure, crop residues that are recycled after a crop is harvested, green manure obtained either on or off the farm, biomass resulting from short to long-term fallows, agro-industrial by-products such as coffee husks or sugarcane bagasse, forest litter, bark or wood shavings, and coarse organic materials applied as surface mulches (Lekasi, 2003). These sources have been recognized as alternative nutrient sources to smallholder farmers to fertilize their soils as their socio-economic limitations prevent them to use mineral fertilizers properly (Bala *et al.*, 2011).

The ability of organic sources to release nutrients is dependent on microbial decomposers present, climate, and their quality such as C: N ratio, lignin and polyphenolic content. Based on the quality of the organic source, Murwira *et al.* (2002) framed a decision tree on how they should be applied to soils. According to Murwira *et al.* (2002), the organic material with N above 2.5%, and lignin and polyphenol contents less than 15% and 4% respectively, can be expected to release nutrients immediately and therefore be applied directly to the soil. The material with N content above 2.5% but lignin and polyphenol contents more than 15% and 4%, respectively, may show a lag phase in N release; therefore need to be mixed with mineral fertilizers to overcome this lag in N availability. Organic materials with N less than 2.5% and lignin content less than 15%, and those with N content less than

2.5% and lignin content more than 15% are expected to show longer periods of immobilization. They should be applied with N fertilizers or applied as mulch.

The organic sources have been reported to improve the soil fertility, promote good soil aggregation, improve moisture infiltration and increase the water holding capacity of the soil, increase the soil organic carbon, soil available nutrients (N, P, and K), soil enzymes (dehydrogenase and alkaline phosphatase), and microbial biomass C in the top 0-15 cm soil, improve the fertilizer use efficiency to a great extent, and to have the ability to prevent nutrient losses due to irregular and heavy rainfall (Dudal, 2002; Mugwe *et al*., 2007; Mucheru-Muna *et al.,* 2009; Ramesh *et al.,* 2009; Bala *et al.,* 2011). Additionally, they have the ability to increase the P availability of the already present P by rendering it more accessible to crops through reducing the soil P absorption capacity, increasing the pH by decreasing the exchangeable acidity and aluminium in soil solution through chelation, and increasing the soil biological activity of the soil (Nziguheba *et al.,* 2004; Bationo *et al.,* 2007; Mukuralinda *et al.,* 2010).

The use of organic sources for soil fertility management in the context of smallholder farmers is however hindered by several bottlenecks. In fact, crop residues have alternative uses as fodder, fuel and building materials, or is burnt in order to control weeds and pests; composting is labour intensive and organic wastes on a small farm are limited; grass, legume cover crops and green manure compete with food crops for land and for available water and nutrients and requires a considerable amount of labour for its incorporation; alley cropping requires high investment in labour and cash, reduces land availability for cropping, lacks the synchrony between supply and need of nutrients, and the increase in yields is uncertain (Dudal, 2002).

Manure is a most important and frequently used organic resource to improve the soil fertility (Mutegi, 2007). It is different from plant material organic sources because it has already undergone a phase of decomposition when passing through the digestive system of animals (Sanginga and Woomer, 2009). Challenges related to the use of manure are its quality and its quantity, both being sizable to smallholder farming systems. Its quality depends on the diet of the animal and the manner the manure is collected, stored and handled before utilization (Lekasi, 2003; Lekasi and Kimani, 2003; Rufino *et al.*, 2007). Mostly, the manure is produced by farmers under uncovered conditions and is subjected to losses of its nutrients due to weather fluctuations. This is why there is a high range of variation between manure qualities in terms of N content (Lekasi and Kimani, 2003; Sanginga and Woomer, 2009; Murwira *et al.*, 2002).

The challenge of manure quality is directly linked to the second challenge which is the quantity. Manure, like other organic sources might be available in quantities not enough to fertilize soils and sustain crop yields (Nziguheba *et al.*, 2004; Vanlauwe, 2004; Mugwe *et al.*, 2007). It is said that the maintenance of yields on 1 ha of cropland using cattle manure requires 10 to 40 ha of dry season grazing and 3 to 10 ha of rangeland of wet season grazing (Bationo *et al.*, 2007) which is not possible in the context of smallholder farming systems. Bationo and Waswa (2011) said that the present livestock systems in West Africa have the annual potential to transfer 2.5 kg of N and 0.6 kg of P ha^{-1} to the crop land. This is a minute quantity compared to 36 –

80 kg of N ha^{-1} lost per year through harvest (Sanginga and Woomer, 2009; Bationo *et al.,* 2011). To maintain maize yields at 2 t ha^{-1}, the application of at least 5 t of manure is needed. To do so, one needs to have 5 units of local unimproved cattle breed which is not possible in the context of smallholder farming systems (Bationo and Waswa, 2011). This is why there is a big gap between applied manure and recommended quantities (Bationo and Waswa, 2011). It is therefore worthy to identify other alternatives to supplement the existing options for soil fertility management.

Though the research of crop response to manure has been done and reported from different lands across Africa, there is scarcity of such information from cropping systems of Rwanda, hence, a need to work on crop responses to manure application miming quantities and quality of available manure in maize cropping systems of the Eastern province of Rwanda.

2.2.3 Combined use of inorganic fertilizers and organic sources for soil fertility management

The combined use of mineral and organic sources of nutrients in soil fertility management is a new approach which evolved from long experiences in soil fertility management (Bationo and Waswa, 2011). During 1960s and 1970s, a green revolution approach based on improved germplasm and external inputs significantly boasted crop yields in Asia and Latin America. This approach neglected the use of organic sources. It resulted in massive environmental degradation due to impaired applications of mineral fertilizers and pesticides, hence the abolition of fertilizer subsidies in Sub-Saharan Africa between mid 1980s and 1990s. By then, the paradigm shifted from intensive use of mineral fertilizers to low input sustainable agriculture LISA where organic resources were believed to enable sustainable agricultural production (Vanlauwe, 2004).

LISA technologies were basically alley cropping and due to technical and socio-economic factors, farmers did not adopt them (Vanlauwe, 2004). A shift occurred again from LISA to integrated nutrient management INM emphasizing on the judicious use of mineral and organic sources of nutrients (Vanlauwe, 2004). This was further shifted to integrated natural resource management INRM which accommodated the all factors on which farmers make their decisions including biophysical, socio-economic and political factors (Vanlauwe, 2004). It was further realized that all these paradigms focused on fertilizer or low-input methods but rarely on both and ignored the essential scientific fact that fertilizers are most effective and efficient in the presence of soil organic matter and well conserved soil structure (Vanlauwe, 2004). This gave raise to integrated soil fertility management ISFM framework based on the application of locally adapted soil fertility management practices to optimize agronomic efficiency of fertilizer and organic inputs in crop production (Vanlauwe, 2004). It necessarily includes locally appropriate management of fertilizers and organic resources. It is also knowledge intensive (Vanlauwe, 2004).

ISFM technologies are based on the use of mineral fertilizers, crop residues, manure management, cropping systems (cereal–legume intercropping, and cereal–legume rotation), interaction between water and nutrients, and combination of two or more of these components (Bationo and Waswa, 2011). Combining mineral fertilizers with organic inputs can substantially improve the agronomic efficiency of the nutrient use compared to the same amount of nutrients applied through either source alone (Sanginga and Woomer, 2009). Results by Vanlauwe *et al.* (2006) in western Kenya revealed the need to apply both mineral and organic sources in a combined fashion. The soil fertility gradient observed between homestead fields and bush fields due to long term accumulation of organic matter in homestead fields than in remote fields resulted in differences in N and P fertilizer efficiencies with higher efficiencies in homestead fields and lower efficiencies in remote fields. A problem arises on how the combined organic sources and mineral fertilizers increase the fertilizer efficiency.

It is known that organic sources are not able to substitute mineral fertilizers because for example, the definition by Dudal (2002) states fertilizers as any material containing at least 5% of one or more major nutrients. This definition excludes almost all organic sources from substituting fertilizers. This is why the sole application of organic sources can seldom furnish plant with required nutrients for sustainable crop production unless huge quantities adjusted to N or P recommendation are applied (Vanlauwe and Giller, 2006, Vanlauwe *et al.,* 2010). While the main role of mineral inputs is to supply nutrients or correct unfavourable soil pH conditions, organic resources contain C, which drives all microbial and faunally mediated soil processes and finally replenishes the soil organic matter (SOM) pool, which maintains the physical and physicochemical components contributing to soil fertility such as cation exchange capacity (CEC) and soil structure (Vanlauwe and Giller, 2006). Fertilizers are able to increase both crop yields and additionally produce enough residues for soil fertility management issues, while organic sources are able to rehabilitate less responsive soils and make them responsive to fertilizers (Vanlauwe *et al.,* 2010). This is the key factor to improved fertilizer efficiency when mineral fertilizers are combined with organic sources.

According to Vanlauwe *et al.* (2010), the ability of fertilizers to produce enough residues for sustainable soil fertility management on one hand, and the ability of organic sources to rehabilitate less responsive soils and make them responsive to fertilizers have been proved by experimental results from Nigeria and Zimbabwe respectively. Nziguheba *et al.* (2004), Bationo *et al.* (2007), and Sanginga and Woomer (2009) had similar views. They also attributed the increment in fertilizer use efficiency to two main reasons: (1) common mineral fertilizers lack the micro-nutrients essential for crop growth while organic resources contain them. Organic resources are not able to meet crop major nutrients needs (N, P, and K) unless it is applied in huge quantities more than 10 t ha^{-1} of dry matter. Therefore, combining both sources enable reasonable supply of all needed nutrients for a balanced growth. (2) a combination of both sources results in improvement in soil fertility status, increased SOM content which improves nutrient retention, turnover and availability; enhanced P availability thank to organic resources, alleviation of soil acidity and aluminium toxicity, improvement of the soil structure leading to reduced erosion, enhanced water infiltration and storage, and improved crop root development.

Blackshaw and Brandt (2009) recognized that the additional Phosphorus (P) supplied by this combination may result in additional benefits in terms of yield and quality as it plays key roles in cellular energy transfer, respiration, and photosynthesis. Additionally, it is an important structural component of nucleic acids, coenzymes, phosphoproteins, and phospholipids. It is also essential for BNF, a source of additional N in legume–cereal cropping systems (Mapfumo, 2011; Jansa *et al.*, 2011). This is very much beneficial to inherently low P fertility soils of this region (including Rwanda) (Amézquita *et al.*, 2007).

The combined application of manure (as other organic sources) and mineral fertilizers improves the mineral fertilizer use efficiency (Mucheru *et al.*, 2003; Nziguheba *et al.*, 2004; Mugwe *et al.*, 2007; Nyamangara *et al.*, 2009). This interaction has been attributable to some non-N nutrient effects of manure (Nyamangara *et al.*, 2009; Vanlauwe *et al.*, 2010). Therefore, in the interface of expanding use of mineral fertilizers countrywide under the sponsorship (subsidized at 50%) of the government of Rwanda, there is a need to work out technologies which will enable to increase the fertilizer use efficiency. Highly responsive plant varieties (Fageria *et al.*, 2011) coupled with the integrated use of mineral and organic sources of nutrient will play a major role in increasing crop yields compared to the 20th century, and a strategy to counteract main challenges due to limited land and water resources available for crop production, higher cost of inorganic fertilizer inputs, declining trends in crop yields, and increasing environmental concerns. Moreover, the ISFM framework has a room to local adaptation (Vanlauwe, 2004; Bationo and Waswa, 2011). Therefore, there is a need to test the ability of locally produced manure to increase the diammonium phosphate DAP fertilizer use efficiency in the eastern province of Rwanda.

2.3 Grain legumes in cereal based systems: a soil fertility management option

2.3.1 Grain legume crops and N_2 fixation

The term grain legume refers to those from which the seed is used directly for human consumption (Giller, 2001). Legume grain provides a protein-rich source of food and is an essential part of the diet in many parts of the tropics, particularly where meat is scarce.

An important characteristic of most species of grain legume crops is their propensity to form root associations with bacteria, primarily members of the genus Rhizobium (Azobacteriaceae). These bacteria infect the roots of legumes, causing the production of nodules and fix N_2 biologically which is further converted into plant available forms of ammonia, nitrite, or nitrate ions, and/or, in organic compounds from decayed organisms (Simpson and Molly, 1986; Giller, 2001; Lindemann and Glover, 2003; Jansa *et al.*, 2011).

Nitrogen (N) fixation by grain legume-Rhizobium symbiosis is important to agricultural productivity and is therefore of great economic interest (Yadegari *et al.*, 2010). The process of biological nitrogen fixation facilitated by the symbiotic association of grain legume roots and bacteria currently contributes 50 to 70 million of tonnes of N annually to the global agricultural N budget which is about half the annual application of mineral fertilizer N to agricultural land (Unkovich *et al.*, 2008). According to several authors (Osunde *et al.*, 2003; Singh *et al.*, 2003; Gwata *et al.*, 2004; Schulze, 2004; Gwata *et al.*, 2005; Sanginga and Woomer, 2009; Bationo *et al.*, 2011; Vanlauwe *et al.*, 2011), most of grain legumes derive their N from this process, and do not require the application of N fertilizers or just a starter N.

Estimates for field grown legumes reveal that up to 80% of the plant nitrogen demand is met by biological N_2 fixation (Schulze, 2004).

The rate at which N_2 is fixed depends on the legume species and strains of microbial population present in the soil (Giller, 2001). Additionally, the environment plays an important role in N_2 fixation. According to Mugendi *et al.* (2011), the amount of N fixed by the legume depends on factors such as climate, soil type, species, plant morphology, planting density of component crops, type of management and competitive abilities of the component crops, while symbiotic fixation is governed by factors such as the presence of appropriate rhizobia, deficiencies of plant nutrients other than nitrogen, soil acidity and aluminium toxicity, water stress, and temperature among others. Bationo *et al.* (2011) grouped factors affecting legume-rhizobia N fixation under environmental, nutritional, and cropping pattern factors. Environmental or physical constraints of nitrogen fixation in grain legumes include temperatures (high temperatures can inhibit nodulation or, if nodulation does occur, can inhibit the activity of N_2 fixation), soil water content (rates of N_2 fixation are sensitive to reduction in soil water content), salinity and sodicity of soils (saline and sodic soils with pH above 8.5 normally have a reduced availability of phosphorus, iron, zinc, manganese and boron, and reduced water availability due to high osmotic potential in the soil resulting in reduced N_2 fixation), water logging (excess of water in soils creating anaerobic conditions may be adverse to microbes and plant growth), etc. Chemical constraints include toxicities (acidity of the soil, aluminium toxicity, manganese toxicity).

Generally, in acid soils, the legume-rhizobia symbiosis is impaired by high concentration of H^+, and particularly Al^{3+} and Mn^{2+} and by low concentration of available Mo and P. High H^+ concentrations depresses the attachment of rhizobia at the root surface and the ability of the root exudates to induce the expression of nodulation genes. High concentration of Al^{3+} inhibits root infection with rhizobium and nodule initiation even in the presence of sufficient number of rhizobia (Bationo *et al.,* 2011). Nutritional constraints include deficiencies of phosphorus, molybdenum, iron, boron, cobalt, copper, nickel, selenium, and zinc, negatively affecting N_2 fixation, calcium and magnesium deficiencies resulting in low rhizobia attachment to legume roots in early stages of infection, hence a low N_2 fixation (Giller, 2001; Bationo *et al.*, 2011).

Rates of N_2 fixation tend to be highest when plant-available mineral N in the soil is limiting and other nutrients are plentiful (Unkovich *et al.,* 2008) meaning an inverse relationship between the amount of N fixed and mineral N concentration in the soil, simply because, if N is plenty, the symbiosis plant-rhizobia will use available mineral N to meet their N needs (Jansa *et al.*, 2011). Satisfying P demands of the plants is of primarily importance for optimizing the BNF efficiency and associated yield increases (Sanginga and Woomer, 2009; Jansa *et al.*, 2011). As far as cropping patterns are concerned, cereal – legume rotation is said to be better than cereal – legume intercropping in terms of N_2 fixation rate and amount (Bationo *et al.*, 2011).

The legume-bacteria symbiosis usually produces an excess of usable N in the soil through the release (excess to the required N for both bacteria and host plant), and decomposition of remaining residues both under and above ground (Bado *et al.*, 2007). This is why to promote BNF is considered as a key to successful ISFM (Sanginga and Woomer, 2009). For example, the study of Hauggaard-Nielsen *et al.* (2009) reported the positive soil N balance of 11 g N m^{-2} in the case of Faba bean (*Vicia faba L.*). Fifteen to twenty percent (15 – 20%) of this N is recycled to succeeding crops through residue decomposition (Bado *et al.*, 2007). A soybean variety able to produce 4 t ha^{-1} is able to fix 250 kg of N ha^{-1} (Sanginga and Woomer, 2009). In the case where only grain is harvested and residues incorporated in the soil, net nitrogen accrual from the incorporation of legume residue can be as much as 140 kg ha^{-1} depending on the legume (Giller, 2001). This N tends to be quickly released into the soil and can contribute to substantial improvements in yields of subsequent crops (Sanginga and Woomer, 2009).

However, though most of grain legume crops have the ability to fix atmospheric N_2, their N content and biological nitrogen fixation capacities vary considerably not only among different species but also among cultivars within the same species (Buah, 2008). For example, Osunde *et al.* (2003) worked on two cultivars of soybean (1456-2E and 1660-19F) in the southern savannah of Nigeria and reported the %Ndfa of 39 and 54%, respectively, and fixed N of 51 and 78 kg ha^{-1}, respectively. In the same area, Singh *et al.* (2003) reported a range of N fixed between 43 and 82 kg ha^{-1} while the previous study by Sanginga (Osunde *et al.*, 2003) had reported 130 kg as the total N fixed (a difference of at least 50 kg of fixed N ha^{-1}). Several methods to estimate N_2 fixation are N balance method, nitrogen difference method, ureide (N solute) method, ^{15}N-isotopic methods, ^{15}N natural abundance method, and ^{15}N isotope dilution method (Unkovich *et al.*, 2008).

The biological nitrogen fixation by legumes has always resulted in a better use of N from soil and fertilizer in the legume-cereal rotations, and high N uptake explaining higher yields of the succeeding cereals (Bado *et al.,* 2007; Yusuf *et al.,* 2009). Therefore, embarking on improvement and exploitation of benefits associated with BNF might be a good alternative for smallholder farmers to replenish fertility of their soils, though most of grain legumes are reported to have high N harvest index, hence a net negative N balance (Mugendi *et al.,* 2011). Bearing in mind that N and P are most limiting elements in soils of Rwanda (Rutunga and Neel, 2006; Mukuralinda *et al.,* 2011; Nabahungu *et al.,* 2011), the integration of grain legumes in maize based systems of the eastern province of Rwanda can reverse the trend through N supply via BNF and P nutrition improvement through residue recycling (benefits other than nutrient supply from the biomass content). However, the literature from Rwanda in the area of BNF and its role in system resilience is missing, hence a great need to carry out investigations in this area.

2.3.2 Grain legume crops in legume-cereal rotation

Crop rotation is one of the well established agronomic practices for successful ISFM (Rayar, 2000). Its advantages are (a) addition of organic matter through incorporation of crop residues, (b) improved soil moisture management (water use efficiency is expected to be improved significantly), (c) addition of N through the inclusion of legume in the rotation, (d) effective control of insects and diseases, (e) effective weed control, (f) better exploitation of moisture and nutrients at different soil depth by differences in rooting pattern of rotating crops, resulting in a greater potential for obtaining nutrients, (g) assured income to the farmers, (h) direct enhancement of environmental sanity through reduced use of mineral fertilizers, and (i) controlling soil erosion (Rayar, 2000). The sum of these effects would explain why maize yields have been reported to be improved by rotation even when N balances of the previous legumes were negative.

Cultivation of leguminous crops in rotation with other food crops such as cereals is recognised as one of cost-effective ways by which farmers can maintain soil fertility. Legumes meet some of their N requirement through N_2 fixation, thus sparing some of the soil N to the subsequent crops in addition to the residual N that accrues due to nodule senescence and fallen leaves (Osunde *et al.*, 2003). Therefore, the integration of grain legumes in maize based systems increases crop yields and N efficiency. For example, Buah (2008) and Yusuf *et al.* (2009) reported higher maize yields in plots of maize following legumes, higher N use efficiency on maize yields, higher total N uptake, higher N agronomic efficiency, and higher N fertilizer recovery efficiency.

Cowpea (*Vigna unguiculata L.*), pigeon pea (*Cajanus cajan L. Millsp.*), ground nut (*Arachis hypogeae L.*), soybean (*Glycina max L.*), and faba bean (*Vicia faba*) have been reported to supply N in different cereal systems like maize, sorghum, wheat, and millet (Bado *et al.*, 2007; Buah, 2008; Wang *et al.*, 2008; Hauggaard-Nielsen, 2009, and Yusuf *et al.*, 2009). According to Mapfumo (2011), grain legumes have the potential to increase the subsequent cereal yields by 50% to > 400%, especially maize. However, the rotational effect of legumes is governed by factors such as the variability between different grain legumes, environment, field types, farmer resource endowment, etc (Mapfumo, 2011). For example, in semi – arid environments of southern Zimbabwe, cowpea, bambara groundnut, groundnut, and pigeon pea were able to increase yields of the subsequent sorghum by > 200% but with relatively higher rainfall amount and distribution during the legume phase. When rainfall amount is small and badly distributed during the legume phase, the increase can hardly exceed 100%. Indeed, it lies between 30 and 100% (Mapfumo, 2011). This is reasonable as it would be expected that crops accumulate dry matter and hence a good N fixation activity when water is not limiting (Giller, 2001).

In rotational maize/soybean systems where legume residues were retained and mineral fertilizers were applied (15 kg of P ha^{-1} applied to soybean and 45 kg of N ha^{-1} applied to maize) in Nigeria, Bationo *et al.* (2011) narrated that soybean yields reached 2.5 t of grain ha^{-1} with N fixation contributing about 50 kg N ha^{-1}. The maize following soybean had 75% greater yields than maize following maize. Fertilizer utilization by maize was improved by 100% because applying soybean residues and 45 kg N ha^{-1} resulted in maize yields equal to those obtained by applying the 90 kg of fertilizer N ha^{-1} without soybean.

According to Sanginga and Woomer (2009), rotational benefits are due to enhanced N supply to maize and other effects such as reduction of soil-borne diseases (in line with Rayar, 2000). N supply from BNF can complement fertilizer application and improve soil fertility status (Sanginga and Woomer, 2009). Therefore, the integration of grain legume in maize based cropping systems might be advisable to farmers especially smallholder farmers to benefit from N fertilizer equivalence of grain legumes hence reduced investment in mineral fertilizers and high potential of grain legumes to increase the applied N and/or P fertilizer efficiency under ISFM framework.

Though cereal–legume crop rotation is common in Rwanda especially common bean–maize and common bean–sorghum, little is known on the contribution of legume phase to the subsequent cereal, calling therefore for an investigation in this area, especially in the Eastern province of Rwanda, a potential ecological niche for both grain legumes (common bean, groundnut, etc) and cereals (maize and sorghum) to understand the mechanism through which maize planted in rotation to legumes has its yield increased.

2.3.3 Changes in soil chemical and physical properties under crop rotation

Most of grain legume species have been reported to improve soil chemical properties through addition of plant nutrients and enhancement of soil organic matter. Most of them have a high N fertilizer replacement value (the fertilizer equivalency in grain yields), and N sparing effect. Cereal–grain legume systems are associated with enhanced infection of cereal roots with arbuscular mycorrhiza, decreased nematode infection, increased pH, improved P availability through changes in soil chemistry, and enhanced phosphatase release (Pypers, 2006; Bado *et al.*, 2007; Buah, 2008).

The integration of grain legumes in cropping systems from agro ecosystems characterized by high acidity and large P-fixing capacity due to large sesquioxide contents would reverse these adverse conditions and at the same time release nutrients to the soil (Pypers, 2006). This is made possible by the decomposition of returned crop residues and fallen leaves in addition to underground remaining parts (during legume phase of cereal–legume rotation) (Sanginga and Woomer, 2009). Grain legume would first of all improve the N pool through BNF (with possibility to be beneficial to the subsequent crop) and release its P content through mineralization (Svubure *et al.,* 2010). This process releases organic acids into the soil solution which are anions (H^+ released) able to compete with orthophosphate for sorption sites on acidic surfaces (Pypers, 2006). As such, rapid P fixation is prevented and a better utilization of P by crops can be obtained. Additionally, the released organic acid react with soluble Al^{3+} in the soil solution and inactivate it through precipitation or complexation forming organic compounds, hence, a reduced Al^{3+} toxicity (Pypers, 2006). According to Pypers *et al.* (2005), mechanisms through which P availability is improved are (i) an increase in soil pH and accompanied P solubilisation, (ii) a reduction in micro porosity and specific surface area, reducing the amount of sorption sites in the soils, (iii) an increase in surface negative charge entailing the repulsion of P and (iv) a decrease in metal concentrations in the soil solution reducing the formation of P-metal complexes. This would impel policy makers and extensionists to promote technologies embedded in crop residue management to increase the P availability in P fixing soils, reduce Al^{3+} hazard, increase soil pH, and improve soil fertility through increase nutrients in the soil system.

Some grain legumes are able to improve their P nutrition. Pypers *et al.* (2006) indicated that these legumes exudates organic acids or phosphatases and change the pH in their rhizosphere. This process enables them to access sparingly soluble P in the soil and take it up, a phenomenon beneficial in legume–cereal rotation systems. The typical example is the white lupin (*Lupinus albus*) which excretes large amounts of citrate.

The change in soil N content is evidenced by the fact that maize succeeding legumes uptake greater quantities of N compared to maize planted after maize. Experiments carried out in Ghana resulted in 58 kg N uptake ha^{-1} by maize following cowpea whereas it was 36 kg N ha^{-1} in maize after maize rotation (a difference of > 20 kg N ha^{-1}) (Buah, 2008).

Grain legumes in cereal–legume systems improve soil physical properties including the improvement of soil aggregation, aggregate stability, and ameliorate compacted soils (Buah, 2008). According to the same author, root penetration and root–length densities of maize is better when planted after legumes than when planted after maize. The soil bulk density and water holding capacity are also improved, and soil erosion is reduced (Buah, 2008).

2.3.4 Grain legume crops in legume-cereal intercropping systems

Intercropping is defined as the growing of two or more crop species simultaneously in the same field during a growing season (Addo-Quaye *et al.,* 2011). This farming practice is common among the smallholder farmers in warmer climates who have been intercropping cereal crops such as maize (*Zea mays*), millet (*Pennisetum glaucum*) and sorghum (*Sorghum bicolor*), dominant crop/plant species, and legume crops such as beans (*Phaseolus vulgaris*), cowpea (*Vigna unguiculata*), groundnut (*Arachis hypogaea*), pigeon pea (*Cajanus cajan*) and soybean (*Glycine max*), associated plant species (Tsubo *et al.,* 2003; Gitari, 2008).

Intercropping is also common in Rwanda and the practice is spread over the Eastern province of Rwanda. Maize–common bean and maize–groundnut, are associations one is likely to encounter in the area, the former being most common than the later. This practice is intended to reduce risks during poor growing seasons and produce modest surpluses. The risk avoidance features of maize–comm. on bean intercropping system is for example linked to the possibility of smallholder farmers to feed on leaves and green pods early in the growing season (Woomer *et al.*, 2004).

Generally, intercropping systems have been shown to be more productive than mono cropping (Carruthers *et al.*, 2000), because they have advantage of exploiting environmental resources more efficiently (soil, water, and light), improving soil fertility through BNF, and increasing crop yield and quality, and uses labour efficiently (Tsubo *et al.*, 2003; Zang and Li, 2003; Addo-Quaye *et al.*, 2011). In fact, many research results testified how much this practice is better than mono cropping. For example, Woomer *et al.* (2004), Muoneke *et al.* (2007), and Ullah *et al.* (2007), reported LER >1 when maize is associated with beans, soybean, cowpea, and groundnut. Martin *et al.* (1991) used ^{15}N dilution method to detect the N transfer from N_2 fixing soybean to associated maize. From their study, it is possible that associated maize benefits from BNF activity of associated legume which result in improved N use efficiency for associated maize.

However, intercropping is not always a straight forward beneficial system. Combination of certain crops may result in increased competition among components which may result in reduced yields. Competition may be for water, nutrients, light, or any combination of these three (Carruthers *et al.*, 2000). Therefore, the success of an intercropping systems is likely to be dependent on intercropped species, their spatial arrangement, involved densities per species, climatic conditions (availability and distribution of rainfall), and managerial practices including irrigation, fertilizer application, timely weeding, etc (Giller, 2001). Same factors will govern the N contribution of the legume component to the system through BNF (Gitari, 2008).

Intercropping systems might also be more depletive when soil fertility is concerned. For example, Mucheru-Muna *et al.* (2010) reported negative N balances from maize intercropped with common bean, and ground nut in different special arrangement of species named conventional practice (in Kenya farming systems) and MBILI. Balances were – 44 and – 78 kg N ha^{-1} for common bean and – 35 and – 28 kg N ha^{-1} for ground nut respectively in conventional and MBILI systems.

In Rwanda (and in the Eastern province of Rwanda), farmers have been intercropping maize and common bean back to many centuries but though, no research was done in the area about these systems. Therefore, there is a greet need to research on common bean and maize intercropping systems from this area to establish whether they are productive or not, or whether they can be a soil fertility management practice among poor farmers of the area.

2.3.5 Summary of literature reviewed and research gaps

The soil fertility depletion is claimed to be the fundamental factor of gradual decrease of per capita food production in Rwanda and elsewhere in Sub-Saharan Africa and the whole continent. In Rwanda, the scenario has been exacerbated by the smallness of per family landholding due to acute population growth suppressing the possibility of fallowing giving raise to continuous cropping without replenishing losses due to the removal of nutrients through harvest.

It comes out clearly from the research publications that mineral fertilizers can be an entry point for ISFM when crop residues are recycled to build up SOM. However, though the government of Rwanda is working hard to increase mineral fertilizer use with the aim of increasing crop yields and eradicate extreme poverty and hunger, little or even nothing is done to increase mineral fertilizer use efficiency in order to make this technology profitable to farmers and alleviate environmental risks possible to evolve from the countrywide intensive use of mineral fertilizers. Though organic sources have been evaluated and proven to work both in terms of soil fertility replenishment and sustain crop yields, their low nutrient content poses the challenge to farmers to apply huge quantities sometimes not available, with extra labour requirement. Manure can be a good source in this regard but cannot replace mineral fertilizers and is available in small quantities either.

The newly developed paradigm of soil fertility management that is ISFM, advocated the judicious use of mineral fertilizers coupled with organic sources with consideration of local adaptation to prevailing conditions. In Rwanda, grain legumes are common in farming systems. Dual purpose grain legumes (able to produce high biomass to build up SOM and food grains such as cowpea, soybean, common bean, ground nut, etc) can be an adapted way farmers can apply ISFM technologies and make a profit from the expending use of mineral fertilizers across Rwanda. Grain legume crops when integrated in cereal based cropping systems bring about a package of advantages. They biologically fix atmospheric N, exudates acids and phosphatase to solubilise P otherwise not available to plant, improve soil physical properties like water infiltration rate, soil bulk density, soil compaction, improve chemical and biological conditions like increase of soil pH through the production of organic anions that react with acid cations (Al^{3+} and Fe^{3+}), release other nutrients in the soil system as they decompose, enhance the mychorrizal symbiosis for maize in rotation, and add to the SOM.

Though research results have revealed benefits associated with the combined use of mineral fertilizers and organic sources, and integration of grain legumes in cropping systems for soil fertility management purpose (rotation and intercropping), this kind of research was not done in the context of Rwanda especially in the maize based cropping systems of the Eastern province of Rwanda, hence a gape of information. Additionally, the existing literature demonstrated that such technologies are able to improve crop yields. However, there is a need to attach to these technologies results of economic analysis because farmers will not adopt technologies unless they fetch additional coins compared to their conventional way of farming. There is need therefore to economically evaluate the profitability of ISFM based technologies in the Eastern province of Rwanda.

CHAPTER THREE

3.0 RESEARCH DESIGN AND METHODOLOGY

3.1 Site description

Field experimental trials were conducted in the Eastern Province of Rwanda at 2.14° S, 30.13° E. The altitude of the Eastern province of Rwanda varies between 1300 and 1600 m above sea level (Figure 3.1).

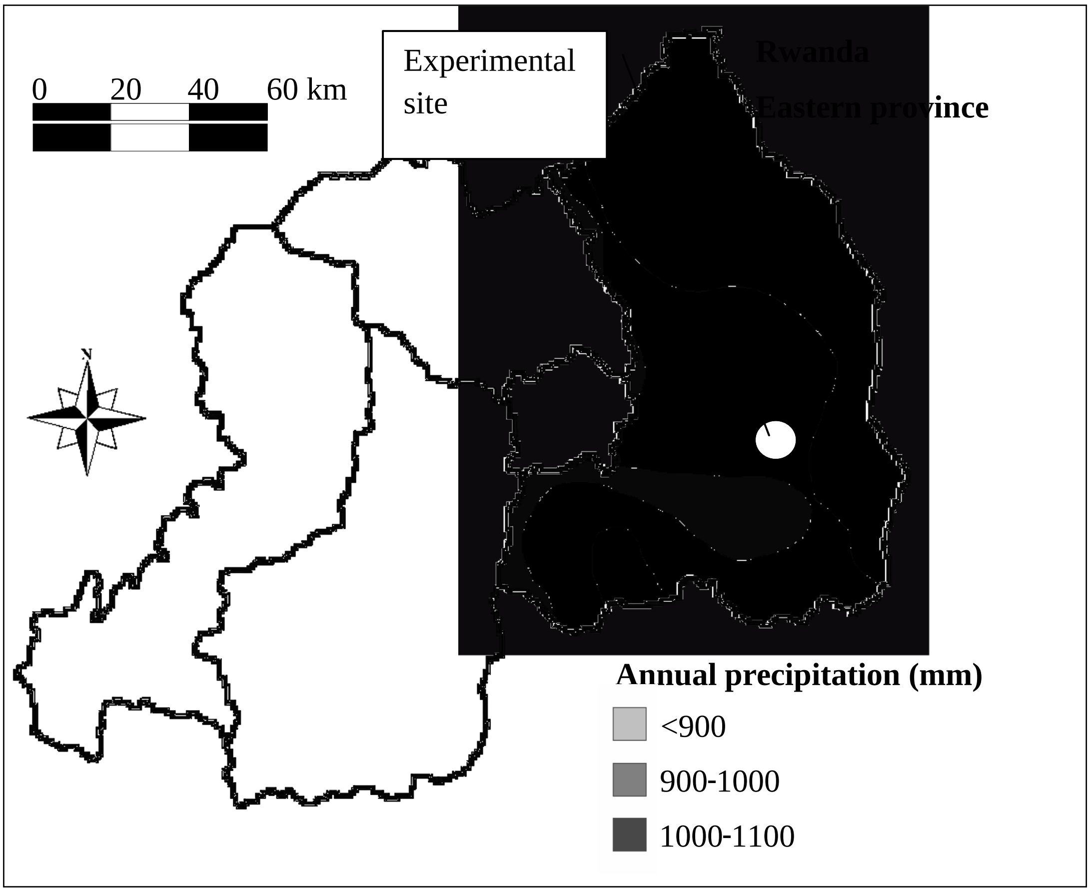

Figure 3.1: Trial location

The region receives between 900 and 1000 mm of annual rainfall (Verdoodt and Van Ranst, 2003; Nielsen, 2009) following a bimodal pattern, which allows for crop cultivation during two seasons per year: the short rain season (September to January) and the long rain season (February to June). During short rains, farmers predominantly grow grain legumes (common beans, soybean and groundnut), followed by a cereal (maize or sorghum) during long rains. The major soil types in the area are Humic Ferralsols, Haplic Acrisols and Dystric Regosols (FAO/IIASA/ISRIC/ISSCAS/JRC, 2009). Farmers identify low soil fertility, lack of manure or mineral fertilizer, and insufficient or unreliable rainfall as the major constraints for crop production.

3.2 Experimental design, treatments and management

The experiment was laid out for three consecutive years (6 seasons) with farmer groups in the Eastern province. Experiments started in 2009 short rain season and were completed in 2011 long rain season. During short rain seasons, test crops comprised of common bean, soybean, and maize mono crops at four different fertilization levels, plus two intercropping treatments which received ½ FYM + ½ DAP, so to make an experiment of 14 treatments. Plots were arranged in an incomplete randomized block design. Treatments were replicated four times. Table 3.1 shows treatment design.

Table 3.1: Experimental treatments

No.	Fertilizer	Cropping system	Crops in short rain seasons	Crops in long rain seasons
1	Control	Monoculture	Maize	Maize
2	Farmyard manure	Monoculture	Maize	Maize
3	DAP	Monoculture	Maize	Maize
4	½ DAP + ½ FYM	Monoculture	Maize	Maize
5	Control	Rotation	Common bean (CB)	Maize
6	Farmyard manure	Rotation	Common bean (CB)	Maize
7	DAP	Rotation	Common bean (CB)	Maize
8	½ DAP + ½ FYM	Rotation	Common bean (CB)	Maize
9	Control	Rotation	Soybean	Maize
10	Farmyard manure	Rotation	Soybean	Maize
11	DAP	Rotation	Soybean	Maize
12	½ DAP + ½ FYM	Rotation	Soybean	Maize
13	½ DAP + ½ FYM	2:2 Intercrop	CB + maize	CB + maize
14	½ DAP + ½ FYM	2:1 Intercrop	CB + maize	CB + maize

Key: No = Treatment number, DAP = di-ammonium phosphate, FYM = Farmyard manure.

The plot sizes were 6 m by 6 m. Fertilizer levels were 0 fertilizer, 5 t of FYM ha^{-1}, 36 kg N + 40.2 kg P ha^{-1}, and 18 kg N + 20.1 kg P ha^{-1} (mixture of FYM and DAP in half quantities). Following N and P content in the applied FYM (Table 3.3), fertilizer input treatments were control (zero fertilizer), 5 t of FYM ha^{-1} (43.2 kg N + 7.8 kg P ha^{-1}), 200 kg of DAP ha^{-1} (36 kg N + 40.2 kg P ha^{-1}), and 100 kg of DAP + 2.5 t of FYM ha^{-1} (40 kg N + 24 kg P ha^{-1}). Diammonium Phosphate (DAP) 18% N and 46% P_2O_5 fertilizer was used as the mineral (inorganic) source of N and P. The applied FYM was a locally produced under oxidized conditions and up to farmers' skills. Table 3.2 shows the quality of FYM used. The N% content of the used FYM (0.3 to 2.0% of N) was very low compared to the threshold of ≥ 2.5% N for a good material for direct application to the soil (Murwira *et al.,* 2002). The C: N ratio was above 10.

Table 3.2: Characteristics of FYM used in experiments

Parameter	Units	Mean	Range
C	(g kg^{-1})	101.5	40.7 – 193
N	(g kg^{-1})	8.64	3.63 – 20.5
P	(g kg^{-1})	1.55	0.65 – 2.72
K	(g kg^{-1})	7.18	2.48 – 22.4
Mg	(g kg^{-1})	2.81	1.09 – 6.65
Ca	(g kg^{-1})	5.78	2.82 – 12.3
S	(g kg^{-1})	0.76	0.28 – 1.48

During long rain seasons, common bean, soybean, and maize mono crops were replaced by maize mono crop to assess rotational effect of legumes versus maize on the subsequent maize. Intercropping treatments were maintained in short and long rain seasons. However, maize and common bean planting rows in intercrops were inter-changed for rotation purposes in long rain seasons.

Soybean was planted at 75 cm x 5 cm, common bean in mono crops at 40 cm x 10 cm, maize in mono crops at 75 cm x 25 cm. In 2:2 intercrops, maize was planted in two paired rows at 50 cm x 25 cm. The next paired rows were always kept at 1 m apart. In 2:1 intercrops, maize was planted at 1 m x 25 cm spacing. Common bean in both 2:2 and 2:1 intercrops was planted at 33 cm x 10 cm between maize rows. The plant population was 266,666 plants of soybean, 250,000 plants of common bean, and 53,333 plants of maize ha^{-1} in monocultures, and 133,333 plants of common bean + 53,333 plants of maize ha^{-1} in 2:2 intercropping, and finally 166,666 plants of common bean + 40,000 plants of maize ha^{-1} in 2:1 intercropping. Common bean was planted by placing one seed per hill, soybean was drilled and thinned at 2 weeks after emergence at 5 cm between two plants, and maize seeds were 2 per hill and thinned 3 weeks after emergence to 1 plant.

The 2:2 intercropping is the MBILI intercropping technology borrowed from Kenya (Woomer *et al.*, 2004; Mucheru-Muna *et al.*, 2010). The 2:1 intercropping treatment was a modification to 2:2 intercropping treatment proposed by farmers in 2008 short rain season while evaluating 1:1 (conventional intercropping from Kenya) and 2:2 intercropping (MBILI) in Umutara (Ndayisaba, data not published). During that evaluation, farmers disqualified the 1:1 intercropping due to visible competition of maize over associated bean whereas farmers' interest was more on bean than on maize production. They proposed that 2:2 (MBILI) be modified into 2:1, meaning one row of maize against two rows of common bean, to minimize the shading effect of maize on common bean by reducing maize population while increasing common bean population.

Five (5) tons of FYM and 200 kg ha^{-1} of DAP treatments were derived from general recommendations in the eastern province of Rwanda, while the ½ DAP + ½ FYM was derived from ISFM indirect hypothesis by Vanlauwe (2004) stating that "*any organic matter-related improvement in soil conditions affecting plant growth (except N) may lead to better plant growth and consequently enhanced efficiency of the applied N",* and aimed at augmenting fertilizer efficiency through addition of organic manure with possibility to reduce both inorganic and organic fertilizers to reflect farmers conditions where neither of these sources is available in right amounts (Vanlauwe, 2004). Legume residues were maintained after harvesting while maize stover was removed totally. Normally, maize residues are exported to other soil systems through mulch in banana and tomato plantations, or given to animals as feeds.

3.3 Sampling

3.3.1 Soil

Soil samples were collected from each plot at the beginning (2009 short rains) and at the beginning of 2011 long rain season (before planting maize of the last season). The sampling depth was 0–20 cm. Samples were taken following a W shape across the plot using an alderman auger and then bulked to one composite sample to reduce variability. A subsample was then taken for laboratory analysis.

3.3.2 Organic material

Before the application of FYM, a composite sample was taken for chemical analysis. The material was thoroughly mixed before sampling.

3.3.3 Biomass and BNF determination

Plants of common bean and soybean were sampled at 50% podding stage from 0.4 and 0.75 m^2 respectively for common bean (0.4 m x 1 m) and soybean (0.75 m x 1m), sun dried, then oven dried at 60^oC for 48 hours, and weighed for biomass dry matter yield estimation, ground, and ball milled for laboratory analysis. Three random maize plants were cut from maize plots, sun dried, oven dried and ground then analysed in the laboratory to serve as the reference plant for soybean and common bean BNF determination (Peoples *et al.*, 1989).

The grains for maize, common bean and soybean were thoroughly mixed and a composite grain sample of 500 g per each species was taken. The sample was weighed to determine its sun dry weight, then oven dried at 60^{o}C for 48 hours to determine the dry matter accumulation in the grains. Samples were analysed for N and P in the laboratory.

3.3.4 Harvesting

Maize grain and stovers were harvested at maturity from a net area of 26 m^2 after leaving out one row on each side of the plot and the first and the last maize plants on each row to minimize the edge effect. The cobs from each plot were separated from the stover and then the fresh weight determined. The cobs in each plot were then air dried to 12.5% moisture content. The maize grains were then separated from core through hand shelling and then weighed to give the net grain weight. The maize stovers were cut at ground level and the total fresh weight determined.

Common bean was harvested at its physical maturity by cutting haulms with secateurs in order to leave in place its underground part. Haulms were cut from a net area of 26 m^2 by leaving out two side rows and 50 cm at each edge of the plot. The grains were separated from the pods through hand threshing. Winnowing was directly done to separate the grains from impurities. The grains were sun dried up to the moisture content of 12.5%, weighed and the dry weight was recorded.

Like common bean, soybean was harvested by cutting haulms with secateurs to leave its below ground part in the soil. Harvesting was done at its physical maturity. Haulms were cut from a 22.5 m^2 plot size after leaving out two extreme rows and 50 cm at each edge of the plot. Haulms were sun dried for three days. The grains were separated from pods by hand threshing. After winnowing to remove impurities, the grain sun dry weight at 12.5% moisture content was determined. Haulms of common bean and soybean were retained after determination of the dry matter accumulation.

3.4 Farmers' evaluation

In order to achieve the adoption of technologies, full involvement of farmers from the initial stages of experimentation was necessary. Trials were therefore located in farms belonging to farmer associations to facilitate the full participation of farmers – members of associations and the access of other farmers not belonging to these associations. At the time of harvesting, farmers evaluated different treatments. The evaluation was done per each season. The evaluation was qualitative. Farmers used 1 – 5 ranking criteria, where:

1- Very poor performance

2- Poor performance

3- Medium performance

4- Favourable performance, and

5- Highly favourable performance

The aim of this evaluation was to get the feedback from farmers on how they perceived technologies. Farmers evaluated the treatments using the following criteria:

Labour requirements – 1 = very high, 5 = very low,

Yield induced by treatments – 1 = very low, 5 = very high

The quality of the product – 1 very bad, 5 = very good

Plant vigour – 1 = less vigorous, 5 = highly vigorous

Diseases – 1 = highly attacked, 5 = disease free

The evaluation tool was in a matrix design with treatments and evaluation criterion, respectively in vertical and horizontal order. During short rain seasons (at harvesting), farmers evaluated fertilizer treatments from maize, common bean and soybean mono crops. They also evaluated common bean–maize intercrops versus mono crops. In long rain seasons (at the end), farmers evaluated the fertilization, rotational, and intercropping effect on yields. Before the evaluation started, farmers were separated into gender groups (one group of female and one group of male farmers).

3.5 Laboratory analysis

Soil samples were analyzed for pH, exchangeable cations (Mg^{2+}, Ca^{2+}, and K^{+}), available P (Olsen-P), organic C, total N, exchangeable acidity, effective cation exchange capacity, and soil texture. The organic material (FYM and plant biomass) analysis determined organic C, total N, Olsen P, K^{+}, Ca^{2+}, Mg^{2+} and S.

Fertilizer agronomic efficiency was calculated using the procedure as outlined by Yusuf *et al.* (2009) as follows:

Fertilizer agronomic efficiency (AEF; kg kg^{-1}) = (yield at Fx – yield at F0) to (applied F at Fx).

Where F is fertilizer, yields at Fx is the yield obtained from the amount of fertilizer applied, and yield at Fo is the yield from the control.

To evaluate the biologically fixed nitrogen by common bean and soybean, the ^{15}N natural abundance method was used (Unkovich *et al.,* 2008). The total N was determined by Kjeldahl method (Stark and hart, 1996). Nitrogen fixation was determined using the ^{15}N natural abundance method (Peoples *et al.,* 1991), using a stable isotope mass spectrometer (European scientific ANCA 20-20/GSL), and the $\delta^{15}N$ value and proportion of N fixed from the atmosphere (%Ndfa) were calculated. *B-values* for both common beans and soybean were determined from literature. These proportions were used to estimate BNF and N balances (N remaining after removal of N through grain harvesting in mono crops of legumes; and maize and legume grains together with maize stover in intercropping systems) in the legume-maize rotation and intercropping. The study assumed the belowground N contribution to be one third of the aboveground N content of the legume (Mucheru-Muna *et al.*, 2010).

$$\text{N balance} = [Biomass\ yield \times N\ concentration\ in\ biomass \times \%Ndfa] - [Grain\ yield \times N\ concentration\ in\ grains]$$

The *B* – values used for common bean and soybean were - 0.482 ‰ (Mucheru-Muna *et al.*, 2010), and -0.982‰, (Houngnandan *et al.*, 2008). Formulae for δ^{15}N (‰) and %Ndfa calculation appropriate to ^{15}N natural abundance were adapted from Peoples *et al.* (1989), Herridge *et al.* (1990), Boddey *et al.* (2000), Gehringa and Vlekb (2004), Okito *et al.* (2004), Urquiaga *et al.* (2006), Houngnandan *et al.* (2008), and Peoples *et al.* (2009), and are as follows:

$$\delta 15\text{N } (‰) = 1000 \frac{(\text{At}\%15\text{N sample} - \text{At}\%15\text{N standard})}{\text{At}\%15\text{N standard}}$$

Where

- δ^{15}N (‰) was the isotope discrimination value of N from atmosphere both in legumes and maize reference crops,

- At%^{15}N sample was the atom ^{15}N abundance value in the sample (either for legume or maize reference) directly read from the mass spectrometer,

- At%^{15}N standard was the natural abundance of ^{15}N in the atmosphere (it is a constant value = 0.3663)

$$\%\text{Ndfa} = \frac{(\delta 15\text{Nref} - \delta 15\text{Nleg})100}{\delta 15\text{Nref} - \text{B value}}$$

Where

- δ^{15}Nref was the δ^{15}N value of reference plants representing values of N from other pools than atmospheric N_2 (fertilizer and soil pools in my study). Maize was the reference plant.

- δ^{15}Nleg was the δ^{15}N value of the total N in soybean and common bean (N_2-fixing crops) grown under conditions in which atmospheric N_2 and N from other sources (soil and fertilizer) were available.

- *B*- values were the isotopic discrimination values of fixed N in the grain legume plots (soybean and common bean) as sourced from Mucheru-Muna et *al.* (2010) and Houngnandan *et al.* (2008).

$$\text{Amount of N fixed} = \frac{\%Ndfa\ x\ Total\ N\ legume}{100}$$

Where

- %Ndfa is the percentage of the portion of N which the plant got through N_2 fixation,

- Total N legume is the %N in the legume plant times the dry biomass yield of the legume plant.

3.6 Land equivalent ratio

LER of maize: common bean intercrops was calculated based on yields obtained from maize and common bean monocultures. The plant population of intercropped maize in 2:2 was similar to the plant population of sole cropped maize. In 2:1 intercrops, the maize population was 75% compared to maize mono crops. Common bean population was 53.3% and 66.6% of sole cropping respectively, in 2:2 and 2:1 intercropping. LER were calculated using the following formula:

$$LER = \frac{Legume\ yied\ in\ intercrop}{Legume\ yield\ in\ monocrop} + \frac{Maize\ yield\ in\ intercrop}{Maize\ yield\ in\ monocrop}$$

Treatments were declared beneficial if their LER was greater than 1 (Mazaheri *et al.*, 2006).

The proportional area occupied by maize and common bean in intercrops was used to calculate their relative aggressiveness to each other (Zang and Li, 2003). In 2:2 intercropping system, maize and bean occupied 55.53% and 44.47%, respectively. Common bean occupied relatively larger area than maize in 2:1 intercropping. Their proportional area was 66.6 % and 33.4%, respectively for common bean and maize. The following formula was used to calculate the relative aggressiveness between common bean and maize in association.

$$Abm = Yib / (Ysb \times Fb) - Yim / (Ysm \times Fm)$$

Where *Abm* is the interspecies aggressiveness measure between common bean and maize, *Yib* and *Yim*, the yield of common bean and maize in intercrops, *Ysb* and *Ysm*, the yield of common bean and maize in sole cropping, and *Fb* and *Fm*, the proportion of the area occupied by common bean and maize in intercropping systems. When *Abm* is greater than 0, the competitive ability of common bean exceeds that of maize crop in intercropping. It is the inverse when *Abm* is smaller than 0 (Zang and Li, 2003).

3.7 Economic analysis

A simplified financial analysis was conducted to evaluate the profitability of the different technologies in the field trials. Costs and benefits were calculated per technology. Costs included the purchasing price of DAP fertilizer (obtained from local agro-dealers) and FYM (obtained from local informants), seed costs (from the local market places), and the labour cost due to the application of treatments calculated based on the labour wage from the study area. The information on labour requirement was collected at the specific time of each activity in the course of each season. Benefits included revenue from maize, bean and soybean grain yield sales. Grain prices were obtained at the farm gate across the 8 locations from the Eastern province of Rwanda. Maize stover had a market value in the study area as it is used as mulch in banana and vegetable (tomato) plantations, and as a feedstuff for livestock (Table 3.4).

An exchange rate of 573 Rwandan francs (RWF) to 1 USD was used (September 2009 – July 2011; National bank of Rwanda). The benefit to cost ratio (BCR) was calculated as net benefits divided by costs. Treatments were declared good when their BCR was ≥ 2.00 USD USD^{-1} (Kelly and Murekezi, 2000). Marginal rates of returns MRR were calculated as the marginal benefit to marginal cost ratio to find out the rationale for farmers to invest in the different technologies. A good technology worthy for adoption by farmers should have a MRR ≥ 1.18 USD USD^{-1} (CIMMYT, 1988).

Table 3.3: Parameters used in the economic analysis of studied technologies (2009 – 2011)

Parameter	Actual value
Price of maize seed (USD kg^{-1})	0.35
Price of common bean seed (USD kg^{-1})	0.53
Price of soybean seed (USD kg^{-1})	0.53
Price of DAP fertilizer (USD kg^{-1})	0.86
Price of FYM (USD kg^{-1})	0.02
Labour cost per hour (USD hr^{-1})	0.17
Price of harvesting maize (USD kg^{-1} of cobs)	0.01
Price of shelling maize (USD kg^{-1} of grain)	0.01
Price of maize grain (USD kg^{-1})	0.26
Price of common bean grain (USD kg^{-1})	0.43
Price of soybean grain (USD kg^{-1})	0.43
Price of maize stover (USD kg^{-1})	0.002

Across short rain seasons, the BCR and MRR were calculated per maize, common bean and soybean and were used to compare fertilizer input treatments with control plots (zero fertilizer) per each crop. In intercropping treatments, BCR and MRR were used to compare intercropping with mono crops of maize. During long rain seasons, both BCR and MRR were calculated. The reference was maize–maize rotation with zero input. Similarly, the calculation of BCR and MRR per cycle had maize–maize rotation with zero input as a reference.

3.8 Statistical analysis

The analysis of variance (ANOVA) was conducted to determine the effects of inputs, intercropping systems, and legume-cereal rotation. Two way ANOVA (to detect differences due to inputs and cropping systems) and one way ANOVA (to detect differences between mono cropping and intercropping) in a randomized block structure (case of uncompleted block design structure) were used (Genstat discovery edition 3 package, 2003). The effect of various factors and their interactions was compared by computing least square means and standard errors of difference (SED). Significance of difference was evaluated at $P \leq 0.05$. The means were separated using the Fisher's protected LSD (Least Significant Differences of means) at $P \leq 0.05$). Spearman rank-order correlation was also used to determine relationships between farmer evaluation by gender and economic aspects of treatments.

CHAPTER FOUR

4.0 RESULTS AND DISCUSSIONS

4.1 General overview

This chapter presents the findings of the study and discussions in five major sections. The first section presents the rainfall amount and distribution during the study period. The second section presents the effect of FYM and/or mineral fertilizers on yields of common bean, soybean, and maize. Intercropping technologies have also been presented and discussed under this section. The same section covers the agronomic efficiency of applied DAP. Additionally, it presents and discusses the rotational effect of common bean, soybean, and maize on yields of the subsequent maize, and its interaction with applied FYM and/or mineral fertilizers. The third section is on BNF and N balances of common bean and soybean, and consideration made on fertilizer inputs and cropping systems. Under the same section, chemical changes in soil fertility status brought about by FYM and/or mineral fertilizer application to common bean, soybean and maize and common bean–maize intercrops are presented and discussed. Additionally, this section covered the part of N and P uptake by common bean, soybean and maize. The fourth section presents and discusses BCR and MRR and their possible implication on adoption by farmers from the Eastern province of Rwanda. The fifth section deals with farmers' views on studied technologies and compared their technology evaluation scores with economic aspects of technologies.

4.2 Rainfall distribution during the experimental period

Figure 4.1 shows rainfall variation during the experimental period.

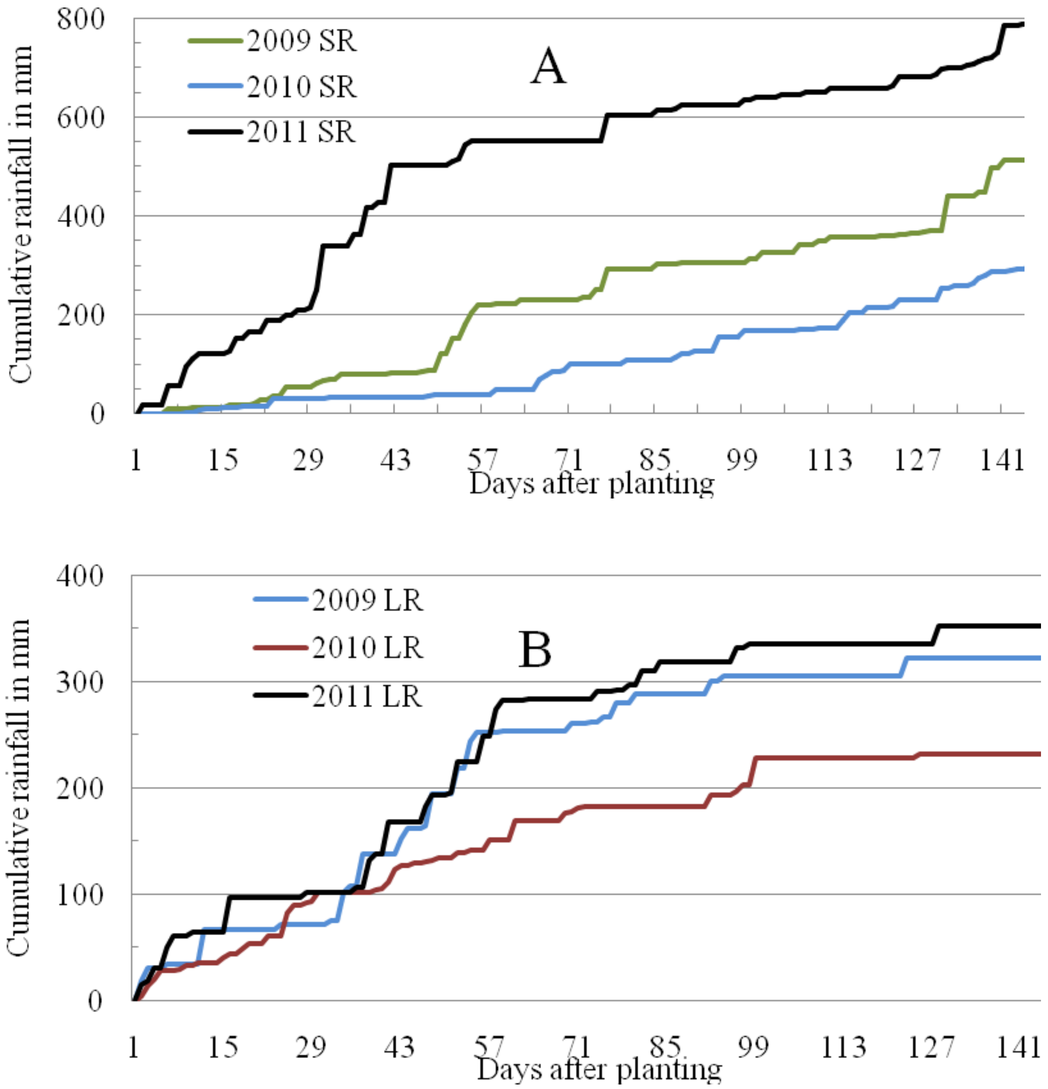

Figure 4.1: Cumulative rainfall amount: A – short rains (SR), B – long rains (LR) observed at Kazo meteorological station – Eastern province of Rwanda

In 2010 short and long rains, the amount of rainfall was lower and poorly distributed across the season compared to other seasons. 2009 and 2010 short rain seasons had dry spells at the onset of the season while 2013 short rains received around 150 mm during 15 first days of the season. Despite small dry spells experienced during long rain seasons, the amount and distribution was relatively better compared to short rain seasons.

4.3 The productivity of maize-based systems

4.3.1 Yields of common bean, soybean and maize mono crops during short rains

The application of FYM, DAP, and ½ DAP + ½ FYM significantly ($P = 0.003$) increased the yield of common bean during 2009 short rains by 37.1, 63.8 and 56.0%, respectively (Figure 4.2).

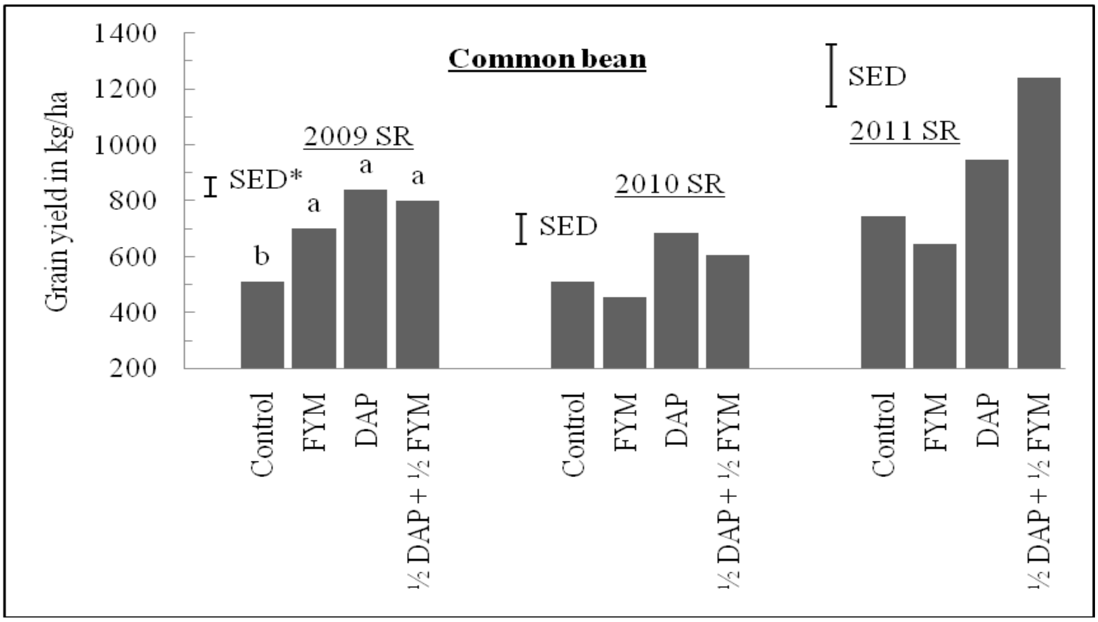

Figure 4.2: Grain yield of common bean during 2009 – 2011 short rains (SR). ***SED = standard error of differences to the mean. Values with different letters are significantly different at P = 0.05. The * indicates that differences are significantly different.***

However, these treatments did not significantly ($P = 0.242$ in 2010 and $P = 0.13$ in 2011) affect common bean yield during 2010 and 2011 short rains. The yield in FYM was less by 10.7 and 13.6%, respectively in 2010 and 2011 short rains. The yield obtained from DAP and ½ DAP + ½ FYM was higher by 34.2 and 26.6% for DAP, and 18.6 and 66.1% for ½ DAP + ½ FYM, respectively in 2010 and 2011 short rains. Yields significantly (*P* = 0.005) decreased by 70.0% and increased by 125.8%, respectively in 2010 and 2011 short rains. The interaction, season/input, was not significant (*P* = 0.655) (Figure 4.2).

Across all seasons, none of inputs applied had significantly (*P* = 0.064 in 2009, 0.465 in 2010 and 0.464 in 2011) affected soybean yields (Figure 4.3).

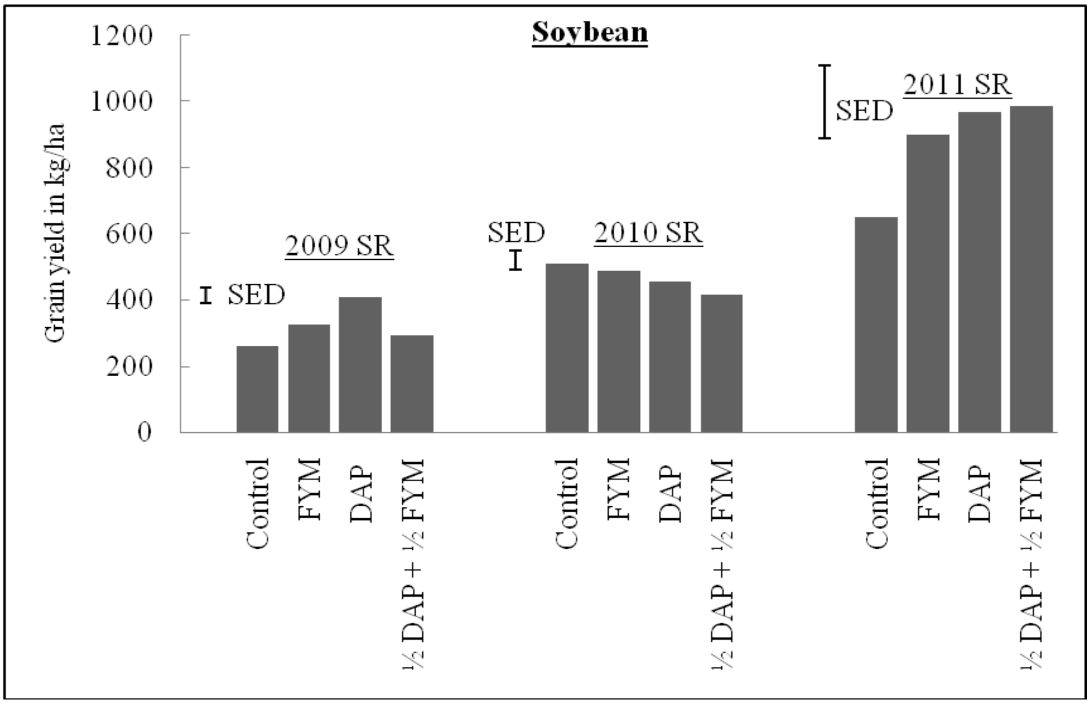

Figure 4.3: Grain yield of soybean during 2009 – 2011 short rains (SR). ***SED = standard error of differences to the mean.***

The application of FYM, DAP, and ½ DAP + ½ FYM treatments increased soybean yields by 24.8, 55.7, and 11.8%, respectively in 2009 short rains, decreased them by 0.2, 10.4, and 18.5%, respectively in 2010 short rains due to poor germination observed in fertilized treatments under dry spells at planting, and finally increased them by 37.9, 48.6, and 51.3%, respectively in 2011 short rains (Figure 4.3). Yields of soybean significantly (P < 0.001) increased by 44.9 and 178.9% respectively in 2010 and 2011 short rains compared to 2009 short rains. The interaction, season/input, was not significant (P = 0.259).

Maize yields were not significantly (P = 0.392 in 2009 and 0.47 in 2010) affected by applied inputs during 2009 and 2010 short rains (Figure 4.4).

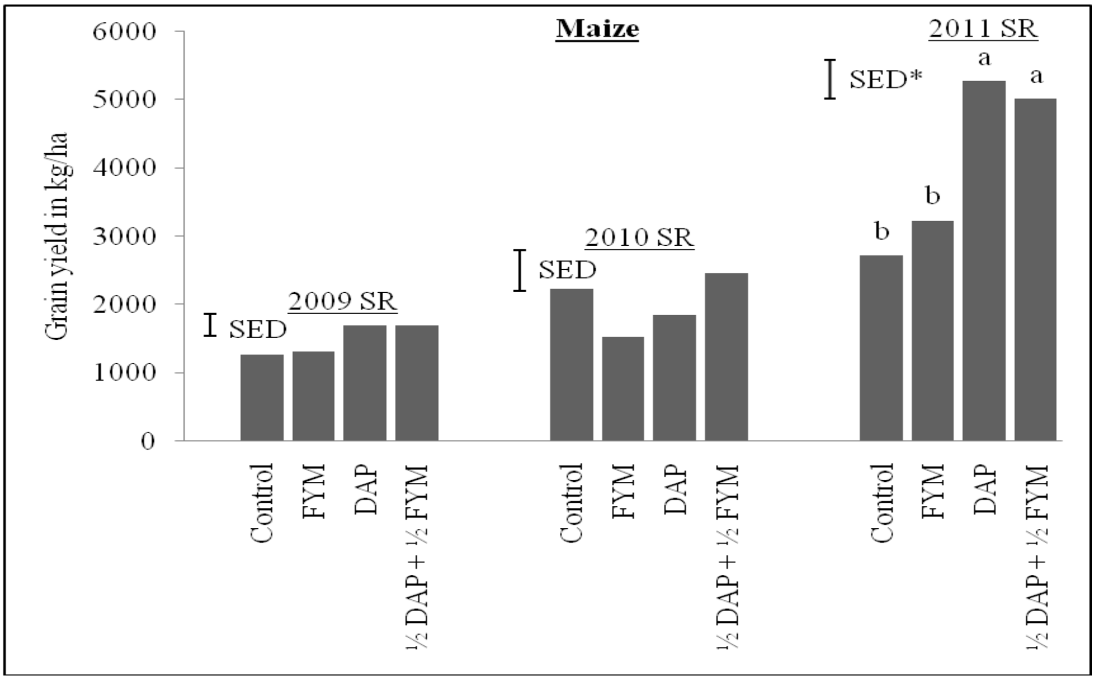

Figure 4.4: Grain yield of maize during 2009 – 2011 short rains (SR). ***SED = standard error of differences to the mean. Values with different letters are significantly different at P = 0.05.***

During 2009 short rains, the application of FYM, DAP, and ½ DAP + ½ FYM increased yields by 4.6, 34.5, and 34.5%, respectively. During 2010 short rains, FYM and DAP treatments decreased yields by 68.1 and 82.8, respectively, while ½ DAP + ½ FYM had increased yields by 10.2%. During 2011 short rain season, maize responded significantly ($P = 0.01$) to the application of DAP and ½ DAP + ½ FYM, but was not significantly affected by the application of FYM (Figure 4.3). Yields were increased by 19.1, 94.2 and 84.6% respectively by FYM, DAP and ½ DAP + ½ FYM. Yields significantly ($P < 0.001$) increased by 48.1 and 147.8% respectively in 2010 and 2011 short rains compared to 2009 short rains, but the interaction, season/input, was not significant ($P = 0.232$) (Figure 4.4).

The DAP agronomic efficiency of common bean was low in DAP treatment (around 1.0 kg kg^{-1} across all seasons). In ½ DAP + ½ FYM, the DAP agronomic efficiency was increased (but not significantly) by 4, 7, and 13 times respectively in 2009, 2010, and 2011 short rains ($P = 0.122$ in 2009, 0.171 in 2010, and 0.064 in 2011) (Figure 4.5).

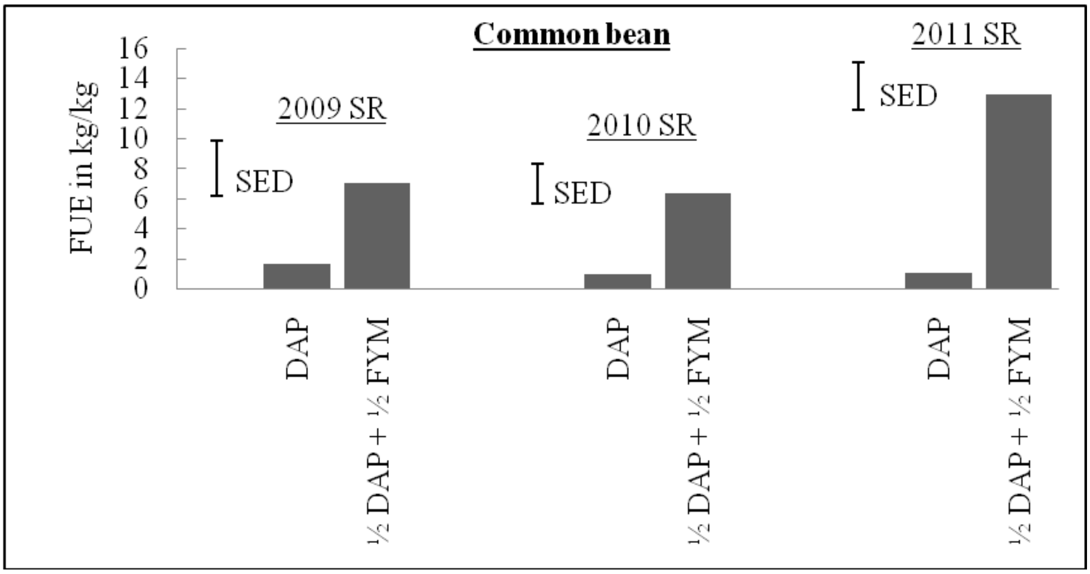

Figure 4.5: Fertilizer agronomic efficiency of common bean during short rains (SR).

Seasonal variations did not affect significantly the fertilizer agronomic use efficiency of DAP in bean treatments ($P = 0.315$).

In soybean treatments, the DAP agronomic efficiency was significantly (*P* = 0.042 in 2009, 0.048 in 2010 and 0.013 in 2011) higher in ½ DAP + ½ FYM by 3, 15, and 5 times than in DAP treatments respectively in 2009, 2010 and 2011 short rain season (Figure 4.6).

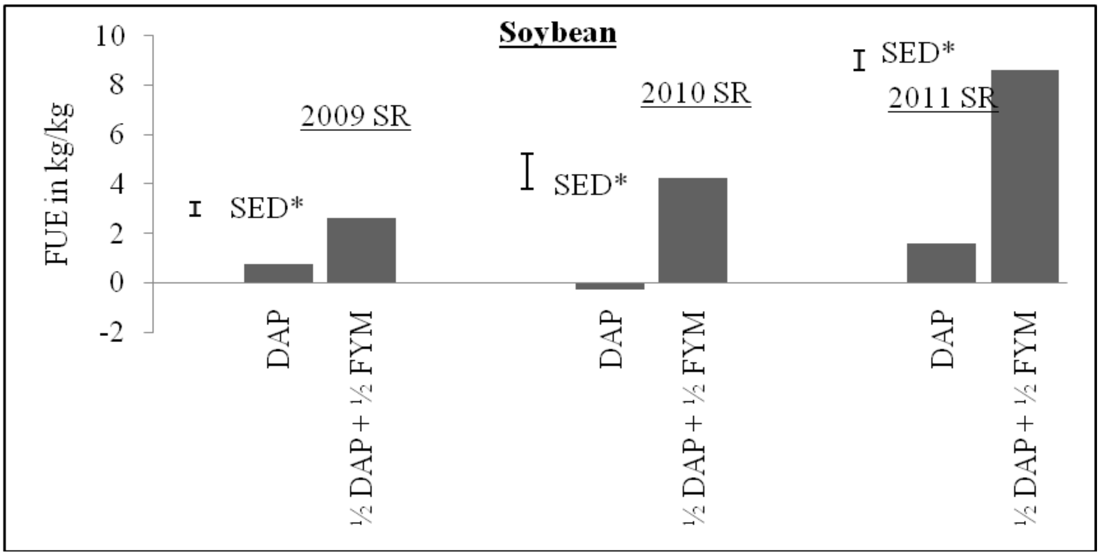

Figure 4.6: Fertilizer agronomic efficiency of soybean during short rains (SR).

In maize treatments, the DAP agronomic efficiency was higher in ½ DAP + ½ FYM by 7, 15, and 4 times than in DAP treatments, respectively in 2009 (*P* = 0.152), 2010 (*P* = 0.207), and 2011 (*P* = 0.015) short rains (Figure 4.7).

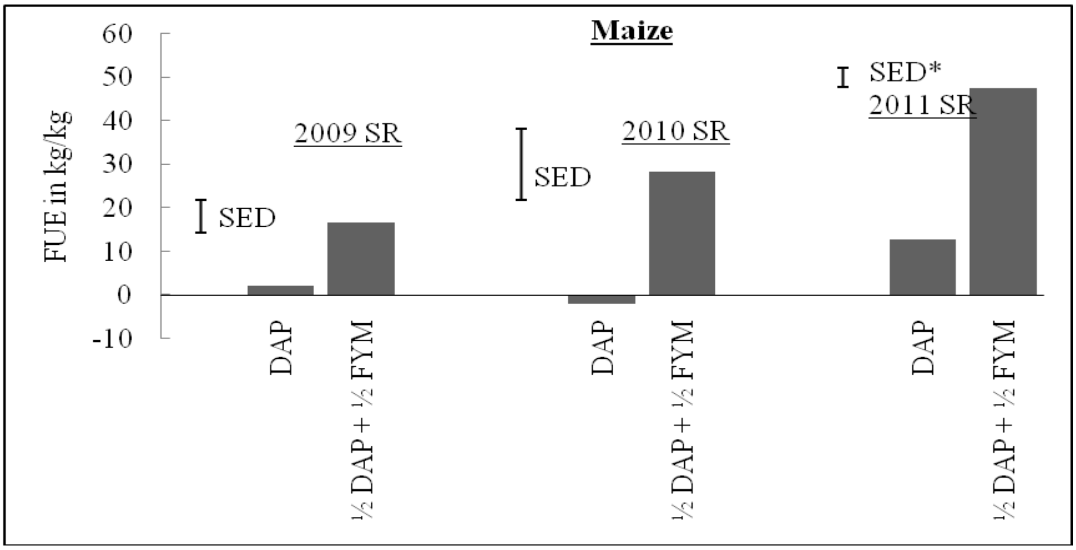

Figure 4.7: Fertilizer agronomic efficiency of maize during short rains (SR).

Similar results have been reported by other researchers; for instance, Obia (2011) and Sulieman *et al.* (2009) observed no significant differences in yields of common bean under different FYM and DAP doses in acid soils of Uganda, and in alkaline soils of Sudan, respectively. The lack of soybean response to fertilization was also reported elsewhere. Indeed, the response of soybean to three categories of N application (0 – 50, 50 – 100, and > 100 kg N ha^{-1}) was not significantly different from observations by Salvogiotti *et al.* (2008) from 108 studies and 637 sets of data. Seasonal variations in crop yields have been due to differences in rainfall amount and distribution across experimental seasons (Figure 3.2). Common bean and soybean have been more vulnerable to poor rainfall amount and distribution than maize because maize lasts longer in the field than do common bean and soybean. Common bean lasted 90 – 95 days; it was 100 – 105 days for soybean, while maize lasted between 130 – 140 days in the field.

The lack of response to FYM observed in this study might be related to the low supply of nutrients in this treatment especially P. The experimental soil pH ranged from strongly to moderately acidic (Landon, 1991) with a pH ranging between 5.14 and 6.23, and the available P ranging from 3.0 mg kg^{-1} of soil (deficient) to 14.3 mg kg^{-1} of soil (slightly adequate) (Table 3.1). These soil conditions are common in highly weathered soils of the humid tropics which cover large areas in South America and Central Africa (Rwanda included) (Fageria and de Calvalho, 1996). Their (soils of the humid tropics) low natural P, high P fixation capacity related to clay, iron and aluminium content of the soil severely affect the crop production in such soils. To obtain good crop yields in such soils, sufficient P fertilization is required (Fageria and de Calvalho, 1996) as good amounts would be fixed by soil colloids dominated by aluminium, and by free aluminium and iron in the soil solution.

Supplying the required quantities of P for good crop production through the application of FYM alone as it was the case in FYM treatment of this study might require huge amount that may be difficult to handle. For example, Negassa *et al.* (2005) found that the application of 4 t of FYM ha^{-1} supplied only 9% of recommended P while 12 t of FYM ha^{-1} supplied only 26% of P requirement of maize in maize farming systems of Western Ethiopia. The application of 5 t of FYM ha^{-1} in this study supplied to the soil the P ranging between 3.25 kg ha^{-1} and 13.6 kg ha^{-1} (Table 3.2) per season of application.

Responses to FYM were lower than responses to DAP and ½ DAP + ½ FYM similar to findings of Nyamangara *et al.* (2003) and Bado *et al.* (2004) especially on maize.

As discussed above, the superiority of the effect of DAP and ½ DAP + ½ FYM reported in this study could have been due to low nutrients in the FYM materials from the Eastern province of Rwanda (Table 3.2). These treatments which received the DAP fertilizer received N and P in bigger amounts and in easily available forms than the FYM treatment. The FYM materials applied were produced under aerobic conditions by farmers where rainfall and temperature fluctuations could have had taken off its elements especially N (Amolo *et al.*, 1996; Nyamangara *et al.*, 2003).

The application of such FYM materials can bring about N hunger in the soil which can last up to four weeks after the application (Vanlauwe *et al.*, 2002; Nhamo *et al.*, 2004). During this period of hunger, young plants compete with soil microbes for N (Van der Heijden *et al.*, 2008). Afterward, the applied material undergoes slow mineralization which slowly releases N, P, K, and other macro and micronutrient contained in it. The study by Mori and Hojito (2011) estimated the mineralization rate of N in the manure to be 13.2, 7.0, 5.5, 4.6, and 3.9%, respectively in the year of application, 2nd, 3rd, 4th and 5th year after it is applied; the annual P mineralization rates in the year of application and the next year to be 20 and 10%, respectively; and the annual K mineralization rates in the year of application and the next year to be 70 and 10%, respectively.

The ½ DAP + ½ FYM increased yields, improved the DAP fertilizer use efficiency, and a positive interaction between DAP and FYM. These results are supported by findings of Nyamangara *et al.*, 2003; Bado *et al.* (2004); Gikonyo and Smithson (2004); and Gikonyo *et al.* (2010). The effect of ½ DAP + ½ FYM observed in this study could be attributed to the improved availability of P (Gikonyo *et al.*, 2010) through the reaction of weak organic acids by FYM with Al^{3+} compounds in the soil, and the release of other cations including bases (Pypers *et al.,* 2005). The P supplied through DAP in these conditions created by the FYM would not be fixed by soil colloids, free iron and aluminium; instead, it would remain in the soil solution for plant uptake. Additionally, FYM decomposition could have been faster in this treatment (½ DAP + ½ FYM) than in FYM treatment due to the application of N containing fertilizer along with the FYM. This could have served as N source for microbial nutrition resulting in a high rate of decomposition (Amolo *et al.,* 1996).

The low DAP agronomic efficiency and its improvement brought about by the application of FYM observed in this study might have been due to the P fixing capacity of the soil in acidic conditions (Rutunga and Neel, 2006). Therefore, results of this study suggest that soils from the Eastern province of Rwanda are poor in N and P content and can respond to any mineral N and P application with significant improvement in the fertilize use efficiency when the organic material is applied simultaneously.

4.3.2 Rotational effect of common bean and soybean on maize yields

During 2009 long rains, maize did not respond significantly to the applied inputs (P = 0.142), neither to the previous crop (P = 0.214), nor to the interaction of the previous crop/input (P = 0.814) (Figure 4.8). However, FYM increased yields by 18.9, 14.2, and 0.5%, respectively in maize–maize, common bean–maize and soybean–maize rotations. Yields were increased by 10.3, 12.0, and 22.8% by DAP, and 11.3, 34.4, and 31.7% by ½ DAP + ½ FYM, respectively in maize–maize, common bean–maize, and soybean–maize rotations. Though the effect of the previous crop was not significant (*P* = 0.214), yields were slightly improved by common bean and soybean planted in the short rain season (previous crop) (Figure 4.8).

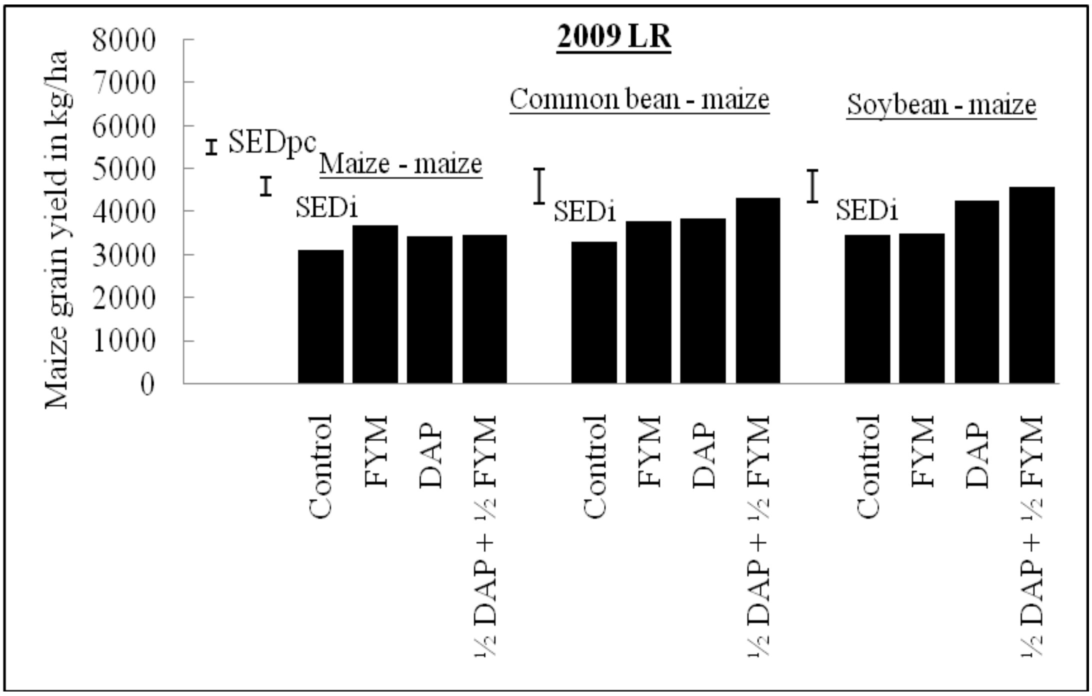

Figure 4.8: Rotational effect during 2009 long rains.

In control treatment, yields were increased by 6.3 and 11.8%, respectively due to common bean and soybean as a preceding crop. In FYM treatment, common bean as a previous crop increased yields by 2%. In DAP treatment; yields were higher by 12 and 24% when maize followed common bean and soybean, respectively. In ½ DAP + ½ FYM treatment, maize planted after common bean and soybean gave yields higher by 25.5 and 32.2%, respectively. Maize yields tended to be higher when maize followed soybean than when it followed common bean (Figure 4.8).

During 2010 short rains, inputs (*P* = 0.311), the previous crop (*P* = 0.063), and their interaction (*P* = 0.568) did not affect significantly the maize yield. FYM and DAP increased the yield in maize–maize rotation by 18.9 and 23.1%, respectively, but reduced yields by 25.3 and 14.3%, respectively in common bean–maize rotation, and 28.5 and 20.8%, respectively in soybean–maize rotation (Figure 4.9). The ½ DAP + ½ FYM treatment increased yields by 21.5, 40.0, and 21.8%, respectively in maize–maize, common bean–maize and soybean–maize rotations (Figure 4.9).

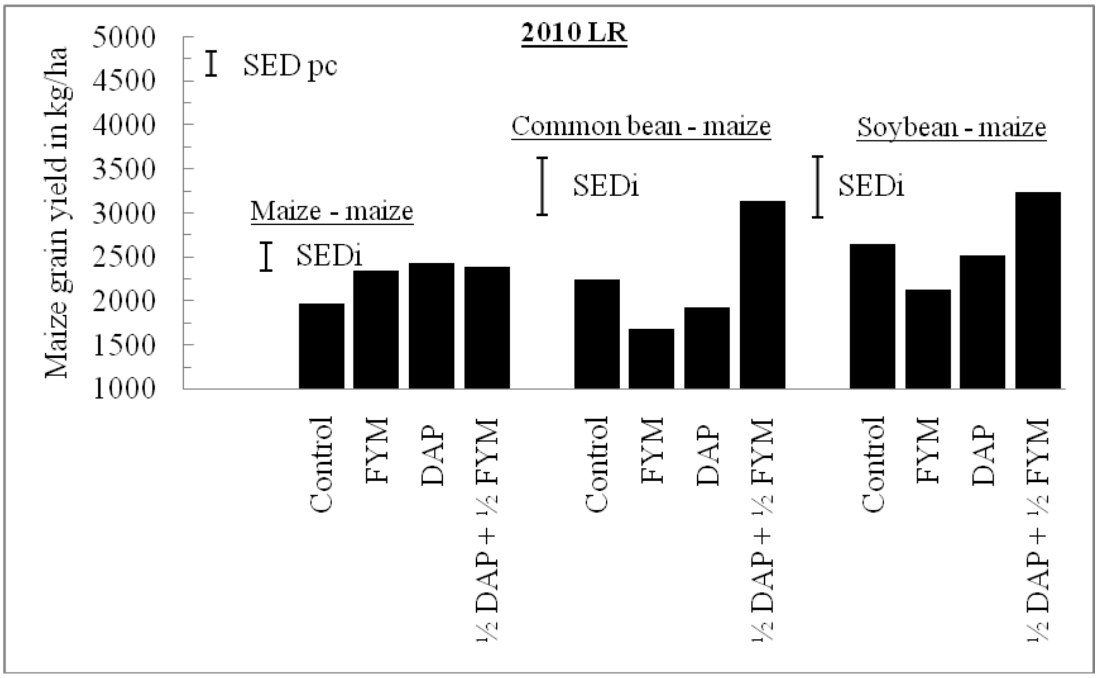

Figure 4.9: Rotational effect during 2010 long rains LR. ***SED = standard error of differences to the mean, pc = previous crop, i = inputs, LR = long rain season.***

The yield of maize planted after common bean and soybean was higher by 13.7 and 34.5%, respectively in control treatments. In DAP treatment, maize following common bean had a higher yield by 3.9%. The yield from ½ DAP + ½ FYM was 31 and 35% greater in common bean–maize and soybean–maize rotations than from maize–maize rotation (Figure 4.9). Low yields and low responses (P < 0.001) to treatments observed in this season are due to long and frequent dry spells which occurred in 2010 long rain season (Figure 4.1). During 2011 long rains, differences due to the previous crop (P = 0.275), inputs (P = 0.262), and their interaction were not significant (P = 0.803) (Figure 4.10).

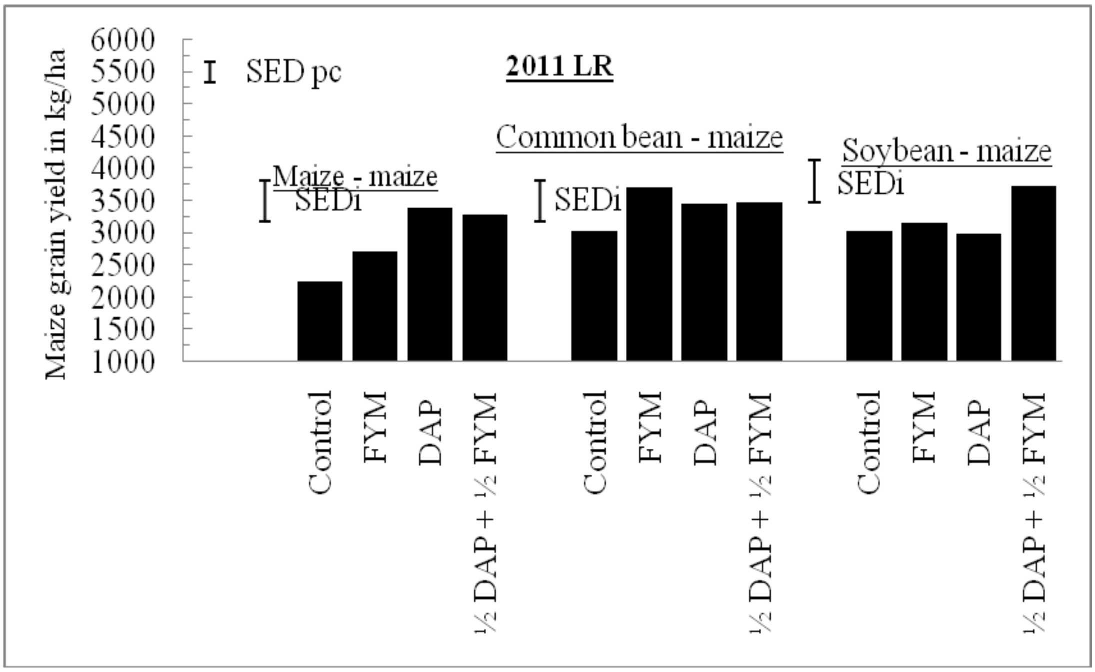

Figure 4.10: Rotational effect during 2011 long rains LR. ***SED = standard error of differences to the mean, pc = previous crop, i = inputs, LR = long rain season.***

FYM, DAP and ½ DAP + ½ FYM treatments increased yields by 20.9, 51.3, and 46.9%, respectively in maize–maize rotation, and 21.9, 13.8, and 14.6% in common bean–maize rotation. In soybean–maize rotation, FYM increased the yield by 4.4%, DAP reduced the yield by 1.5%, while ½ DAP + ½ FYM increased the yield by 23.1%. In control treatments, common bean and soybean increased maize yields by 35.6% (both) compared to maize as a preceding crop (Figure 4.10). In FYM plots, increments due to common bean and soybean grown in the previous season were 36.8 and 17.0%, respectively. In DAP plots, yields were increased by 2.1 and reduced by 11.7%, while it was increased by 5.7 and 13.6% in ½ DAP + ½ FYM treatments, respectively in common bean–maize and soybean–maize rotations compared to continuous maize cropping (Figure 4.10). Similarly as during the short rain seasons, the agronomic efficiency of DAP fertilizer was more than five times as when combined with FYM (significant at $P = 0.05$) than when applied solely, and not affected by the crop grown in the preceding season, but the difference tended to be larger when maize followed soybean (Figure 4.11).

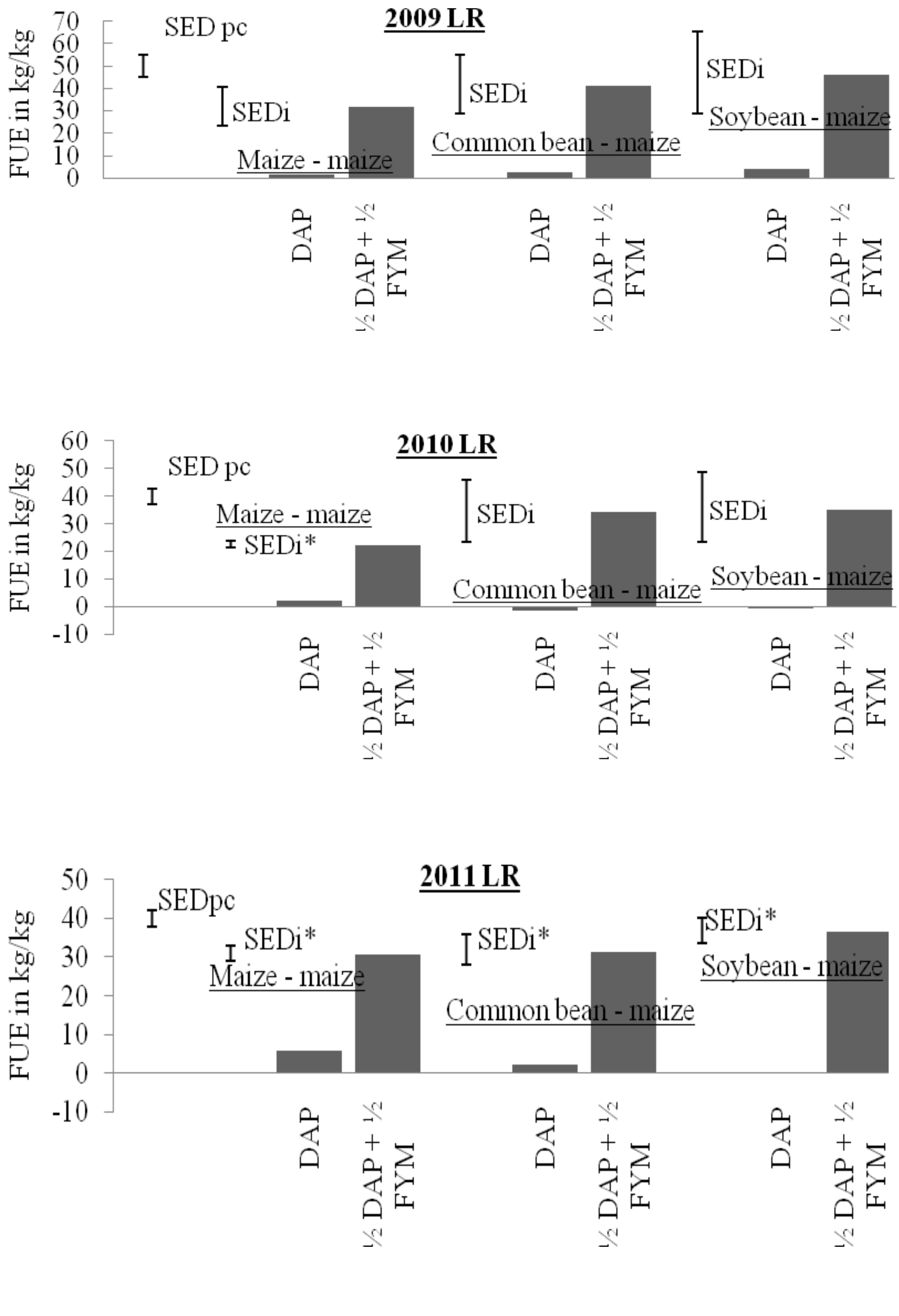

Figure 4.11: Rotational effect on fertilizer agronomic use efficiency

The positive effects of legume rotation on a subsequent maize crop were also reported by Sanginga *et al.* (2003), Osunde and Bala (2005), Yusuf *et al.* (2009a and b), and Svubure *et al.* (2010). Sanginga *et al.* (2003) reported maize yield increases of 14% due to beans or soybean grown in rotation with maize. Yusuf *et al.* (2009a) reported an increase in maize yields by 20 to 30% due to soybean–maize rotation, while Yusuf *et al.* (2009b) reported an increase of maize yield by 68% when maize followed soybean. Svubure *et al.* (2010) observed maize yields improvement by common bean and soybean whether stover was removed or not. Osunde and Bala (2005) reported an increase of maize yield by at least 25% following the soybean as a preceding crop in rotation.

Maize yield improvement due to common bean and soybean planted in rotation were not due to N contribution to the soil system as evidenced by net negative N balances for both common bean and soybean. Additionally, yields tended to be higher in soybean than in common bean treatments despite the larger negative N balance observed in soybean than in common bean treatments. This may suggest that the rotational effect of soybean is greater than that of common bean regardless of their N contribution to the succeeding maize (N balance). This is not surprising as Osunde *et al.* (2003) observed higher maize yields in soybean treatment than from fallow though soybean had net negative N balances. In this study (Figure 4.5), maize residues were totally removed while common bean and soybean residues were kept in the field after harvesting. The C:N ratio of legume crop residues being low, the decomposition of the leftover material would have been fast and released the contained N, P, and other nutrients to the soil for further uptake by the maize planted in rotation.

The legume–maize rotation systems have also been reported to improve the rhizosphere environment of the plant grown in rotation. This includes the improvement of the soil bulk density allowing a good root development and respiration, the improvement of the soil aggregation, improved soil microbial activity, and other benefits related to the soil organic matter decomposition such as the complexation of Al^{3+} and Fe^{3+} in the soil solution and the preservation of P from fixation to the soil system. The rotational effect of soybean being greater than the rotational effect of common bean would have been due to the belowground biomass of these two plants. The dry matter accumulation in the underground part was assumed to be one third of the total biomass production both for common bean and soybean (Unkovich *et al.*, 2008), hence parameters such as total N and fixed N were calculated based on this assumption. However, the belowground biomass of soybean may have been better than that of common bean in terms of nodulation and microbial colonization. The decomposition of nodules and microbial bodies would therefore have released comparably higher N and other nutrients in soils treated with soybean than those treated with common bean.

The rotational benefits observed in this study may therefore at least in part be a result of lower nutrient removals due to the N sparing effect of common bean and soybean planted in the previous season through their BNF activity and the decomposition of common bean and soybean crop residues both underground and aboveground, together with the microbial senescence in the soil after legumes were harvested. The other possible contribution of legumes versus maize as a previous crop to the relatively increased maize yields would be the improved maize root–Arbuscular mycorrhiza fungal symbiosis responsible for additional plant nutrition as it helps the plant to reach additional volume of soil layers with possibility to solubilise P that would otherwise be inaccessible (Osunde *et al.*, 2003). The study by Yusuf *et al.* (2009b) reported an improvement in microbial N and C in legume–maize rotation than in continuous maize suggesting an improved microbial activity in the former system.

4.3.3 Yields of common bean and maize in intercrops

The effect of intercropping common bean and maize was evaluated using the analysis of variance, LER, and the aggressiveness measure. Results from short rain seasons are presented in Table 4.1.

Table 4.1: Yields of common bean and maize in intercrops in short rains 2008 – 2011

Treatment	Maize			Bean			System		
	2009 SR	**2010 SR**	**2011 SR**	**2009 SR**	**2010 SR**	**2011 SR**	**2009 SR**	**2010 SR**	**2011 SR**
					Yields (kg ha^{-1})				
Mono crop	1700	2471	5016	911	606	1241			
2:2 IC	1114	2304	3819	385	461	395			
2:1 IC	752	2149	2627	474	484	614			
SEDtreat	454.7ns	140.3ns	974.3ns	233.5ns	97.6ns	258.5ns			
SEDs	518.8**	518.8**	518.8**	110.6ns	110.6ns	110.6ns			
SEDtreat/s	898.6ns	898.6ns	898.6ns	191.6ns	191.6ns	191.6ns			
					Land equivalent ratio LER (Maize, bean, and Maize + bean)				
Mono crop	1.00	1.00	1.00	1.00a	1.00	1.00a	1.00	1.00	1.00
2:2 IC	0.81	0.89	0.74	0.54b	0.76	0.35b	1.35	1.692	1.097
2:1 IC	0.44	0.78	0.537	0.53b	0.78	0.54b	0.97	1.570	1.077
SEDtreat	0.213ns	0.088ns	0.174ns	0.16*	0.14ns	0.107**	0.361ns	0.196ns	0.176ns
SEDs	0.1ns	0.1ns	0.1ns	0.078*	0.078*	0.078*	0.164*	0.164*	0.164*
SEDtreat/s	0.173ns	0.173ns	0.173ns	0.136ns	0.136ns	0.136ns	0.284ns	0.284ns	0.284ns
					Aggressiveness (Maize, bean, and Maize/bean)				
Mono crop	1.00	1.00b	1.00	1.00	1.00	1.00	0.00	0.00b	0.00
2:2 IC	1.47	1.67ab	1.33	1.21	1.71	0.79	0.255	-0.068b	0.53
2:1 IC	1.32	2.36a	1.61	0.8	1.17	0.81	0.522	1.183a	0.80
SEDtreat	0.401ns	0.262*	0.36ns	0.325ns	0.206ns	0.211ns	0.187ns	0.18*	0.49ns
SEDs	0.205*	0.205*	0.205*	0.153*	0.153*	0.153*	0.159ns	0.159ns	0.159ns
SEDtreat/s	0.355ns	0.355ns	0.355ns	0.266ns	0.266ns	0.266ns	0.276ns	0.276ns	0.276ns

Key: Treat = Treatments, s = season, treat/s = interaction treatment/season, IC = Intercropping, SED = standard error of differences to the mean, *, **, ***, and ns = significant at P = 0.01, 0.05, < 0.001, and not significant at P = 0.05, respectively, coloured cell = void cells.

Across all the short rain seasons, maize yields were not significantly (*P* = 0.19 in 2009, 0.219 in 2010 and 0.16 in 2011) affected by the associated common bean. However, yields from intercrops were lower by 81 and 44% in 2009, 89 and 78% in 2010, and 74 and 53.7% in 2011 short rains, respectively in 2:2 and 2:1 intercropping compared to maize mono crops. Maize yields were always better in 2:2 than in 2:1 intercrops. Yields of maize were improved by 47 and 32% in 2009 (*P* = 0.335), 67 and 136% in 2010 (*P* = 0.032), and 33 and 61% in 2011 short rains (not significantly at *P* = 0.528), respectively in 2:2 and 2:1 intercrops. Seasonal variations were significant (*P* = 0.002) (Table 4.1).

Common bean like maize was also not significantly (*P* = 0.131 in 2009, 0.375 in 2010 and 0.066 in 2011) affected by maize in intercrops (Table 4.1). However, irrespective of seasons (*P* = 0.3), yields of common bean were lower in intercrops than in mono crops. In 2:2 intercrops, yields were reduced by 54% in 2009 short rains, 76% in 2010 short rains, and 35% in 2011 short rains. In 2:1 intercrops, common bean yields were reduced by 53% in 2009 short rains, 78% in 2010 short rains, and 54% in 2011 short rains, but differences were not significant (*P* = 0.3). The yield tended to be better in 2:1 than in 2:2 but differences were slight. In the land occupancy, common bean yields were improved in 2:2 by 21% and reduced to 80% in 2009 short rain. In 2010 short rains both 2:2 and 2:1 intercrops improved common bean yields by 71 and 17% respectively (*P* = 0.219). Common bean was negatively affected by maize both in 2:2 and 2:1 in 2011 short rains and yields were reduced by 21% and 19% respectively (*P* = 0.16) (Table 4.1).

On LER (Table 4.1), 2:2 intercrop improved the land productivity by 35, 69.2, and 9.7%, respectively in 2009, 2010, and 2011 short rains though the improvement was not significant (P = 0.3). In 2:1 intercrops, the land productivity dropped by 3% in 2009. In 2010 and 2011 short rains, the land productivity increased by 57 and 7.7%, respectively, in 2:1 intercrops but was not significant (P = 0.3). Table 4.2 presents yields from maize–bean intercrops during long rain seasons between 2009 and 2011 in the Eastern province of Rwanda.

Table 4.2: Yields of common bean and maize in intercrops during long rains

Treatments	**Maize**			**Bean**		
	2009 LR	**2010 LR**	**2011 LR**	**2009 LR**	**2010 LR**	**2011 LR**
Grain yield (kg ha^{-1})						
Mono crop	3459	2397	3289a			
2:2 IC	3360	2372	3455a	1411	516	1036b
2:1 IC	3446	2025	1730b	1153	834	1707a
SEDtreat	531.5ns	641.7ns	448.2*	741.2ns	118.3ns	189.8*
SEDs	692.1ns	692.1ns	692.1ns			
Land equivalent ratio LER (Maize, bean, and Maize + bean)						
Mono crop	1.00	1.00	1.00a			
2:2 IC	1.12	0.93	1.05a			
2:1 IC	0.83	0.87	0.50b			
SEDtreat	0.292ns	0.267ns	0.124**			
SEDs	0.117ns	0.117ns	0.117ns			
Aggressiveness (Maize, bean, and Maize/bean)						
Mono crop	1.00	1.00	1.00b			
2:2 IC	2.50	2.10	2.38a			
2:1 IC	2.52	2.57	1.55b			
SEDtreat	0.703ns	0.554ns	0.302*			
SEDs	0.272ns	0.272ns	0.272ns			

Key: IC = intercropping, SED = standard error of differences to the mean, treat = treatment, s = season, **, * = significant at P = 0.01 and P = 0.05, ns = not significant at P = 0.05, coloured cells = absence of partial LER and aggressiveness of common bean.

During 2009 long rains, intercropped common bean did not significantly (P = 0.98) affect the yield of maize. Yields were 97.1 and 99.6% in 2:2 and 2:1 intercrops, respectively of the maize yield in monoculture. Like in 2009 long rains, maize yields in intercrops were not significantly different from monocultures of maize (*P* = 0.819) in 2010 long rains. Yields were 98.9 and 84.5% respectively in the 2:2 and 2:1 intercrops compared to maize mono crops (in 2010 long rains). During 2011 long rains, yields obtained from 2:2 intercrops were statistically similar to those from mono crops and even increased by 5% compared to monocultures of maize. In 2:1 intercrops, maize yields were significantly (*P* = 0.016) affected by intercropped common bean and were reduced by 52.6% compared to mono crops. On the other hand, during the same season (2011 long rains), common bean yields from 2:1 intercrops were significantly higher than those from 2:2 intercrops by 64.7% (*P* = 0.039). In the previous season, though not significantly different (*P* = 0.227), common bean had also done better in 2:1 than in 2:2 with a yield increment of 61.6%, and had lowered the maize performance by 14.5% compared to 2:2. During the 2009 long rains, common bean yields were lower in 2:1 than in 2:2 by 18.3% (*P* = 0.786) while its maize yield was comparatively increased by 2.5%, though not significantly (*P* = 0.98) (Table 4.2).

During good rainfall seasons (Figure 4.1), common bean yields were higher in 2:1 than in 2:2 intercrops. This could have been due to the relatively lower shade effect of intercropped maize on the understory common bean in 2:1 than in 2:2 intercrops. In this case, maize yields were reduced in 2:1 than in 2:2 intercrops due to increased competition of the understory common bean over the intercropped maize. Therefore, when rainfall is favourable, 2:1 is likely to give higher yields of common bean and reduced maize yields, while 2:2 is likely to give lower common bean and higher maize yields. When dry spells occurred (Figure 4.1), the yield of common bean tended to increase in 2:2 intercrops than in 2:1. It could have been due to the greater shade effect in 2:2 intercrops brought about by the intercropped maize. In this treatment (2:2), the shade was thicker than in 2:1 treatment. The former had paired rows while the later had single rows of maize staggered by 1m. In this case, maize yields tended to decrease in 2:2. In 2:1 intercrops, common bean yield tended to decrease while maize yields increased. Simply put, the maximization of one of participating components might reduce the yield of its counterpart.

Considering the partial land equivalent ratio of maize in intercrops, 2:2 intercrop improved the land productivity of maize by 12% but not significantly (P = 0.613) in 2009 long rains compared to maize mono crop. The same intercropping treatment (2:2 intercrop) significantly increased the land productivity by 5% in 2011 long rains (P = 0.008) compared to maize mono crop. The land productivity of 2:2 intercrop was 93% of the one from maize mono crops during 2010 long rains (P = 0.886). In 2:1 intercrops, the land productivity in terms of maize yields was 83% compared to the maize mono crop in 2009 long rains and was not significantly different (P = 0.613). In 2010 long rains, the land productivity of 2:1 intercrop was 87% compared to maize mono crop and was not significantly different from mono crops (P = 0.886). In 2011 long rains, the land productivity of maize in 2:1 intercrop was significantly lower by 50% compared to maize mono crops (P = 0.008). The aggressiveness measure of maize during long rain seasons was greater than 1.0 both in 2:2 and 2:1 intercrops (Table 4.2) but was not significant in 2009 (P = 0.12) and 2010 long rains (P = 0.104), and significant in 2011 long rains (P = 0.011). Therefore, common bean did not affect negatively the associated maize. Partial LER and aggressiveness of common bean could not be calculated during long rain seasons (Table 4.2) due to rotational issues which eliminated common bean mono crops from the study during long rain seasons.

According to Zang and Li (2003) maize is able to improve the iron nutrition of associated legumes which can be beneficial in terms of hormones and N fixation. Additional benefits are weed control in intercropping than in mono cropping, enhanced N and P uptake (Charineh and Moosavi, 2010), and shading of the bean from direct sunlight (Jansa *et al.*, 2011). However, results obtained from intercropping systems revealed lower common bean yields than in mono cropping, and the partial LER of common bean lowered with increase in maize population density. Similar results were reported by Tsubo *et al.* (2003) and Morgado and Willey (2008). Also, Cardoso *et al.* (2007) reported only 49% of the yield of common bean in mono crops when it was intercropped with maize at 50% of its population in mono crops. The effect of maize shade could also have played a role in lowering yields of common bean in intercropping treatments when rainfall was not limiting. In fact, when intercropped with maize, common bean dry matter and grain yields can reduce up to 90% (Tsubo and Walker, 2004) while maize yield is not affected at all.

This phenomenon of maize negatively affecting the grain yield and dry matter accumulation by the associated common bean has widely been reported by several studies on intercropping technologies. For example, the study by Woomer *et al.* (2004) compared two different intercropping systems and observed that benefits were higher (LER, investment returns, common bean yields) when common bean was given more space, which increased its intercepted photo synthetically active radiation (PAR) and reduced the underground competition by associated maize. In the context of this study, the competition in terms of PAR and nutrient uptake would have been alleviated in 2:1 than in 2:2 due to the relatively reduced thickness of maize rows. Tsubo and Walker (2004) found an inverse relationship between common bean yields and population density of associated maize. The lesser the maize plant population, the higher the yield of associated common bean.

The yield and partial LER of common bean were higher in 2:1 than in 2:2. In 2:1 intercropping treatment, the population of common bean was higher compared to the population of common bean in 2:2 intercrops. The maize population in this treatment (2:1) was lower than in 2:2. Additionally, maize was planted in single rows staggered by 1m allowing more light penetration which could have increased the photosynthetic activity of common bean in 2:1 than in 2:2 intercrops. If this was the case, then the dry matter accumulation in common bean grains would be expected to be greater in 2:1 than in 2:2 intercrops. In the below ground part, the root density of maize would have been less in 2:1 intercrops than in 2:2. This would have reduced the competition exerted by the associated maize in 2:1 than in 2:2. Findings of this study on the aggressiveness measure together with partial LER (Table 4.1 and 4.2) revealed that common bean was negatively affected by associated maize. The aggressiveness of maize was greater in 2:1 intercrop than in 2:2 which reduced common been yields at lower records than expected. The reduction of common bean yields in intercropping technologies could have been due to the inter-specific competition and depletive effect of maize, a C_4 plant, on common bean, a C_3 crop, C_4

plants being always dominant when in association with C_3 crops (Furbank and Taylor, 1995; Muoneke *et al.,* 2004).

Maize yields in intercropping were improved rather than affected by intercropping. Results of this study are consistent with findings reported by Tsubo and Walker (2004), Woomer *et al.* (2004), Morgado and Willey (2008), and Mucheru-Muna *et al.* (2010). Mucheru-Muna *et al.* (2010) observed slight increases of maize yields in intercropping than in sole cropping especially in areas where drought spells are frequent while Tsubo and Walker (2004) reported higher water use and radiation use efficiency in intercropping than in mono cropping systems. Morgado and Willey (2008) observed maize yield increase with common bean population in intercropping. Therefore, the improvement of maize yields in intercropping systems in this study would be attributed to better utilization of soil moisture and radiation, and the beneficial effect of the associated bean which may be in terms of soil moisture conservation, decay of shaded leaves, and BNF activity of the common bean (Martin *et al.,* 1991). Common bean matures within 90 days (Giller 2001). It reaches its maximal growth at the pod filling stage after which the senescence starts. The common bean shades its leaves and nodules and microbial bodies decompose releasing extra nutrients to the intercropped maize (Giller, 2001). The period of common bean senescence corresponds with the grain forming and grain filling stage of maize which extends from 60 to 104 days after planting (Sugihara *et al.*, 2010). Therefore, nutrients supplied by the understory common bean would have been synchronized to the period of peak nutrient uptake by maize. It is also said that common bean is able to transfer its N to the intercropped maize though the transferred quantities are less than 5% of the total N in common bean (Giller, 2001).

4.4 Biological nitrogen fixation, N balance, N and P uptake, and changes in soil chemical properties

This section presents and discusses results on BNF and N balances of common bean and soybean (first subsection), N and P uptake (second subsection), and lastly, changes in soil chemical properties due to ISFM treatments in the Eastern province of Rwanda.

4.4.1 Biological Nitrogen fixation (BNF) and N balance

The BNF and N balance of common bean and soybean under different input treatments were analysed using the analysis of variance and results are presented in Table 4.3.

Table 4.3: Amount of N fixed and N balance in pure stands

Treatments	Common bean			Soybean		
	N fixed (kg ha^{-1})	N grain (kg ha^{-1})	N balance (kg ha^{-1})	N fixed (kg ha^{-1})	N grain (kg ha^{-1})	N balance (kg ha^{-1})
	2009 short rains					
Control	25.4	17.4b	8.0	10.0	16.9	-6.9
FYM	11.8	24.52ab	-12.8	11.8	20.7	-8.9
DAP	21.4	30.18a	-8.8	6.7	25.6	-18.9
½ DAP + ½ FYM	18.2	27.65a	-9.4	5.4	19.5	-14.1
SEDi	7.61ns	2.36**	8.8ns	4.05ns	2.96ns	5.6ns
SEDc	3.04**	2.09ns	4.29ns	3.04**	2.09ns	4.29ns
SEDi/c	6.09ns	4.19ns	8.59ns	6.09ns	4.19ns	8.59ns
	2010 short rains					
Control	52.0	13.02	39.0	30.5	29.7	0.7
FYM	29.2	13.00	16.2	44.5	28.3	16.2
DAP	46.2	19.27	26.9	34.4	25.9	8.5
½ DAP + ½ FYM	53.9	15.57	38.3	41.4	25.4	16.0
SEDi	15.52ns	2.8ns	16.7ns	10.5ns	3.15ns	13.21ns
SEDc	6.76ns	2.48***	8.0*	6.76ns	2.48***	8.0*
SEDi/c	13.52ns	4.96ns	16.0ns	13.52ns	4.96ns	16.0ns
	2011 short rains					
Control	15.6b	26.7	-11.1	6.8	40.7	-34.0
FYM	9.8b	21.6	-11.8	8.2	52.2	-44.0
DAP	17.6ab	35.0	-17.4	9.5	63.5	-53.9
½ DAP + ½ FYM	32.9a	42.1	-9.2	14.6	67.2	-52.6
SEDi	6.38*	7.5ns	12.71ns	7.83ns	10.27ns	8.38ns
SEDc	3.68*	5.01***	6.53***	3.68*	5.01***	6.53***
SEDi/c	7.36ns	10.01ns	13.06ns	7.36ns	10.01ns	13.06ns
SEDs	8.22*	4.16**	11.0***	8.14**	3.34***	7.93***

Key: SED = standard error of differences to the mean, i, c, i/c, s = inputs, crop, interaction input/crop, and season. *, **, ***, ns = significant at *P* = 0.05, 0.01, < 0.001, and not significant at *P* = 0.05. Means with different letters are significantly different at *P* = 0.05.

During 2009 short rains, fertilizer application did not affect significantly the amount of N fixed neither for common bean (*P* = 0.38) nor for soybean (*P* = 0.418). In common bean treatments, the higher amount of N fixed was in the control while the lower amount was from FYM treatment (Table 4.3). In soybean treatments, higher amounts of N fixed were from FYM treatments while the lowest was from ½ DAP + ½ FYM. The amount of N fixed by common bean was 46, 84, and 72% of the amount fixed in the control, respectively in FYM, DAP, and ½ DAP + ½ FYM treatments (*P* = 0.38). The amount of N fixed by soybean increased by 18% in the FYM treatment, and decreased to 67 and 54%, respectively in DAP, and ½ DAP + ½ FYM treatments (*P* = 0.418). These increases were however not significantly different. The amount fixed by common bean was significantly (*P* = 0.002) higher than the amount fixed by soybean across all fertilizer treatments except in FYM treatments where N fixed was similar for both crops. N fixed by common bean was higher by 154, 219, and 237% than by soybean, respectively in the control, DAP and ½ DAP + ½ FYM treatments (Table 4.3).

During the 2010 short rains, fertilizer treatments did not affect the amount of N fixed in both common bean (*P* = 0.417) and soybean treatments (*P* = 0.554) (Table 4.3). In common bean treatments, the amount of N fixed in FYM and DAP treatments was lower than the amount fixed in the control. It was 56% in the FYM treatment and 89% in the DAP treatment compared to the amount fixed in the control. In ½ DAP + ½ FYM treatment, common bean fixed N amount higher by 4% compared to the control. In soybean treatments, the amount of N fixed in FYM, DAP, and ½ DAP + ½ FYM was higher by 46, 13, and 36%, respectively compared to the control (*P* = 0.554). The amount of N fixed per common bean was greater than the one fixed by soybean (P = 0.272) across all fertilizer treatments except in FYM treatments. The amount fixed by common bean was 170, 66, 134, and 130% of the amount fixed by soybean, respectively in the control, FYM, DAP, and ½ DAP + ½ FYM treatments (Table 4.3).

During 2011 short rains, ½ DAP + ½ FYM treatment significantly (P = 0.05) improved the amount of N fixed by the common bean by 111% (Table 4.3). The amount of N fixed in FYM treatment was 63% compared to the amount fixed in the control (in common bean treatment). In DAP treatment of common bean, the amount of N fixed was higher by 13% compared to the control. Though not significant (P = 0.769), the application of FYM, DAP and ½ DAP + ½ FYM in soybean treatments increased the amount of N fixed by 21, 40, and 115%, respectively. The amount of N fixed by common bean in control, DAP, and ½ DAP + ½ FYM treatments was significantly (P = 0.026) different from the one fixed by soybean by 129, 85, and 125%, respectively. The amount fixed in FYM treatments by common bean was higher by 20% compared to the amount fixed by soybean in the same treatment. Seasonal variations were significant (P < 0.001) especially between 2009 and 2010 short rains where the amount of N fixed doubled and quadrupled, respectively in common bean and soybean treatments. The amount of N fixed in 2009 was quite similar to the amount fixed in 2011 short rains both in common bean and soybean treatments (Table 4.3).

The amount of N removed through common bean grains during 2009 short rains was significantly (P = 0.002) higher in FYM, DAP, and ½ DAP + ½ FYM treatments than in control (Table 4.3). The increment was 41, 73, and 59%, respectively. N removal by soybean grains in 2009 short rains were not significantly (*P* = 0.087) affected by fertilizer treatments, but was higher by 22, 51, and 15% for FYM, DAP and ½ DAP + ½ FYM, respectively (Table 4.3). N removal was higher in common bean than in soybean but not significantly (*P* = 0.056). The increment was 3, 18, 18, and 42%, respectively in control, FYM, DAP, and ½ DAP + ½ FYM treatments. In 2010 short rains, N removal was 86% in FYM compared to the control. DAP and ½ DAP + ½ FYM treatments recorded higher N removal by 32 and 11%, respectively, but were not significantly different compared to the (*P* = 0.166). The N removal from soybean was 95, 87 and 86% in FYM, DAP, and ½ DAP + ½ FYM treatments, respectively (*P* = 0.513) compared to the control. By then, N removal through grains was significantly (*P* < 0.001) lower in common bean than in soybean and was decreased to 53, 48, 81, and 69%, respectively in control, FYM, DAP, and ½ DAP + ½ FYM treatments (Table 4.3).

During 2011 short rains, N removal from common bean grains was not affected by the application of fertilizer treatments (*P* = 0.124). In FYM treatments, the N removal was 81% of N removed in the control. The N removed from DAP and ½ DAP + ½ FYM treatments was higher by 31 and 58%, respectively compared to the control (Table 4.3) (in common bean treatments). Like common bean, soybean grain N removal was not affected by fertilizer treatments (*P* = 0.138) though an increase of 28, 56, and 65% was observed in FYM, DAP, and ½ DAP + ½ FYM treatments. Grain N removal was significantly higher in soybean treatments than in common bean treatments (*P* < 0.001). The N removal through common bean grains was 66, 41, 55, and 63% of soybean grain N removal from the control, FYM, DAP, and ½ DAP + ½ FYM treatments, respectively (Table 4.3).

During 2009 short rains, fertilizer treatments did not affect N balances neither for common bean (*P* = 0.152) nor for soybean (*P* = 0.209). Common bean N balances were highly negative from FYM treatments by 60%, and slightly negative by 10 and 18%, respectively in DAP and ½ DAP + ½ FYM treatments (Table 4.3). The N balance was positive in control treatments of common bean. N balances were more negative when soybean was treated with FYM, DAP, and ½ DAP + ½ FYM by 29, 174, and 104%, respectively. N balances were more negative in soybean than in common bean treatments (*P* = 0.146).

During the 2010 short rain season, N balances were positive both for common bean and soybean but significantly higher in common bean than in soybean treatments (*P* = 0.047). The N balance from the control, FYM, DAP and ½ DAP + ½ FYM treated common bean were higher by 65 times, 19, 278, and 213%, respectively compared to N balances from soybean treatments (Table 4.3). The effect of fertilizer treatments on N balances was not significant for both common bean (*P* = 0.45) and soybean (*P* = 0.619). In common bean treatments, FYM and DAP N balances were reduced to 42 and 71%, respectively. ½ DAP + ½ FYM increased the N balance by 10%. In soybean treatments, FYM, DAP, and ½ DAP + ½ FYM increased the N balance by 23, 12, and 23 folds, respectively compared to the control (Table 4.3).

In 2011 short rains, common bean N balances were negative across all fertilization treatments and ranged between -9 and -17.5 kg ha^{-1} (*P* = 0.923). On the other hand, soybean N balances were highly negative compared to common bean (*P* < 0.001) and ranged between -34 and -54 kg ha^{-1} (*P* = 0.164). Similar to common bean treatments, fertilizer treatments did not affect N balances of the soybean (*P* = 0.164). Differences due to seasons were significant ($P < 0.001$) with better N balances from 2010 (positive N balance), followed by 2009 (negative N balance) and lastly by 2011 (negative N balance) short rain seasons (Table 4.3).

The amount of N fixed and N balance of common bean intercropped with maize was analysed and presented in Table 4.4.

Table 4.4: Amount of N fixed and N balance in intercrops

Treatment	N fixed (kg ha^{-1})	N bean grain (kg ha^{-1})	N balance for legumes (kg ha^{-1})	N maize grain (kg ha^{-1})	N maize stover (kg ha^{-1})	N balance for the system (kg ha^{-1})
				2009 short rains		
Monoculture	17.5	32.8	-15.3	0	0	-15.3
2:2 intercrop	8.4	11.8	-3.3	32.7	14.3	-36.0
2:1 intercrop	17.1	16.0	1.1	26.2	15.7	-25.1
SED	4.06ns	8.45ns	8.75ns	9.31ns	8.43ns	15.96ns
				2010 short rains		
Monoculture	70	17.6	52.4	0	0	52.0
2:2 intercrop	33.3	14.1	19.2	35.7	29.8	-42.0
2:1 intercrop	50.6	14.5	36.1	31.5	26.4	-22.0
SED	14.33ns	3.06ns	15.65ns	1.159ns	2.52ns	34.8ns
				2011 short rains		
Monoculture	32	42.0	-9.0	0	0	-9.0a
2:2 intercrop	19.3	13.6	5.7	58.5	62.2	-78.5b
2:1 intercrop	24.5	21.5	2.9	41.9	56.9	-21.3b
SED	7.32ns	9.48ns	15.75ns	13.42ns	11.47ns	19.2*
SEDs	9.25*	3.93ns	10.38**	9.75*	7.34***	14.92**
SEDs/treat	16.02ns	6.8ns	17.99ns	13.78ns	10.39ns	25.84ns

Key: Monoculture = common bean monoculture, IC = Intercropping, SED = standard errors of differences to the mean, s = season, s/treat = interaction season/treatment, * = significant at *P* = 0.05, ** = significant at *P* = 0.01, *** = significant at *P* < 0.001, ns = not significant at *P* = 0.05, means with different values are significantly different at *P* = 0.05.

During 2009 short rains, the amount of N fixed was not significantly different between monocultures and intercrops (P = 0.114), but higher records were from monocultures (Table 4.4). The N fixed was 48 and 98%, respectively in 2:2 and 2:1 intercrops compared to common bean grown alone. N removal was higher in intercrops than in mono crops due to the additional removal of N in maize grains and stover (Table 4.4). Henceforth, N removal was higher by 79 and 77%, respectively in 2:2 and 2:1 intercrops compared to common bean mono crops. N balances were negative both in mono crops and intercrops but were highly negative in intercrops than in mono crops though the differences were not significant (P = 0.475). Net N balances were 135 and 64% lower in 2:2 and 2:1 intercrops, respectively.

During 2010 short rains, intercrops did not significantly affect the amount of N fixed (P = 0.144). However, N fixation in 2:2 and 2:1 intercrops was respectively 48 and 72% of N fixed in mono crops (Table 4.4). The N removal was higher in intercrops by 352 and 311% respectively in 2:2 and 2:1 intercrops. N balance was not significantly different from cropping systems (P = 0.14) but was negative by 81 and 42% respectively in 2:2 and 2:1 intercrops. The balance was positive in mono crops (Table 4.4).

During 2011 short rains, the N fixed was not affected significantly by cropping treatments (P = 0.284) but the amount fixed in 2:2 and 2:1 intercrops was 60 and 77% of the amount fixed in mono crops, respectively. N removal was higher, 220 and 186%, respectively in 2:2 and 2:1 making N balances higher in intercrops than in mono crops by 9 and 2.5 times, respectively in 2:2 and 2:1 intercrops (P = 0.045).

Seasonal variations on N fixation and N balances were significant (P = 0.015 and 0.008, respectively).

Results from this study are similar to findings of other researchers; for instance, Araujo *et al.* (2012) worked on different cultivars of common bean and reported a mean of 39.7 kg N fixed ha^{-1}. Fixed amounts of N ranged from 34.3 to 48.7 kg N fixed ha^{-1}. Yadegari *et al.* (2010) found that some varieties of common beans were able to fix N amounts as low as 24 kg ha^{-1} though they were inoculated and received fertilizers. Jemo *et al.* (2010) worked on different soybean genotypes under different P fertilization and found that their BNF values varied between – 8.2 and 16.1 kg ha^{-1}.

According to Giller (2001), Abendroth *et al.* (2006), Unkovich *et al.* (2008) and Jansa *et al.* (2011), the activity of nitrogen fixation by symbiotic bacteria under the support of host plants is dependant on several factors which include soil pH, the optimum being 6 to 7; root temperature, the soil water holding capacity, and soil texture with low fixation in sand prone soils. The soil pH of the study area ranges between 5.14 and 6.23. The imbalanced nutrition could have impaired the process of BNF in these soils low in native P (Table 3.1) and with high content in exchangeable Al^{3+} (Rutunga and Neel, 2006).

In acidic soils, high H^+ concentrations depresses the attachment of rhizobia to the root surface and the ability of the root exudates to induce the expression of nodulation genes (Giller, 2001). Additionally, high concentration of Al^{3+} inhibits root infection with rhizobium and nodule initiation even in the presence of sufficient number of rhizobia (Bationo *et al.,* 2011). These acid cations (H^+ and Al^{3+}) also binds to the bacterial DNA and inhibits its DNA replication, hence reducing the population or survival of BNF bacteria in acidic soil (Giller, 2001). These conditions could also be the cause of the absence of BNF response of common bean and soybean to applied fertilizer treatments. Findings by László (2009) on calcareous soils with neutral conditions (pH = 7) would bring about the insight on results of this study about BNF and fertilizer application. László (2009) reported a positive and linear relationship between N fixation of soybean and the amount of N fertilizer and inoculants used. Therefore, the lack of BNF response to fertilizer application could be attributed to unfavourable conditions of BNF including acidic soils (high H^+ and Al^{3+}), low P availability; water stress due to frequent drought spells, and coarse soil texture.

The other possible reason behind the low BNF and lack of response to fertilizer application could be either the absence of high potential specific common bean-rhizobia and soybean-rhizobia strain in soils of the eastern province of Rwanda, or the competition between multiple strains in the soil to infect common bean and soybean roots to form nodules, which can bring about nodule multiple occupancy and thus affecting the efficiency of otherwise high potential strains (Zdor and Pueppke, 1988; Nguyen *et al.,* 2010). Comparing findings of this study and findings by László (2009) may suggest that it would be imperative to reverse the existing conditions which are the soil acidity and the possible low microbial colonization of the soil through liming and inoculation in order to get the response of BNF to the applied N and/or P fertilizer. Soybean BNF was lower than that of common bean. This was mainly driven by the low biomass production of soybean compared to common bean (Peoples and Griffiths, 2009) observed across all seasons. This additionally explains why N fixed was higher in common bean monocultures than in intercrops, and higher in 2:1 than in 2:2 intercrops.

Larger negative N balances observed in intercropping treatments than in mono crops were reported elsewhere by Mucheru-Muna *et al.* (2010). When N removed through maize grain and maize stover is added to N removed through common bean grain yields, the N balance is more negative. Moreover, the intercropping technology associated with high maize yields (grain and stover) has a greater negative N balance than otherwise expected. Findings of this study corroborated findings of Mucheru-Muna *et al.* (2010) in a way that N balances were found to be slightly negative in common bean mono crops (higher N removal than N fixed) and highly negative in intercrops with balances more negative when maize yields (grain and stover) increased. In fact, high negative N balances were observed from MBILI system both from Mucheru-Muna *et al.* (2010) and from this study due to higher maize grain and stover yield from this system compared to conventional intercropping in Kenya (1:1 intercrop) (Mucheru-Muna *et al.*, 2010) and 2:1 intercrop in Rwanda (this study).

Negative N balance from soybean experiments has been reported by other researchers (Alves *et al.*, 2003, Ogoke *et al.*, 2003; Osunde *et al.*, 2003; Singh *et al.*, 2003; and Amy *et al.*, 2006), and were reported to be more negative when N fertilizer was applied or when an early maturing variety was grown. Reported N balances ranged between -126 and -42 kg in Argentina (Amy *et al.*, 2006), -132 and 104 kg in Brazil (Alves *et al.*, 2003), and -12.2 kg ha^{-1} in early maturing soybean varieties in the Guinea savannah of Nigeria (Ogoke *et al.,* 2003). The work by Osunde *et al.* (2003) on N fertilized soybean reported a negative relationship between the %Ndfa and N applied. According to Singh *et al.* (2003), early maturing varieties of soybean have a high nitrogen harvest index than medium and late maturing varieties. Therefore, the low N fixation and negative N balance observed in this study could have been due to the low %Ndfa, low biomass yields, and high N content in the soybean grain (Nyabyenda, 1992). Results of this study are not consistent with Ogoke *et al.* (2003) when it comes to P effect on N balances. Ogoke *et al.* (2003) found positive and high N balances when P fertilizer was applied to soybean. On the contrary, P fertilized soybean resulted in higher N losses in this study (larger negative N balances). This could have resulted from inactivity of applied P when soils have a high P sorption capacity (or high P immobilization) especially in acidic conditions (Table 3.1). According to Reddy *et al.* (1991), in soils with the pH ≤ 5.5, the mobility of manganese may increase and reach the level of toxicity to the soybean plant, affecting its N fixation activity.

Negative balances imply reductions of N in soil organic matter and net loss of nitrogen from agro ecosystems (Amy *et al.,* 2006). However, legumes still have the ability to partially meet their N needs through BNF (Giller, 2001) hence sparing soil N which would otherwise have been taken up, and save it for the subsequent crop in rotation, or do not compete or slightly compete with the associated cereal for soil N (Giller, 2001; Jensen and Hauggaard-Nielsen, 2003). Observations from this study corroborated Giller (2001) and Jensen and Hauggaard-Nielsen (2003) work because, though BNF was not as high as expected, common bean met 3.2% - 57.3% of its N demand sparing 0.3 to 67.4 kg of N ha^{-1}, while soybean was able to spare between –

4.5 and 71.6 kg of N ha^{-1} depending on seasonal variations. The N spared by common bean in intercrops was 8.4 – 33.3 kg of N ha^{-1} in 2:2 and 17.1 – 50.6 kg of N ha^{-1} in 2:1 intercrops. Results also revealed that some N fertilizer application to the subsequent crop would be necessary to replenish N losses due to removal of grain yields and stover for sustainable or resilient agro ecosystems. Intercropping systems are more depletive than legume mono crops and needed relatively higher external N addition.

4.4.2 N and P uptake

This subsection presents and discusses results of N and P uptake during short and long rain seasons. Results of N and P uptake during short and long rain seasons are presented in Table 4.5 and 4.6, respectively.

During 2009 short rains, DAP and ½ DAP + ½ FYM significantly increased N uptake in maize treatments by 34 and 19%, respectively (P = 0.022). FYM increased the N uptake of maize by 11% but not significantly (Table 4.5). The P uptake of maize during 2009 short rains was not affected by inputs (P = 0.745) and varied between 4 and 5.11 kg ha^{-1} (Table 4.5). During 2010 short rains, inputs could not increase the N uptake significantly (P = 0.489) but increments of 8 and 21% were recorded in DAP and ½ DAP + ½ FYM, respectively. FYM and control had similar results. P uptake was not significantly affected (P = 0.287) but ½ DAP + ½ FYM recorded higher values (Table 4.5). During 2011 short rains, DAP and ½ DAP + ½ FYM significantly (P = 0.008) improved the N uptake of maize by 105 and 115%, respectively. FYM recorded an increase of 32% but was not significant (Table 4.5). Similarly, P uptake was significantly (P = 0.006) higher in DAP and ½ DAP + ½

FYM treatments by 64 and 85%, respectively. FYM increased P uptake by 10% but not significantly (Table 4.5).

Table 4.5: N and P uptake (kg ha^{-1}) in short rains (SR)

Treatments	2009 SR		2010 SR		2011 SR	
	N	P	N	P	N	P
Continuous maize						
Control	58.3c	5.11	52.8	5.32	80.2b	8.94b
FYM	64.5bc	4.02	50.3	3.19	105.8b	9.79b
DAP	78.3a	4.55	56.8	4.31	164.5a	14.68a
½ DAP + ½ FYM	69.1ab	4.98	63.7	5.99	172.5a	16.5a
SEDi	4.13*	1.04ns	8.65ns	1.37ns	19.64**	1.5**
SEDs	12.78***	1.4***	12.78***	1.4***	12.78***	1.4***
SEDi/s	25.57ns	2.8ns	25.57ns	2.8ns	25.57ns	2.8ns
Common bean – maize rotations						
Control	76.4	8.12b	154.5	15.5	109	9.7
FYM	78.3	9.54ab	134.7	15.5	183	20.4
DAP	94.5	11.04a	171.0	18.8	184	17.1
½ DAP + ½ FYM	80.3	9.05b	154.7	14.7	222	21.2
SEDi	6.26ns	0.75*	21.54ns	2.83ns	45.5ns	6.52ns
SEDs	21.62***	2.73**	21.62***	2.73**	21.62***	2.73**
SEDi/s	43.24ns	5.45ns	43.24ns	5.45ns	43.24ns	5.45ns
Soybean – maize rotations						
Control	55.1	3.58	140	9.7	105	7.89
FYM	62.9	5.44	158	12.7	113	8.63
DAP	58.2	5.11	130	13	183	15.29
½ DAP + ½ FYM	48.4	4.55	187	17.5	192	13.82
SEDi	6.38ns	0.67ns	34.4ns	3.92ns	28.3ns	2.5ns
SEDs	26.8***	2.5**	26.8***	2.5**	26.8***	2.5**
SEDi/s	53.5ns	4.99ns	53.5ns	4.99ns	53.5ns	4.99ns
Common bean + maize + ½ DAP + ½ FYM						
Monoculture	69.1	4.98	63.7b	5.99b	172.5	16.5
2:2 IC	73.7	11.7	115ab	10.9ab	186.0	16.8
2:1 IC	81.5	10.2	174a	21.0a	219.0	22.9
SED	17.58ns	3.15ns	31.6*	5.56*	48ns	6.28ns
SEDs	23.69***	3.29**	23.69***	3.29**	23.69***	3.29**
SEDi/s	41.04ns	5.69ns	41.04ns	5.69ns	41.04ns	5.69ns

Key: IC = intercrop, SEDi, SEDc, SEDi/c, SEDs = standard error of differences to the mean of inputs, crop, interaction input/crop, and seasons respectively, *** = significant at $P < 0.001$, ns = not significant at $P = 0.05$.

During 2009 short rains, DAP treatment recorded the highest N uptake by the common bean which was higher by 24%, but was not significantly different (P =

0.065). FYM and ½ DAP + ½ FYM increased N uptake respectively by 2 and 5% but not significantly (*P* = 0.065). The P uptake was significantly higher in DAP treatments by 36 (*P* = 0.023) and by 17 and 11% in FYM and ½ DAP + ½ FYM, respectively (Table 4.5). During 2010 short rains neither N (*P* = 0.457) nor P uptake (*P* = 0.506) was significantly affected by inputs. However, DAP treatment increased N and P uptake by 11 and 21%, respectively (Table 4.5). In 2011 short rains, all input treatments increased the N uptake by 68, 69 and 104%, respectively in FYM, DAP and ½ DAP + ½ FYM treatments, but not significantly (*P* = 0.195). FYM, DAP and ½ DAP + ½ FYM increased P uptake by 110, 76 and 119%, respectively, but not significantly (*P* = 0.354) (Table 4.5).

In soybean treatments, during 2009 short rains, fertilizer inputs did not affect the N uptake (*P* = 0.216) though FYM and DAP treatments recorded 14 and 6% increments respectively. The P uptake was higher by 52, 43 and 27%, respectively in FYM, DAP and ½ DAP + ½ FYM treatments (*P* = 0.208) (Table 4.5). During the 2010 short rains, inputs did not significantly affect N (*P* = 0.414) and P uptake (*P* = 0.532) though FYM and ½ DAP + ½ FYM recorded an increase of 13 and 34% in N uptake, respectively, while P uptake was increased by 31, 34 and 80%, respectively by FYM, DAP, and ½ DAP + ½ FYM (Table 4.5). During 2011 short rains, inputs did not affect the N and P uptake significantly (*P* = 0.281 for N uptake and *P* = 0.313 for P uptake). However, DAP increased N uptake by 74% and P uptake by 83%, while ½ DAP + ½ FYM increased the N uptake by 94% and P uptake by 75%. The increment due to FYM was 8 and 9%, respectively for N and P uptake (Table 4.5).

In 2009 short rains, intercrops did not affect N (P = 0.182) and P uptake (P = 0.198) significantly, but observations indicate that intercrops were higher by 7 and 18% for N and 135 and 105% for P respectively in 2:2 and 2:1 intercrops (Table 4.5). During 2010 short rains, 2:1 intercrops increased N uptake significantly (P = 0.014) by 173%. The 2:2 intercrop increment was 81% but not significant (Table 4.5). Likewise, 2:1 intercrop increased P uptake by 251% significantly (P = 0.044), while 2:2 increment was 82% but not significant (Table 4.5). In 2011 short rains, differences due to intercrops were not significant but intercrops had higher records by 8 and 27% and 2 and 39%, respectively in 2:2 and 2:1 for N (P = 0.638) and P uptake (P = 0.563). Seasonal variations were significant for both N (P < 0.001) and P uptake (P = 0.003) but its interaction with inputs was not significant (P = 0.611 for N and 0.541 for P) (Table 4.5).

During 2009 long rains (Table 4.6), FYM, DAP and ½ DAP + ½ FYM treatments did not affect significantly (P = 0.122) the N uptake by maize in maize–maize rotations. However, these treatments recorded N uptake higher by 30, 27, and 26%, respectively. In common bean–maize rotation, these treatments, respectively increased the N uptake by 38, 46, and 75% but not significantly (P = 0.315). Likewise, in soybean–maize rotations, these treatments (FYM, DAP and ½ DAP + ½ FYM) increased N uptake by 28, 21, and 49%, respectively, but not significantly (P = 0.239).

Table 4.6: N and P uptake (kg ha^{-1}) in long rains (LR)

Treatments	2009 LR		2010 LR		2011 LR	
	N	P	N	P	N	P
Continuous maize						
Control	65.1	9.95	87.1	5.83	41.2	7.85
FYM	84.5	12.43	113.5	6.1	64.2	11.12
DAP	82.8	11.73	118.7	6.67	69.7	13.12
½ DAP + ½ FYM	81.9	11.58	91.2	6.67	64.7	12.22
SED	8.04ns	0.766ns	22.7ns	0.601ns	11.45ns	1.996ns
SEDs	14.47ns	1.711ns	14.47ns	1.711ns	14.47ns	1.711ns
Common bean – maize rotations						
Control	66.0	9.7	80	6.47	55.2	10.98
FYM	91.3	12.7	63	4.6	61.9	12.6
DAP	96.6	15.1	86	4.9	74.7	13.63
½ DAP + ½ FYM	115.8	15.2	130	8.83	85.3	16.08
SED	24.87ns	3.36ns	32.5ns	2.188ns	10.77ns	1.651ns
SEDs	17.99ns	2.246**	17.99ns	2.246**	17.99ns	2.246**
Soybean – maize rotations						
Control	74.4	11.5	83.8	7.27	48.5b	8.75c
FYM	95.1	13.4	85.3	5.9	55.2b	10.5bc
DAP	90.2	12.2	92.9	7.63	64.6ab	13.03ab
½ DAP + ½ FYM	111.1	14.3	128.7	7.53	84.8a	13.9a
SED	16.47ns	3.3ns	26.88ns	1.755ns	10.2*	1.123**
SEDs	14.93ns	1.959**	14.93ns	1.959**	14.93ns	1.959**
SEDi/s	29.85ns	3.917ns	29.85ns	3.917ns	29.85ns	3.917ns
SEDpc	8.65ns	1.316ns	13.04ns	0.813ns	5.4ns	0.792*
SEDpc/i	17.3ns	2.633ns	26.07ns	1.626ns	10.8ns	1.585ns
Common bean + maize + ½ DAP + ½ FYM						
Monoculture	81.9	11.58	91.2	6.67	64.7c	12.22c
2:2 IC	126	16.6	211	18.2	235.7a	32.9a
2:1 IC	120	16.2	194	20.1	165.7b	22.9b
SED	26.8ns	2.68ns	58.1ns	5.61ns	20.27***	2.57***
SEDs	26.9ns	3.09*	26.9ns	3.09*	26.9ns	3.09*
SEDtr/s	46.6ns	5.56ns	46.6ns	5.56ns	46.6ns	5.56ns

Key: IC = intercrop, SEDi, SEDpc, SEDi/pc, SEDs = standard error of differences to the mean of inputs, previous crop, interaction input/previous crop, and seasons respectively, **** = significant at $P < 0.001$, ns = not significant at $P = 0.05$.

The effect of the previous crop and its interaction with fertilizer inputs ($P = 0.558$) was not significant ($P = 0.234$ for the previous crop and 0.558 for the interaction previous crop/fertilizer inputs), but common bean as a preceding crop recorded higher N uptake by 1, 8, 17, and 41%, and soybean by 14, 13, 9, and 36%, respectively in the control, FYM, DAP, and ½ DAP + ½ FYM treatments compared to maize as a previous crop. 2:2 and 2:1 intercrops also had higher N uptake by 54 and 47%, respectively but not significantly (*P* = 0.283) compared to maize mono crop.

During 2009 long rains (Table 4.6), FYM, DAP, and ½ DAP + ½ FYM did not increase significantly (*P* = 0.054) the P uptake in maize–maize rotations, but P uptake was higher by 25, 18, and 16% were recorded from these treatments, respectively. Though not significant, these treatments (FYM, DAP, and ½ DAP + ½ FYM) recorded higher P uptake by 31, 56, and 57% in common bean–maize rotations (*P* = 0.366), and 17, 6, and 24%, respectively in soybean–maize rotations (*P* = 0.831). P uptake was not significantly affected by the preceding crop (*P* = 0.382) or by its interaction with fertilizer inputs (*P* = 0.843). However, compared to maize–maize rotations, P uptake was increased by 2, 29, and 31%, respectively by FYM, DAP, and ½ DAP + ½ FYM in common bean–maize rotations, and by 16, 8, 4, and 23%, respectively in the control, FYM, DAP, and ½ DAP + ½ FYM in soybean–maize rotations (Table 4.6). The 2:2 and 2:1 intercrops increased P uptake by 43 and 40%, respectively compared to the mono crop, but not significantly (*P* = 0.194) (Table 4.6).

During 2010 long rains (Table 4.6), across all rotation systems, fertilizer inputs did not increase N uptake significantly (*P* = 0.467 in maize–maize, 0.296 in common bean–maize, and 0.379 in soybean–maize rotations). However, FYM, DAP, and ½ DAP + ½ FYM treatments increased N uptake by 30, 36, and 5%, respectively in maize–maize rotations, and 2, 11, and 54%, respectively in soybean–maize rotations.

In common bean–maize treatments, only DAP and ½ DAP + ½ FYM increased N uptake by 8 and 63%, respectively. The previous crop (*P* = 0.617) and its interaction with inputs (*P* = 0.322) were not significant, but records of N uptake from ½ DAP + ½ FYM in common bean–maize and soybean–maize rotations were higher by 43 and 41%, respectively compared to maize–maize rotations. N uptake records were higher by 131 and 113%, respectively in 2:2 and 2:1 intercrops but were not significantly higher (*P* = 0.199) than maize mono crops (Table 4.6).

Similar to N uptake during 2010 long rains, inputs (*P* = 0.466 in maize–maize, 0.292 in common bean–maize, and 0.746 in soybean–maize rotations), the previous crops (*P* = 0.509) and their interaction (*P* = 0.546) did not affect P uptake significantly. However, FYM, DAP, and ½ DAP + ½ FYM increased P uptake by 5, 14, and 14%, respectively in maize–maize, ½ DAP + ½ FYM increased P uptake by 36 and 4%, respectively in common bean–maize and soybean–maize rotations. Compared to maize–maize rotations, P uptake increased by 11 and 32% in the control and ½ DAP + ½ FYM in common bean–maize, and 25, 14, and 13% in the control, DAP and ½ DAP + ½ FYM treatments in soybean–maize rotations. Though not significantly (*P* = 0.138), 2:2 and 2:1 intercrops improved P uptake by 173 and 201%, respectively (Table 4.6).

During 2011 long rains (Table 4.6), FYM, DAP and ½ DAP + ½ FYM did not increase significantly (*P* = 0.122) the N uptake in maize–maize rotations, but N uptake increased by 56, 69, and 57%, respectively by the above said inputs. In common bean–maize rotations, FYM, DAP and ½ DAP + ½ FYM increased the N uptake by 12, 35 and 55%, respectively, but not significantly (*P* = 0.081). In soybean–maize rotations, FYM, DAP and ½ DAP + ½ FYM increased N uptake by 14, 33 and 75%, respectively (*P* = 0.029). Though the previous crop (*P* = 0.234) and its interaction with inputs (*P* = 0.558) were not significant, N uptake was higher by 34, 7, and 32% in the control, DAP, and ½ DAP + ½ FYM in common bean–maize, and 18 and 31% in the control and ½ DAP + ½ FYM treatments of soybean–maize rotations compared to maize–maize rotations. The 2:2 and 2:1 intercrops significantly (*P* < 0.001) increased the N uptake by 264 and 156%, respectively compared to maize mono crops (Table 4.6).

P uptake (Table 4.6) was higher by 42, 67, and 56%, respectively in FYM, DAP, and ½ DAP + ½ FYM treatments from maize–maize rotations (*P* = 0.111) in 2011 long rains. In common bean–maize rotations, the highest P uptake was recorded from the ½ DAP + ½ FYM treatment (higher by 46%) but was not significant compared to the control (*P* = 0.069). FYM and DAP recorded P uptake higher by 15 and 24% (*P* = 0.069) (Table 4.6). In soybean–maize rotations, FYM, DAP and ½ DAP + ½ FYM significantly (*P* = 0.005) increased P uptake by 20, 49, and 59%, respectively. The effect of the previous crop was significant (*P* = 0.02). The P uptake from the control and ½ DAP + ½ FYM in common bean–maize rotations was significantly higher by 40 and 32%, respectively. FYM and DAP increased P uptake by 13 and 4%, respectively but not significantly (Table 4.6) in the same rotation system (common bean–maize). Soybean–maize rotations treated with ½ DAP + ½ FYM significantly increased P uptake by 14%. The control (in soybean–maize) recorded 11% of increase in P uptake but not significantly. The interaction previous crop/input was not significant (*P* = 0.781). The 2:2 and 2:1 intercrops significantly (*P* < 0.001) increased the P uptake by 169 and 87%, respectively (Table 4.6).

The N uptake was increased by fertilizer treatments both in short and long rains. This implies that the application of FYM and DAP either separately or in combination improves the nutrient availability to plants. The amounts of N uptake reported from this study were in the range reported by Chikowo *et al.* (2010) whose treatments included manure, Sugihara *et al.* (2010), and Gong *et al.* (2011) whose research included manure, mineral N fertilizers and their combination. The combination of manure and mineral N fertilizers was reported to improve the total organic N, the microbial biomass N, the labile N, the inorganic N including ammonium (NH_4^+)–N and nitrate (NO_3-)–N contents, the net ammonification rate, the net nitrification rate, the net N mineralization rate, and the N management index (Gong *et al.,* 2011) through the comparatively prolonged N supply and uptake by plants (Sugihara *et al.*, 2010). This would explain why N uptake was increased by FYM, DAP and ½ DAP + ½ FYM, and why ½ DAP + ½ FYM had higher N uptake than DAP treatments.

N uptake was not affected by the previous crop but higher values were recorded from legume–maize treatments. These results are consistent with findings of Pal and Shehu (2001) and Yusuf *et al.* (2009b) where soybean was reported to improve the N uptake of the subsequent maize and to improve grain yields compared to continuous maize cropping. Additionally, its rotation with maize was reported to improve the microbial N and C compared to the continuous maize. This may result in the better microbial activity and release of N from soil pools (Gong *et al.,* 2011). Therefore, the improvement of N uptake observed in legume–maize treatments could be attributed to the accumulation of organic matter during the legume phase (fallen leaves and underground biomass) which underwent decomposition and release of additional N, with possibility to improve soil conditions for better maize growth than in continuous maize (Giller, 2001). The N sparing effect of common bean and soybean reported in the 4.3.1 subsection could also have brought about higher N supply from legume–maize rotations than from the continuous maize cropping coupled with a rational exploitation of soil layers under legume–maize rotation than continuous maize (Yadegari *et al.*, 2010). N uptake was improved by intercrops both in short and long rains across the experimental period implying that intercrops might be better in terms of nutrient recycling than mono crops. The amount taken up tended to improve when rains were better, similar to findings by Yusuf *et al.* (2009b) who reported differences in N recovery between seasons due to differences in rainfall patterns.

4.4.3 Changes in soil pH, N, P, and organic carbon

The effect of treatments on soil pH, N, P and organic carbon at the end of the fifth growing season was analysed using the analysis of variance and results are presented in Table 4.7.

The soil pH was not affected by fertilizer inputs (P = 0.972 in maize–maize, 0.922 in common bean–maize, and 0.222 in soybean–maize rotations), the previous crop (P = 0.827) or the interaction fertilizer/previous crop (P = 0.675) neither did the intercrops (P = 0.097). The pH increased by 0.24 – 0.86 units in the various treatments throughout the study period (Table 4.7).

Table 4.7: Changes in soil pH, N, organic C, and Olsen P (0 – 20 cm)

Treatments	pH H_2O	N in g kg^{-1}	Organic C in g kg^{-1}	Olsen P in mgP kg^{-1}
Continuous maize				
Control	0.54	0.153	0.15	2.62
FYM	0.58	0.16	0.8	3.13
DAP	0.63	0.203	0.69	7.52
½ DAP + ½ FYM	0.62	0.13	-0.18	4.7
SED	0.21ns	0.096ns	1.654ns	2.343ns
Common bean – maize rotation				
Control	0.50	0.12	-0.15	4.8
FYM	0.64	0.18	0.51	6.8
DAP	0.50	0.3	1.22	31.3
½ DAP + ½ FYM	0.44	0.157	0.55	5.0
SED	0.296ns	0.054ns	0.823ns	17.45ns
Soybean – maize rotation				
Control	0.403	0.137	0.14	2.2
FYM	0.713	0.173	0.62	3.2
DAP	0.86	0.213	0.61	11.2
½ DAP + ½ FYM	0.31	0.137	0.37	5.7
SED	0.261ns	0.0544ns	0.616ns	2.89ns
SEDpc	0.1237ns	0.0375ns	0.572ns	5.05ns
SEDi/pc	0.2473ns	0.0749ns	1.143ns	10.1ns
Common bean + maize intercrops + ½ DAP + ½ FYM				
Monoculture	0.62	0.13	-0.18	4.7
2:2 IC	0.243	0.117	-0.35	8.0
2:1 IC	0.51	0.123	-0.22	9.4
SED	0.1305ns	0.0504ns	0.526ns	10.15ns

Key 1: IC = Intercropping, i = inputs, pc = previous crop, SED = Standard error of deviation, i/pc = interaction inputs/previous crops. **Key 2:** Values are differences between measurements by the end of 2011 short rains and measurements by 2009 short rains.

The application of DAP improved the N concentration in the soil by 32.6% in maize–maize rotations (P = 0.89), 150% in common bean–maize rotations (P = 0.064), and 55.4% in soybean–maize rotations (P = 0.493). The previous crop (P = 0.729) and the interaction fertilizer/previous crop (P = 0.932) did not affect the N concentration in the soil. Intercropping common bean and maize in 2:2 and 2:1 did not affect the N concentration in the soil (P = 0.966) (Table 4.7).

The organic C was not affected by fertilizer inputs (*P* = 0.922 in maize–maize, 0.482 in common bean–maize, and 0.845 in soybean–maize rotations). The previous crop (*P* = 0.957) and the interaction fertilizer/previous crop (*P* = 0.989) did not affect the soil organic C significant. The Olsen P was not significantly affected by input treatments. However, highest values of Olsen P were recorded from DAP treatments across all rotation systems. In maize – maize, common bean – maize, and soybean – maize rotations, DAP increased the Olsen P by 2.8 folds, 6.5 folds, and 5 folds, respectively (*P* = 0.253 in maize – maize, 0.421 in common bean – maize, and 0.076 in soybean – maize rotation system). The previous crop (*P* = 0.292) and the interaction fertilizer/previous crop (*P* = 0.662) did not increase significantly the Olsen P. Intercrops did not affect the soil Olsen P (*P* = 0.895) (Table 4.7).

N and P concentration in the soil was comparatively higher in DAP treatment regardless of the preceding crop. Compared respectively to the control, FYM, and ½ DAP + ½ FYM, N was higher by 33, 27, and 56%, P was higher by 187, 140, and 60% in maize–maize cropping systems; N was higher by 150, 67, and 91%, and P was higher by 552, 360, and 526% in common bean–maize rotations, N was higher by 55, 23, and 55%, and P was higher by 409, 250, and 96% in soybean–maize rotations (Table 4.7).

The absence of significant soil pH changes due to cropping systems was recorded elsewhere by Triplett *et al.* (1993) in soybean–corn and corn–corn cropping systems after 22 years of experiments. The soil pH was neither affected by the application of input treatments but slight differences were observed (Table 4.7). According to McCauley *et al.* (2009), soil pH can be affected by fertilizer application. Mineral fertilizers may change long-term soil pH after years of application or have a more short-term and microsite effect (area directly surrounding the fertilizer material and extends approximately 1 inch (2.54 cm) from the site of placement). FYM also has been found to increase the soil pH by Opala (2011) and Opala *et al.* (2012). The increase in pH observed in FYM treatments could have been due the exchange of the proton (H^+) between the soil and organic anions found in the applied FYM such as phenolic and humic acids which consume the proton and increase the soil pH (Haynes and Mokolobate, 2001). The other possible mechanism through which FYM has increased the soil pH is the specific adsorption of organic acids from the FYM decaying process onto hydrous surfaces of Al and Fe oxides by ligand exchange with corresponding release of OH^- (Hue *et al.*, 1986). However, changes due to DAP, FYM or their combination was not significant because other factors such as the soil texture, pH, and the soil buffering capacity (McCauley *et al.*, 2009) may have played in enabling the study soil to resist to changes brought about by DAP and FYM applications.

N and P levels being higher in DAP treatments could be explained by the fact that these treatments received 36 kg of N and 40 kg of P ha^{-1} per season for five consecutive seasons. Mbah and Onweremadu (2009) reported significant increases in soil total N and available P from a degraded Ultisol in Nigeria when NPK mineral fertilizer was applied. Increases in N and P concentrations in the soil observed in this study (Table 4.7) could have been due to the accumulation of N and P season after season in the soil as DAP solubility in water is low (Mekong Delta Agricultural Extension Project, 2013). Poor rainfall and its bad distribution during some seasons could have left good amounts of insolubilized DAP in the soils. This could be linked to low fertilizer agronomic use efficiency of DAP observed in this study (section 4.3.1) when DAP was applied alone. Low fertilizer agronomic use efficiency would mean a failure of plants to uptake the applied fertilizer and turn it into yields. The other possible mechanism through which N and P were higher in DAP treated soils could be the steady supply of N and P to plants from the fertilizer. In these conditions, plants did not depend much on soil N and P while soil N and P from other treatments were being depleted by growing plants.

The absence of high N and P concentrations in ½ DAP + ½ FYM could be linked to the improvement in N and P uptake together with the improved fertilizer use efficiency observed throughout the experimental period. The lack of differences in N and P concentrations from FYM treatments could be explained by the feature of FYM to release nutrients slowly in the soil, and is supported by findings of Nyamangara and Bergström (2004). This is consistent with the discussion on the response of crops to FYM and DAP (section 4.2.1) and could be supported by Vanlauwe *et al.* (2002); Chirwam *et al.* (2004); Nhamo *et al.* (2004); Ayuke *et al.* (2004); and Mori and Hojito (2011). Differences in N concentrations tended to be lower in intercropping treatments than in mono cropping ones. The reason could be the ability of these systems to access to additional N from soil pools than maize mono crops.

P concentrations tended to be higher in intercropping treatments than in mono crops. Under such systems, it is believed that a tri-association (symbiotic association) is established between legume roots, rhizobia bacteria, and arbuscular fungal mycorrhiza underground (Jansa *et al.,* 2011). This association improves the availability of P in the soil solution through releasing exudates to solubilise P otherwise not available (Sanginga and Woomer, 2009; Jansa *et al.*, 2011). According to Jansa *et al.* (2011) P availed as such may be greater by a factor of 2 or even more the acquisition of the same element by non mycorrhizal plants. Though this P might be shared through direct transfer between networking plant roots under the architecture of arbuscular mycorrhiza, it would be imaginable that some P may be found in soil solution.

4.5 Economic analysis

This section presents and discusses results on the BCR and MRR analysis of treatments per season and per cycle (two consecutive seasons, the first being a legume phase and the second, the maize planted in rotation). It gives an overview on the crop production cost components and their estimated proportions on their total.

Table 4.8 presents costs components and their relative proportion in the total. Main costs are encountered in harvesting maize (28%), buying mineral fertilizers (DAP) (17%), weeding (13%), buying FYM (10%), and buying seeds (10%). If all costs related to fertilizer application are taken into account, fertilization covered about 30% of all costs (Table 4.8).

Table 4.8: Costs involved in crop production and their relative proportion

Item/Activity	Portion (%)
Buying seeds	10
Buying DAP fertilizer	17
Buying FYM	10
Row making	3
DAP application	1
FYM application	1
Input covering	1
Planting	3
Covering seeds	1
Thinning	2
First weeding	13
Harvesting legumes	4
Harvesting maize	28
Threshing maize	6
Total	**100**

The benefit to cost ratio analysis BCR and the marginal rate of returns analysis from short rain seasons are presented in Table 4.9.

During short rain seasons, the total gross benefit in maize mono crops were higher in DAP and ½ FYM by 43 and 48%, respectively (P = 0.058). FYM records were lower by 2% in short rains. Total costs were higher by 126, 255, and 193% from FYM, DAP and ½ DAP + ½ FYM. The net benefit was not significantly different from the control (*P* = 0.347) and was less by 23% in the FYM and higher by 9 and 25%, respectively in DAP and ½ DAP + ½ FYM treatments. The BCR analysis however disqualified DAP treatments (Kelly and Murekezi 2000) and maintained the control, FYM, and ½ DAP + ½ FYM, the control being more profitable than the two later treatments (*P* < 0.001). The FYM treatment had negative marginal benefits and positive marginal costs resulting in a negative marginal rate of return, meaning that each extra dollar invested in applying FYM makes a loss equivalent to 16% (*P* =

0.11). The extra dollar invested in DAP and ½ DAP + ½ FYM returns a 52 and 102%, respectively (P = 0.11) (Table 4.9).

Table 4.9: BCR and MRR during the short rains (2009 – 2011)

Treatments	TGB	TC	NB	BCR	MB	MC	MRR
Continuous maize							
Control	530	73.5	456	6.18a	0	0	0
FYM	518	166.3	352	2.35b	-13	92.8	-0.16
DAP	757	260.6	497	2.11b	86	187.1	0.52
½ DAP + ½ FYM	787	215.2	572	2.75b	140	141.6	1.02
SED	120.8ns	-	120.8ns	0.93***	75.9ns	-	0.52ns
Common bean – maize rotation							
Control	243	136.6	108.0	0.81a	0	0	0
FYM	255	230.2	19.0	0.11b	-88	93.6	-0.94b
DAP	347	325.0	16.0	0.04b	-91	188.4	-0.47ab
½ DAP + ½ FYM	368	280.9	83.0	0.28ab	-24	144.3	-0.18a
SED	56.7ns	-	51.5ns	0.26*	35.9ns	-	0.28*
Soybean – maize rotation							
Control	208	108.9	99a	0.9a	0	0	0
FYM	249	197.6	52ab	0.28b	-50.0	88.7	-0.55
DAP	266	292.4	-26c	-0.08b	-128.0	183.5	-0.69
½ DAP + ½ FYM	246	240.8	6bc	0.02b	-96.0	131.9	-0.73
SED	29.6ns	-	29.6***	0.18***	32.8ns	-	0.25ns
Common bean + maize + ½ DAP + ½ FYM							
Monoculture	787	215.2	572	2.75	0	0	0
2:2 IC	748	308.8	439	1.42	-87	93.5	-0.92
2:1 IC	678	299.2	379	1.24	-196	83.9	-2.34
SED	147.8ns	-	147.8ns	0.57ns	146.9ns	-	1.64ns

Key 1: TGB = total gross benefit, TC = total costs, NB = net benefit, BCR = benefit to cost ratio, MB = marginal benefit, MC = marginal cost, MRR = marginal rate of return, IC = Intercropping, SED = standard error of deviation to the mean, *, **, *** = significant at P = 0.01, 0.001, < 0.001, respectively, ns = not significant at P = 0.05.

Key 2: values with different letters are significantly different at P = 0.05.

In common bean treatments, the total gross benefit was higher by 5, 43, and 51%, respectively in FYM, DAP and ½ DAP + ½ FYM, but not significantly (P = 0.293). Total costs were higher by 69, 138 and 106%, respectively. The net benefit was higher in the control and less by 23% in the ½ DAP + ½ FYM (P = 0.213). It was too low in FYM and DAP treatments and less by 82 and 85%, respectively (P = 0.213).

The BCR was < 1.0 across all treatments including the control, but was significantly higher in the control treatment (*P* = 0.024). All treatments had a negative marginal benefit (*P* = 0.137) with positive marginal costs meaning a loss of funds while investing extra money in these technologies, hence, negative MRR (*P* = 0.042).

In soybean treatments, the total gross benefit was higher by 20, 28, and 18%, (*P* = 0.26) with total costs higher by 81, 169 and 121%, respectively in FYM, DAP and ½ DAP + ½ FYM treatments. The net benefit was significantly lower in DAP and ½ DAP + ½ FYM by 126 and 94%, respectively (*P* = 0.001). DAP had a negative net benefit (loss). The BCR was < 1.0 across all treatments including the control (*P* < 0.001). All treatments had negative marginal benefits (*P* = 0.081) and positive marginal costs meaning a loss of funds while investing in these technologies. The MRR was negative (*P* = 0.739).

In intercrops, the total gross benefit was less in intercrops by 5 and 14% respectively (*P* = 0.789) with total costs higher by 43 and 39%, respectively in 2:2 and 2:1 intercrops. The net benefit was also lower by 23 and 36%, respectively (*P* = 0.466). The BCR was > 2.0 in mono crops and < 1.5 in intercrops (*P* = 0.051). Intercrops had negative marginal benefits (*P* = 0.479) and positive marginal costs, hence a loss of funds in investing in such systems. The MRR was negative (*P* = 0.41) (Table 4.9).

According to Kelly and Murekezi (2000), treatments with BCR values lower than 2 are not worthy in farmers' perspectives. The control, FYM, and ½ DAP + ½ FYM in maize are economically acceptable. The application of fertilizer and FYM in common bean and soybean are not beneficial and may mean that venturing in such technologies would bring about a loss of fund. This applies also to intercropping technologies. The farmer cannot shift from one technology to another unless benefits are sure. According to CIMMYT (1988), marginal benefits need to be 1.18 times the marginal costs to be attractive to farmers. All fertilizer treatments did not meet this requirement across all species. Shifting from mono crops to intercrops was also found not economically acceptable. The lack of significant economic viability of fertilizer technologies is linked to yields obtained during short rain seasons which were negatively affected by dry spells during the growth stage of crops coupled with relatively higher total costs and marginal costs associated to applying these technologies.

Table 4.10 presents results of BCR and MRR analysis of treatments during long rain seasons. During long rain seasons, FYM, DAP and ½ DAP + ½ FYM did not increase significantly the total gross benefit of maize across different rotational systems (*P* = 0.695 for maize–maize, 0.68 for common bean–maize, and 0.549 for soybean–maize systems). However, fertilizer treatments increased the total gross benefit by 21, 28, and 27% in continuous maize, 7, 8, and 29% in common bean–maize rotation, and -4, 7, and 28% in soybean–maize rotations, respectively by FYM, DAP and ½ DAP + ½ FYM. Differences due to the previous crop were not significant (*P* = 0.419). Though the interaction inputs/previous crop was not significantly (*P* = 0.978), the gross benefit was higher by 19% in common bean–maize and 25% in soybean–maize rotations. ½ DAP + ½ FYM applied to these rotations (common bean–maize and soybean–maize) increased the total benefit respectively by 22 and 27%. Total costs were higher by 126, 255, and 193% in FYM, DAP and ½ DAP + ½ FYM treatments (Table 4.10).

Table 4.10: BCR and MRR during the long rains (2009 – 2011)

Treatments	TGB	TC	NB	BCR	MB	MC	MRR
Continuous maize							
Control	597	73.5	523	7.39a	0	0	-
FYM	722	166.3	555	3.25b	48.0	92.8	0.44
DAP	765	260.6	504	1.76b	-3.0	187.1	-0.01
½ DAP + ½ FYM	780	215.2	565.1	2.62b	35	141.6	0.23
SED	157.9ns	-	157.9ns	1.24***	104.2ns	-	0.74ns
Common bean – maize rotations							
Control	713	73.5	639	8.92a	0	0	-
FYM	762	166.3	596	3.53b	-31	92.8	-0.35
DAP	768	260.6	508	1.83b	-119	187.1	-0.59
½ DAP + ½ FYM	922	215.2	707	3.17b	80.0	141.6	0.59
SED	179.7ns	-	179.7ns	1.16***	148.8ns	-	1.23ns
Soybean – maize rotations							
Control	749	73.5	675	9.53a	0	0	-
FYM	719	166.3	552	3.29b	-133	92.8	-1.39
DAP	804	260.6	544	1.94b	-142	187.1	-0.77
½ DAP + ½ FYM	959	215.2	744	3.35b	58	141.6	0.41
SED	178.2ns	-	178.2ns	1.44***	130.8ns	-	0.99ns
SEDpc	74.4ns	-	74.4ns	0.55ns	65.9ns		0.50ns
SEDi/pc	148.9ns	-	148.9ns	1.1ns	114.1ns		0.87ns
SEDs	74.4***	-	74.4***	0.55***	65.9ns		0.50ns
Common bean + maize + ½ DAP + ½ FYM							
Monoculture	780b	215.2	565.1b	2.62	0	0	-
2:2 IC	1249a	308.8	940.6a	3.06	465	93.5	4.83
2:1 IC	1129a	299.2	829.5a	2.78	403	83.9	4.83
SED	122.5**	-	122.5**	0.51ns	37.2ns	-	0.47ns

Key 1: TGB = total gross benefit, TC = total costs, NB = net benefit, BCR = benefit to cost ratio, MB = marginal benefit, MC = marginal cost, MRR = marginal rate of return, IC = Intercropping, SED = standard error of deviation to the mean, *, **, *** = significant at P = 0.01, 0.001, < 0.001 respectively, ns = not significant at P = 0.05.

Key 2: values with different letters are significantly different.

Net benefits were not significantly affected by inputs (P = 0.989 in maize–maize, 0.733 in common bean–maize, and 0.622 in soybean–maize systems) and the previous crop (P = 0.419) or by their interaction (P = 0.978). In the continuous maize, FYM and ½ DAP + ½ FYM slightly increased the net benefit by 6 and 4%, respectively. In common bean–maize rotations, FYM and DAP decreased the net benefit by 7 and 21%, respectively while ½ DAP + ½ FYM increased it by 11%. In soybean–maize rotation, FYM and DAP decreased the net benefit by 18 and 19%, respectively while ½ DAP + ½ FYM increased it by 10%. Net benefits were generally higher in soybean–maize and common bean–maize than in maize–maize rotations. The BCR was < 2 in DAP treatments across all cropping systems and > 2 for other treatments across all cropping systems. All treatments were significantly different from each other as far as BCR was concerned ($P < 0.001$ in maize–maize, common bean–maize, and soybean–maize systems), the control being more profitable than other treatments across all cropping systems. Legume–maize systems were generally more profitable than the continuous maize but not significantly (P = 0.381). Marginal benefits were too low and tended to be negative in FYM and DAP treatments and low in ½ DAP + ½ DAP (P = 0.879 in maize–maize, 0.422 in common bean–maize, and 0.247 in soybean–maize rotations) while marginal costs were positive and high. Therefore, the MRR tended to be negative for FYM and DAP treatments, and < 1.0 in ½ DAP + ½ FYM treatments across all cropping systems (P = 0.832 in maize–maize, 0.603 in common bean–maize, and 0.211 in soybean–maize systems).

In intercrops, the total gross benefit was significantly (P = 0.002) higher by 54 and 45%, respectively in 2:2 and 2:1 intercrops. Total costs were higher by 43 and 39%, respectively in 2:2 and 2:1 intercrops but were not significant (P = 0.65). The net benefit was significantly (P = 0.009) higher in intercrops by 58 and 47%, respectively in 2:2 and 2:1. Their BCR was comparable to the one from mono crops but tended to be higher (P = 0.581) in intercrops and was > 2.0. Intercrops made a marginal benefit > 400 USD ha^{-1} compared to mono crops (P = 0.14) and were able to make a return of 4.83 USD USD^{-1} invested (P = 0.982) (Table 4.10).

According to Kelly and Murekezi (2000), technologies with BCR < 2.0 are not economically advisable to farmers. The DAP treatment application was not economically acceptable across all cropping systems (Table 4.10). Intercrops were also economically feasible during long rain seasons. All input treatments have poor or negative marginal benefits and high marginal costs which made them not attractive to farmers when it comes to adoption of technologies. Shifting from mono crops to intercrops is economically acceptable to farmers during long rain seasons.

Table 4.11 presents results of BCR and MRR analysis per cycle. Per cycle, the total gross benefit was significantly (P = 0.041) higher in continuous maize than from common bean–maize and soybean–maize rotations across all fertilizer treatments. The total gross benefit from FYM, DAP and ½ DAP + ½ FYM were higher in continuous maize by 18, 25, and 15% compared to common bean–maize and 22, 28 and 21% compared to soybean–maize rotations. Differences due to inputs were not significant (P = 0.376 in maize–maize, 0.488 in common bean–maize, and 0.598 in soybean–maize systems) but FYM, DAP and ½ DAP + ½ FYM increased the total gross benefit by 10, 32 and 34% in continuous maize treatments, 6, 16 and 33% in common bean–maize, and 0, 11 and 24% in soybean–maize rotations. Total costs were lower in the continuous maize than in legume–maize rotations with higher values from common bean–maize rotations (Table 4.11).

Table 4.11: BCR and MRR per cropping cycle (2009 – 2011)

Treatments	TGB	TC	NB	BCR	MB	MC	MRR
Continuous maize							
Control	1120	147	930	6.65a	0	0	-
FYM	1230	332.6	898	2.66b	99	92.8	0.99
DAP	1473	521.2	952	1.76b	47	187.1	0.27
½ DAP + ½ FYM	1499	430.4	1069	2.42b	85	141.7	0.58
SED	253.5ns	-	253.5ns	0.911***	106.6ns	-	0.777ns
SEDcycle	219.5*	-	219.5*	0.911ns	106.6ns	-	0.777ns
Common bean – maize rotations							
Control	950	210.1	740	3.61a	0	0	-
FYM	1006	396.5	610	1.52b	-118	186.4	-0.65
DAP	1106	585.6	521	0.84b	-207	375.5	-0.53
½ DAP + ½ FYM	1267	496.1	771	1.51b	44.0	286.0	0.16
SED	216.1ns	-	216.1ns	0.549***	161.6ns	-	0.642ns
SEDcycle	187.1**	-	187.1**	0.476***	161.6ns	-	0.642ns
Soybean – maize rotations							
Control	958	182.4	776	4.39a	0	0	-
FYM	955	363.9	591	1.62b	-196	181.5	-1.05
DAP	1059	553.0	506	0.86b	-282	370.6	-0.76
½ DAP + ½ FYM	1185	456.0	729	1.57b	-58	273.6	-0.21
SED	192.3ns	-	192.3ns	0.656***	150.8ns	-	0.584ns
SEDcycle	166.6*	-	166.6*	0.568ns	150.8ns	-	0.584ns
SEDpc	109.5*	-	109.5*	0.358***	93.3ns	-	0.348ns
SEDi/pc	219.1ns	-	219.1ns	0.716ns	161.7ns	-	0.603ns
Common bean + maize + ½ DAP + ½ FYM							
Monoculture	1499	430.4	1069	2.42	0	0	-
2:2 IC	1740	617.6	1122	1.82	156	187.2	0.84
2:1 IC	1768	598.4	1170	1.95	204	168.0	1.21
SED	248ns	-	248ns	0.528ns	139.7ns	-	0.792ns
SEDcycle	248**	-	248**	0.528*	171.1*	-	0.97*

Key 1: TGB = total gross benefit, TC = total costs, NB = net benefit, BCR = benefit to cost ratio, MB = marginal benefit, MC = marginal cost, MRR = marginal rate of return, IC = Intercropping, SED = standard error of deviation to the mean, *, **, *** = significant at P = 0.01, 0.001, < 0.001 respectively, ns = not significant at P = 0.05.

Key 2: values with different letters are significantly different.

The net benefit per cycle was also significantly higher in continuous maize than in legume–maize rotations (P = 0.012) across all input treatments. It was higher by 32, 45 and 28% compared to common bean–maize and by 34, 47, and 32% in soybean–maize rotations, respectively in FYM, DAP, and ½ DAP + ½ FYM treatments. In the control, the net benefit was higher by 20% in common bean–maize and 17% in soybean–maize rotations (Table 4.11). Within a cropping system, inputs did not differ significantly (P = 0.923 in maize–maize, 0.633 in common bean–maize, and 0.485 in soybean–maize systems), but decreased the net benefit in legume–maize systems.

The BCR was > 2.0 in maize–maize systems except in DAP treatments (P < 0.001). In legume–maize treatments, only the control had the BCR > 2.0. Fertilizer treatments were < 2.0. Differences between fertilizer treatments were significant (P < 0.001 in maize–maize, common bean–maize, and soybean–maize systems) as well as those due to the previous crop (P < 0.001). Though not significantly affected by the previous crop, marginal benefits (P = 0.2) were positive and ≥ 40 USD ha^{-1} in the continuous maize, while they were negative in legume–maize systems (dominated) with consequent positive MRR in the continuous maize and negative MRR in legume–maize rotations (P = 0.231) (Table 4.11).

In intercrops (Table 4.11), differences were not significant compared to mono crops across all economic parameters calculated (P = 0.589 for the total gross benefit, 0.96 for the net benefit, 0.37 for the BCR, 0.743 for the marginal benefit, and 0.649 for the MRR). However, the gross benefit was 37 and 40% higher in 2:2 and 2:1 intercrops with additional gross benefit of 500 USD ha^{-1}. These intercrops had a net benefit ≥ 350 USD ha^{-1} with higher records from 2:1. The BCR analysis per cycle revealed that intercrops are more profitable than mono crops but their BCR was < 2.0. Their marginal benefits were positive and > 100 USD ha^{-1}. The MRR was < 1.18 in 2:2 intercrop, while it was > 1.18 in 2:1 intercrops (Table 4.11).

Generally, the low responses of legumes (common bean and soybean) to applied fertilizers during short rain seasons was the main reason for low MRR values reported by this study and made the application of inputs in legume–maize systems look economically unviable (per cycle results). However, presented data stressed the advantage of observing a reasonable rotation between maize and grain legumes which would provide services such as food and money to farmers with low or neutral nutrient losses, and increased yields of the subsequent maize compared to continuous maize production. In fact, during long rain seasons, all treatments with legumes as a previous crop or as associated crop to maize gave higher net benefits than maize mono cropping. Therefore, there is a need to work on common bean and soybean varieties to identify varieties with high potential yield and highly responsive to fertilizers. These varieties should be able to give net benefits approaching those from maize (net benefits from legumes were 25% of those from maize) in short rain season. This would increase the total net benefit per cycle from maize–legume systems.

Negative marginal benefits, BCR < 2.0 and negative MRR observed from common bean and soybean with inputs suggests that the application of FYM, DAP and ½ DAP + ½ FYM are not good options to farmers from the Eastern province of Rwanda. On the other hand, maize planted in rotation with common bean and soybean was more profitable when it followed common bean and soybean without inputs (higher BCR). Therefore, during the legume phase of the cycle, grain legumes would be planted without inputs with the perspective to apply them during the maize phase.

During the long rain seasons, higher net benefits were recorded from ½ DAP + ½ FYM fertilized treatments of previous maize, common bean, and soybean but values from legume treatments being higher than those from maize treatments. This is consistent with the ISFM principle (Vanlauwe, 2004) stating the need to reduce mineral fertilizer application and supplement it with organic sources (FYM in this study) but both in doses affordable by smallholder farmers as they are not able to buy recommended quantities of either sources. Therefore, farmers from the eastern province of Rwanda would be encouraged to adopt the combined application of DAP and FYM because FYM was found to be a key to augment the profitability of DAP through the improvement of DAP fertilizer use efficiency. This is evidenced by observations from the long rain seasons where DAP and FYM treatments gave more or less similar net benefits but with a tendency to be higher in FYM treatments than in DAP treatments.

4.6 Assessment of treatments by farmers

Table 4.12 and 4.13 present the mean scores given by male and female farmers to different treatments across short and long rain seasons respectively. Additionally, a correlation analysis between scores of male and female farmers on one hand and economic characteristics of treatments on the other hand was done and presented in Table 4.14 and 4.15, respectively for short and long rain seasons.

Table 4.12: Evaluation scores per gender in short rains (2009 - 2011)

Treatments	Male	Female
Maize		
Control	3	3
FYM	3	3
DAP	4	4
½ DAP + ½ FYM	4	3
Common bean		
Control	3	3
FYM	3	3
DAP	4	4
½ DAP + ½ FYM	5	4
Soybean		
Control	4	3
FYM	5	4
DAP	5	4
½ DAP + ½ FYM	4	4
Intercropping		
Mono crop	4	4
2:2 Intercrop	4	3
2:1 Intercrop	4	4
Legumes		
Common bean	4	4
Soybean	4	4

Key: 1= very bad; 2= Bad; 3= Medium; 4= Favourable; 5= Very favourable

Across the short rain seasons, male farmers appreciated that DAP and ½ DAP + ½ FYM treatments applied in maize were higher than the control (4 versus 3). They did not view any difference between the control and FYM treatment in maize. On the other hand, female farmers viewed that only DAP treatment was different from the control, other treatments being similar to the control (4 for DAP and 3 for other treatments). In common bean treatments, male farmers viewed that FYM was similar to the control. DAP and ½ DAP + ½ FYM treatments were more interesting to male farmers and were scored 4 and 5 respectively, meaning that ½ DAP + ½ FYM treatment is better than DAP treatment. On the other hand, female farmers found no difference between FYM and the control, and between DAP and ½ DAP + ½ FYM treatments. Male farmers found differences between FYM and DAP compared to the control (5 versus 4), and no difference between the control and ½ DAP + ½ FYM in soybean fields (4). On the other hand, female farmers found the control to be medium and lower than all input treatments (3 versus 4). Male farmers found no differences between maize mono crops and intercrops in terms of maize yields. According to female farmers, 2:2 intercrop is lower than maize mono crop and differs from 2:1 intercrop. Both male and female farmers found similarities between common bean and soybean yields.

Generally, male farmers would accept the use of DAP and ½ DAP + ½ FYM in maize and bean, and FYM and DAP in soybean. Additionally, they would accept to intercrop maize and common bean because intercrops do not affect negatively the maize yield. They accept equally common bean and soybean. Female farmers would accept only DAP application in maize plantations, the application of DAP and ½ DAP + ½ FYM in common bean, and FYM, DAP, and ½ DAP + ½ FYM in soybean plantations. They would not accept the 2:2 intercrop. They also would accept both common bean and soybean.

Scores by male and female farmers were significantly and positively ($P < 0.001$) correlated ($r = 0.671$). Farmers found interest in stover yields due to its direct use as mulch in banana, coffee, tomato and other vegetable plantations, or as an animal feed or litter. All of these uses are beneficial to the soil. However, it is an exhaustive management as it exports nutrients to other cropping systems. The other use which was of female interest was fire wood. This use of crop residues results in a big loss of stalk accumulated nutrients.

During long rain seasons, both male and female farmers' criteria of evaluation were similar and evenly ranked (Table 4.13).

Table 4.13: Evaluation score per gender in long rains (2009 - 2011)

Treatments	Male	Female
Fertilization		
Control	3	3
FYM	3	3
DAP	5	5
½ DAP + ½ FYM	4	4
Crop rotation		
Maize – maize	4	4
Common bean - maize	5	5
Soybean – maize	5	5
Intercropping		
Mono cropping	4	4
2:2 intercrop	4	4
2:1 intercrop	3	3

Both female and male found no difference between FYM and the control. DAP and ½ DAP + ½ FYM treatments were found to be better than the control and FYM. Both male and female farmers found that yields of maize were better in common bean–maize and soybean–maize than in maize–maize mono crops. The 2:2 intercrop was found to be similar to maize mono crop in terms of maize yields, but 2:1 intercrop was found lower (in terms of maize yield). Generally, both male and female farmers would accept to apply DAP and ½ DAP + ½ FYM in maize plantations. They may also accept the integration of common bean and soybean in rotation with maize, and intercrop maize and common bean in 2:2 row arrangement. Their scores were strongly and significantly correlated (r = 1 at $P < 0.001$). Table 4.14 presents correlations between male and female farmers' scores and economic parameters of treatments.

Table 4.14: Farmers' views versus economic aspects during short rains (2009 – 2011)

	Male farmers							
	Grain yield	**TGB**	**TC**	**NB**	**BCR**	**MB**	**MC**	**MRR**
Fertilization								
Maize	0.98**	0.98**	0.872**	0.771*	-0.56*	0.871ns	0.94*	0.829*
Common bean	0.7**	0.7**	0.224**	0.903**	-0.024*	0.908ns	0.276*	0.939**
Soybean	0.96***	0.96***	0.859**	-0.788**	-0.911**	0.103*	0.051*	0.671**
Common bean versus soybean	-1*	-1*	1*	-1**	-1*	-1*	-1**	-1*
Intercropping versus mono cropping	-0.55**	-0.08***	0.757**	-0.441**	-0.600*	-0.428ns	-0.573*	-0.325*
	Female farmers							
Fertilization								
Maize	0.78**	0.78**	0.877**	0.461**	-0.612ns	0.48ns	0.977*	0.408**
Common bean	0.79**	0.79**	0.704**	-0.64**	-0.829**	0.809ns	-0.89*	0.305***
Soybean	0.886***	0.889***	0.863**	-0.809**	-0.952**	-0.804*	0.86*	-0.982***
Common bean versus soybean	1*	1*	-1*	1*	1*	1*	1**	1*
Intercropping versus mono cropping	-0.51***	-0.03***	-0.722**	-0.394**	-0.557*	-0.38ns	-0.529*	-0.275*

Key: TGB = total gross benefit, TC = total costs, NB = Net benefit, BCR = benefit–cost ratio, MRR = marginal rate of returns, * = significant at P = 0.05, ** = significant at P = 0.01, *** = significant at P < 0.001.

The correlation between scores given by male and yields, total gross benefit, total costs and net benefits was stronger than female evaluation especially in maize and soybean treatments. For example, the correlation evaluation/Net benefit in maize was 0.98 for male and 0.78 for female (*P* = 0.01). In maize treatments, the evaluation scores given by male farmers in short rain seasons were positively correlated to the grain yield (*P* = 0.001), total gross benefit (*P* = 0.001), total costs (*P* = 0.001), net benefits (*P* = 0.01) marginal costs (*P* = 0.05) and the MRR (*P* = 0.01). The BCR was negatively correlated with scores (*P* = 0.05). Similar correlation was observed from common bean treatments. In soybean treatments, the correlation was positive and significant with grain yield, total gross benefit, and total costs and marginal rate of returns (*P* = 0.001 – 0.05).

The scores for the net benefit and BCR were negatively correlated (*P* = 0.001). Marginal benefits and marginal costs were weakly correlated with the scores. Scores given to soybean versus common bean were negatively correlated to the grain yield, total gross benefit, net benefit, BCR and MRR, and perfectly and negatively correlated to total costs. This is because scores given to soybean were similar to those given to common bean while the yield and other economic parameters except total costs are lower in soybean than in common bean. Farmers might have other reasons to prefer soybean. These might include its various uses in the daily diet.

Scores given by female farmers during short rain seasons to maize were positively and significantly correlated to the grain yield (*P* = 0.005), total gross benefit (*P* = 0.003), total costs (*P* = 0.003) and net benefit (*P* = 0.015), marginal costs (*P* = 0.022) and the MRR (*P* = 0.042). Their scores were positively and significantly correlated to the yield ($P = 0.005$), total gross benefit ($P = 0.005$), total cost ($P = 0.009$) and the MRR ($P < 0.001$) in common bean treatments. The net benefits ($P = 0.001$), BCR ($P = 0.002$), and marginal benefits ($P = 0.065$) were negatively correlated to scores given by female farmers. This means that treatments which attracted most farmers are those with high yields but unfortunately, these were also associated to high production costs which drastically decreased their net benefit, marginal benefit, and their BCR. In soybean treatments, scores given by female farmers were positively and significantly correlated with the yield ($P < 0.001$), the total gross benefit ($P < 0.001$), total costs ($P = 0.001$) and marginal costs ($P = 0.03$). Their scores (scores by female farmers) were negatively and significantly correlated to the net benefit ($P = 0.003$), the BCR ($P = 0.003$), marginal benefits ($P = 0.032$) and the MRR ($P < 0.001$). This means that attractive technologies were associated to high costs of production. The comparison between common bean and soybean by female farmers was positively and significantly correlations with yields, total gross benefit, net benefit, BCR, marginal costs, marginal benefits, and MRR but perfectly and negatively correlated with total costs, meaning that highly productive treatments were associated with lower production costs.

The comparison of intercrops and mono crops was quite similar between male and female farmers and was negatively correlated to the yield, the total gross benefit, the net benefit, the BCR and the MRR. Farmers may have been driven by other factors than yields. Generally, in mono crops of maize, soybean and common bean, both male and female farmers had their score positively correlated with yields, gross benefits, and total costs, and negatively correlated to the BCR. This means that they preferred high yielding treatments regardless the cost of production encored to produce such much. Table 4.15 presents correlation during long rains.

Table 4.15: Farmers' views versus economic aspects during long rains (2009 – 2011)

Area of evaluation	Grain yield	TGB	TC	NB	BCR	MB	MC	MRR
	Male farmers							
Fertilization	0.937***	0.937***	0.994**	-0.29***	-0.94***	-0.91ns	0.993ns	-0.98***
Crop rotation	0.434**	0.434**	-	0.453**	0.7**	-0.95ns	-	-0.931**
Intercropping	0.999***	0.058**	0.062**	0.055**	-0.094**	0.055ns	0.062ns	-0.061**
	Female farmers							
Fertilization	0.937***	0.937***	0.994**	-0.29***	-0.94***	-0.91ns	0.993ns	-0.98***
Crop rotation	0.434**	0.434**	-	0.453**	0.7**	-0.95ns	-	-0.931**
Intercropping	0.999***	0.058**	0.062**	0.055**	-0.094**	0.055ns	0.062ns	-0.061**

Key: TGB = total gross benefit, TC = total costs, NB = Net benefit, BCR = benefit–cost ratio, MRR = marginal rate of returns, * = significant at P = 0.05, ** = significant at P = 0.01, *** = significant at P < 0.001.

The scores by female and male farmers were positively and significantly (P = 0.05) correlated to the yield, the gross benefit and total costs in comparing rotations, inputs and intercrops. This emphasized that highly productive treatments needed additional production costs. The correlation was too weak or negative with net benefits and BCR, and negative with MRR in comparing fertilizers and intercrops. In comparing crop rotation systems, the correlation was positive and significant with the yield, total gross benefit, net benefit, and BCR, but negatively correlated to the MRR (P = 0.05). This means that treatments with high production were also likely to have high net benefits but did not have positive marginal benefits (high production costs).

CHAPTER FIVE

5.0 CONCLUSIONS AND RECOMENDATIONS

5.1 Conclusions

Results from this study revealed that ½ DAP + ½ FYM increased the yield of common bean and soybean in short rains, and maize in short and long rains, and improved the agronomic use efficiency of DAP both in the short and long rains. It also improved the N and P uptake of common bean, soybean and maize. Intercrops improved both maize and common bean yields, improved the land productivity compared to mono crops both in short and long rains, and increased N and P uptake both in short and long rain seasons. The application of DAP at 200 kg ha^{-1} each season resulted in the accumulation of N and P in the top soil layer. Its application (same rate) in maize, common bean, and soybean was not profitable either in short or long rain seasons. FYM and ½ DAP + ½ FYM were profitable in maize both in short and long rains, but not in common bean and soybean. Intercrops were profitable in long rains but not in short rains.

The application of FYM or ½ DAP + ½ FYM was profitable in continuous maize cropping together with the no input option (zero fertilization). In common bean–maize and soybean–maize rotations, the application of inputs was not economically feasible. The zero fertilizer inputs option was more applicable to these systems. The adoption of input technologies may not take place due to the very low or negative marginal benefits associated with high marginal costs observed in these technologies.

2:1 intercrop was profitable on per cycle basis and guaranteed returns on the extra investment, but 2:2 did not.

Both common bean and soybean derive a part of their N requirement from the atmosphere through the biological N fixation. Common bean fixed higher N amounts than soybean. The N removal through grains exceeded the N fixed hence a net negative N balance for both common bean and soybean. The N balance was more negative for soybean due to its comparatively higher N content in the grain. The N fixed by common bean in intercrops was lower than N fixed in mono crops and N balances were highly negative in intercrops due to increased N sinks (N in grains of common bean and maize + N in maize stalk) compared to the source (N fixation). Both common bean and soybean had a positive rotational effect on maize through their N sparing capacity. Their rotational effect improved maize yields, and N and P uptake of the subsequent maize. Both female and male farmers had a positive view on demonstrated technologies, appreciated those having a high yielding potential both quantitatively and qualitatively regardless of the cost of production brought about by these technologies.

5.2 Recommendations

It would be recommendable to farmers from the Eastern province of Rwanda to apply FYM or ½ DAP + ½ FYM only when they plant maize. It is not recommendable to apply fertilizers in common bean and soybean. In common bean and soybean–maize rotations, neither FYM nor fertilizers would be applied in the legume phase, but the maize planted in rotation would receive FYM or ½ DAP + ½ FYM both for soil fertility and economic benefit. Intercropping common bean and maize in 2:1 row arrangement is also recommended to farmers from the Eastern province of Rwanda.

An additional study is needed to find out the fate of N and P accumulated in the soil following the seasonal application of 200 kg of DAP each season.

REFERENCES

Abendroth, L. J., Elmore, R. W., and Ferguson, R. B. (2006). *Soybean inoculation: understanding the soil and plant mechanisms involved (part one of a two part series).* Lincoln-Nebraska: The board of regents of the University of Nebraska on behalf of the University of Nebraska-Lincoln extension.

Abuja Fertilizer Summit. (2006). *Abuja Declaration on Fertilizer for African Green Revolution.* Abuja, Nigeria: African Union Special Summit of the Heads of State and Govenment.

Addo-Quaye, A. A., Darkwa, A. A, and Ocloo, G. K. (2011). Yields and productivity of component crops in a maize - soybean intercropping system as affected by time of planting and spatial arrangement. *Journal of Agricultural and Biological Science, Vol. 6, No. 9* , 50 - 57.

Alves, B. J. R., Boddey, R. M., and Urquiaga, S. (2003). The success of BNF in Brazil. *Plant and Soil 252* , 1 - 9.

Amede, T., and Kirkby, R. (2004). Guidelines for integration of legumes into the farming systems of East African Highlands. In A. (. Bationo, *Managing Nutrient Cycles to Sustain Soil Fertility in Sub-Saharan Africa* (pp. 43 - 64). Nairobi, Kenya: Academy Science Publishers, A Division of African Academy of Sciences .

Amede, T., Geta, E., and Belachew, T. (2001). *Reversing degradation of arable lands in Ethiopia highlands. Managing African soils. Series no. 23.* London: IIED.

Amezquita, E., Rao, I. M., Hoyos, P., Molina, D., Chavez, L. F., and Bernal, J. F. (2007). Development of an arable layer: A key concept for better management of infertile tropical savanna soils. In A. W. Bationo, *Advances in soil fertility management in Sub-Saharan Africa: Challenges and Opportunities* (pp. 99 - 104). The Netherlands: Springer.

Amolo, R. A., Karanja, N. K., and Palm, C. A. (1996). Nitrogen mineralization from cattle manure, filtermud, factory ash and Nitrogen uptake by maize (Zea mays) in a glasshouse experiment. *Soil technologies for sustainable smallholder farming systems in East Africa. 15th annual general meeting.* Nanyuki, Kenya: Soil Science Society of East Africa.

Amy, T. A., Pineiro, G., and Marina, G. P. (2006). More is less: agricultural impacts on the N cycle in Argentina. *Biochemistry 79* , 45 - 60.

Anderson, J. M., and Ingram, J. S. L. (1993). *Tropical Soil Biology and Fertility: A Handbook of Methods.* Wallingford, UK: CAB International.

Araujo, A. P., Pin, B. D., and Teixeira, M. G. (2012). Nitrogen and Phosphorus in senescent leaves of field-grown common bean cultivars and their contribution to crop nutrient budget. *Field Crops Research 127* , 35 - 43.

Ayuke, F. O., Rao, M. R., Swift, M. J., and Opondo-Mbai, M. L. (2004). Effect of organic and inorganic nutrient sources on soil mineral Nitrogen and maize yields in Western Kenya. In A. Bationo, *Managing Nutrient Cycles to Sustain Soil Fertility in Sub-Saharan Africa* (pp. 65 - 76). Nairobi, Kenya: Academy Science Publishers, A Division of African Academy of Sciences .

Bado, B. V., Bationo, A., Lompo, F., Cescas, M. P., and Sedogo, M. P. (2007). Mineral fertilizers, organic amendments and crop rotation managements for soil fertility maintenance in the Guinea zone of Burkina Faso (West Africa). In A. W. Bationo, *Advances in soil fertility management in Sub-Saharan Africa: Challenges and Opportunities* (pp. 171 - 194). The Netherlands: Springer.

Bado, B. V., Sedogo, M. P., and Lompo, F. (2004). Long term effect of mineral fertilizers, phosphorus rock, dolomite and manure on the characteristics of an ultisol and maize yield in Burkina Faso. In A. (. Bationo, *Managing Nutrient Cycles to Sustain Soil Fertility in Sub-Saharan Africa* (pp. 77 - 88). Nairobi, Kenya: Academy Science Publishers, A Division of African Academy of Sciences.

Bala, A., Osunde, A. O., and Odofin, A. J. . (2011). Organic matter utilization and the determinants of organic manure use by farmers in the Guinea savanna zone of Nigeria. In A. W. Bationo, *Innovation as key to the green revolution in Africa. Exploring the scientific facts, vol 2* (pp. 965 - 974). Springer science + Business media.

Bationo, A., and Waswa, B. S. (2011). New challenges and opportunities for integrated soil fertility management in Africa. In A. W. Bationo, *Innovation as key to the green revolution in Africa. Exploring the scientific facts, vol 1* (pp. 3 - 18). Springer science + Business media.

Bationo, A., Fairhurst, T., Giller, K., Kelly, V., Lunduka, R., Mando, A., Mapfumo, P., Oduor, G., Romney, D., Vanlauwe, B., Wairegi, L., and Zingore, S. (2012). *Handbook for integrated soil fertility management.* Pondicherry, India: African Soil Health Consortium.

Bationo, A., Kihara, J., Vanlauwe, B., Waswa, B., and Kimetu, J. (2007). Soil organic Carbon dynamics, functions and management in West African agro-ecosystems. *Agricultural Systems 94* , 13 - 25.

Bationo, A., Kimetu, J., Vanlauwe, B., Bagayoko, M., Koala, S., and Mukwunye, A. U. (2011). Comparative analysis of the current and potential role of legumes in integrated soil fertility management in West and Central Africa. In A. W. Bationo, *Fighting poverty in Sub Saharan Africa: The multiple role of legumes in integrated soil fertility management* (pp. 117 - 150). Springer science + Business media.

Blackshaw, R. E., and Brandt, R. N. (2009). Phosphorus fertilizer effects on the competition between wheet and several weed species. *Weed Biology and Management 9* , 46 - 53.

Boddey, R. M., Peoples, M. B., Palmer, B., and Dart, P. J. (2000). Use of the 15N natural abundance technique to quantify biological Nitrogen fixation by woody perennials. *Nutrient Cycling in Agroecosystems 57* , 235 - 270.

Buah, S. S. (2008). Role of legumes in soil fertility maintenance in Ghana. In A. T. Bationo, *Synthesis of soil, water and nutrient management research in the Volta Basin* (pp. 99 - 126). Nairobi, Kenya: Ecomedia Ltd.

Cardoso, E. J. B., Nogueira, M. A. and Ferraz, S. M. G. (2007). Biological N2 fixation and mineral N in common bean - maize intercropping or sole cropping in southeastern Brazil . *Expl Agric. 43* , 319 - 330.

Carruthers, K., Printiviraj, B., Fe, Q., Cloutier, D., Martin, R. C., and Smith, D. L. (2000). Intercropping corn with soybean, lupin and forages: yield component responses. *European Journal of Agronomy 12* , 103 - 115.

Chikowo, R., Corbeels, M., Mapfumo, P., Tittonel, P., Vanlauwe, B., and Giller, K. E. (2010). Nitrogen and Phosphorus capture and recovery efficiencies, and crop responses to a range of soil fertility management strategies in Sub-Saharan Africa. *Nutr Cycl Agroecosyst 88* , 59 - 77.

Chirwam, T. S., Mafongonyoya, P. L., Mbewe, D. N. M., and Chishala, B. H. (2004). Changes in soil properties and their effects on maize productivity following Sesbania sesban and Cajanus cajan improved fallow systems in Eastern Zambia. In A. (. Bationo, *Managing Nutrient Cycles to Sustain Soil Fertility in SubSaharan Africa* (pp. 89 - 112). Nairobi, Kenya: Academy Science Publishers, A division of African Academy of Sciences.

CIMMYT. (1988). *From agronomic data to farmer recommendations: An economic training manual. Completely revised edition.* Mexico D. F.: CIMMYT.

Clement, A., Francois-P., Chalifour, F. P., Maheshwar, P. B., and Gendron, G. (1992). Nitrogen and high partitioning in a maize - soybean intercropping system under a humid subtropical climate. *Can. J. Plant Sci. 72* , 69 - 82.

Donovan, G., and Casey, F. (1998). *Soil fertility management in Sub-Saharan Africa. World Bank Technical Paper No. 408.* Washington, D. C.: World Bank .

Dorich, R. A. and Nelson, D. W. (1984). Evaluation of manual Cadmium reduction methods for determination of nitrate in potassium chroride extracts of soil. *Soil Science Society of America Journal 48* , 72 - 75.

Dudal, R. (2002). Forty years of soil fertility work in Sub-Saharan Africa. In B. D. Vanlauwe, *Integrated plant nutrient management in Sub-Saharan Africa: From concept to practice* (pp. 7 - 22). CAB International.

Eck, H. V. (1982). Irrigated corn yield response to nitrogen and water. *Agronomy Journal 76 No. 3* , 421 - 428.

Fageria, N. K. and de Carvalho, A. M. (1996). Response of common bean to Phosphorus on acid soils. *Communication in soil science and plant analysis 27: 5 - 8* , 1447 - 1458.

Fageria, N. K., Baligar, V. C., and Li, Y. C. (2011). The role of nutrient efficient plants in improving crop yields in the twenty first century . *Journal of Plant Nutrition 31* , 1121 - 1157.

FAO. (2009). Retrieved from www.faostat.org.

FAO/IIASA/ISRIC/ISSCAS/JRC. (2009). *Harmonized world soil database (version 1.1).* Rome, Italy and IIASA, Luxenburg, Austraria: FAO.

Furbank, R. T., and Taylor, W. C. (1995). Regulation of photosynthesis in C3 and C4 plants: A molecular approach. *The plant cell 7* , 797 - 807.

Gehringa, C., and Vlekb, P. L. G. (2004). Limitations of the 15N natural abundance method for estimating biological nitrogen fixation in Amazonian forest legumes. *Basic and Applied Ecology 5* , 567 - 580.

Gikonyo, E. W., and Smithson, P. C. (2004). Effects of farm yard manure, potassium and their combination on maize yields in the high and medium rainfall areas of Kenya. In A. (. Bationo, *Managing Nutrient Cycles to Sustain Soil Fertility in Sub-Saharan Africa* (pp. 137 - 150). Nairobi, Kenya:

Academy Science Publishers, A Division of African Academy of Sciences.

Gikonyo, E. W., Zaharah, A. R., Hanafi, M. M., and Anuar, A. R. (2010). Extractable Bray - 1 phosphorus and crop yields as influenced by addition of phosphatic fertilizers of various solubilities integrated with manure in an acid soil. *Nutr Cycl Agroecosyst 88* , 79 - 90.

Giller, K. E. (2001). *Nitrogen fixation in tropical cropping systems - 2nd ed.* CABI Publishing.

Gitari, J. N. (2008). *Determination of factors influencing the efficiency of legume green manures for maize production in Embu, Kenya. PhD thesis.* Kenyatta University.

Gong, W., Yan, X., and Wang, J. (2011). Long-term applications of chemical and organic fertilizers on plant-available nitrogen pools and nitrogen management index. *Biol Fertil Soils 47* , 767 - 775.

Governing Body of Jehovah's Witnesses. (2011). *2011 yearbook of Jehovah's Witnesses.* Pennsylvania: Watchtower Bible and Tract Society of Pennsylvania.

Gwata, E. T., Wofford, D. S., Boote, K. J., Blout, A. R., and Pfahler, P. L. (2005). Inheritance of promiscuous nodulation in soybean. *Crop Science 45* , 635 - 638.

Gwata, E. T., Wofford, D. S., Pfahler, P. L., and Boote, K. J. (2005). Genetics of promiscuous nodulation in soybean: Nodule dry weight and leaf colour score . *Journal of Heredity 95 (2)* , 154 - 157.

Hauggaard-Nielsen, H., Mundus, S., and Jensen, E. S. (2009). Nitrogen dynamics following grain legumes and subsequent catch crops and the effects on succeeding cereal crops. *Nutrient Cycling in Agroecosystems 84* , 281 - 291.

Haynes, R.J., and Mokolobate, M.S. (2001). Amelioration of Al toxicity and P deficiency in acid soils by additions of organic residues: a critical review of the phenomenon and the 10 ISRN Agronomy mechanisms involved. *Nutrient Cycling in Agroecosystems 59, no. 1* , 47 - 63.

Herridge, D. F., Bergersen, F. J., and Peoples, M. B. (1990). Measurement of nitrogen fixation by soybean in the field using the ureide and natural 15N abundance methods. *Plant Physiol 93* , 708 - 716.

Herzog, H., and Gotz, K. P. (2004). Influence of water deficit on uptake and distribution of nitrogen in soybeans monitored by soil injected 15N. *J. Agronomy & Crop Science 190* , 161 - 167.

Houngnandan, P., Yemadge, R. G. H., Oikeh, S. O., Djidohokpin, C. F., Boeckx, P., and Van Cleemput, O. (2008). Improved estimation of biological nitrogen fixation of soybean cultivars (Glycine max L. Merril) using 15N natural abundance technique. *Biol Fertil Soils 45* , 175 - 183.

Hue, N.V., Craddock, G.R., and Adams, F. (1986). Effect of organic acids on aluminum toxicity in subsoil. *Soil Science Society of America Journal 25* , 3291 - 3303.

Jansa, A., Bationo, A., Frossard, E., and Rao, I. M. (2011). Options for improving plant nutrition to increase common bean productivity in Africa . In A. W. Bationo, *Fighting poverty in Sub-Saharan Africa: The multiple roles of legumes in integrated soil fertility management* (pp. 201 - 240). Springer science + Business media.

Jemo, M., Nolte, C., Tchienkoua, M., and Abaido, R. C. (2010). Biological nitrogen fixation potential by soybeans in two low-P soils of southern Cameroon. *Nutrient Cycling in Agroecosystems 88* , 49 - 58.

Jensen, E. S. and Hauggaard-Nielsen, H. (2003). How can increased use of biological N2 fixation in agriculture benefit the environment? *Plant and soil* , 252, 177 - 186.

Kamanga, B. C. G., Shamudzarira, Z., and Vaughan, C. (2003). *On-farm legume experimentation to improve soil fertility in the Zimuto Communal Area, Zimbabwe: Farmer perceptions and feedback. Risk management working paper Series 03/02.* Harare, Zimbabwe: CIMMYT.

Kelly, V., and Murekezi, A. (2000). *Fertilizer response and profitability in Rwanda - A synthesis of findings from MINAGRI studies conducted by the food security research project (FSRP) and the FAO soil fertility initiative* . Kigali, Rwanda: Ministry of Agriculture, Animal Resources, and Forestry.

Kiiya, W., Onyango, R. M., Mwangi, T., Kamidi, M., Muyekho, F. N., and Bantatta, D. K. (1996). Effect of organic manures as alternatives or supplements to inorganic fertilizers on maize yield in Western Kenya. *Soil technologies for sustainable smallholder farming systems in East Africa. 15th annual general meeting.* Nanyuki, Kenya: Soil science society of East Africa (SSSEA).

Landon, R. (. (1991). *Booker Tropical Soil Manual: A handbook for soil survey and agricultural land evaluation in the tropics and subtropics.* Harlow, UK: Booker Tate, Longman Scientific & Technical.

Laszlo, M. (2009). *Biological N2-fixation and mineral N-fertilization effects on soybean (Glicine max L. Merr.) yields under temperate climate conditions. Geophysical Research Abstracts, Vol. 11.* EGU 2009 - 1374, EGU General Assembly 2009.

Lekasi, J. K. (2003). Organic resource management in smallhold agriculture. In C. E. Savala, *Organic resource management in Kenya: Perspectives and guidelines* (pp. 6 - 12). Nairobi, Kenya: Forum for Organic Resource Management and Agricultural Technologies, FORMAT.

Lekasi, J. K., and Kimani, S. K. (2003). Livestock management and manure quality. In C. E. Savala, *Organic resource management in Kenya: Perspectives and guidelines* (pp. 12 - 17). Nairobi, Kenya: Forum for Organic Resource Management and Agricultural Technologies, FORMAT.

Lindemann, W. C. (2003). *Nitrogen fixation by legumes. Guide A - 129.* Cooperative Extension Service College of Agriculture and Home Economics, New Mexico State University, Electronic Distribution May 2003 .

Mapfumo, P. (2011). Comparative analysis of the current and potential role of legumes in integrated soil fertility management in Southern Africa. In A. W. Bationo, *Fighting poverty in Sub-Saharan Africa: The multiple roles of legumes in integrated soil fertility management* (pp. 175 - 200). Springer science + Business media.

Mapfumo, P., Mtambanengwe, F., and Vanlauwe, B. (2007). Organic matter quality and management effects on enrichment of soil organic matter fractions in contrasting soils in Zimbabwe. *Plant Soil 296* , 137 - 150.

Marenya, P. P., and Barrett, C. B. (2007). Household level determinants of adoption of improved natural resources management practices among smallholder farmers in Western Kenya. *Food Policy 32* , 515 - 536.

Martin, R. C., Voldeng, H. D., and Smith, D. L. (1991). Nitrogen transfer from nodulating soybean to maize or to nonnodulating soybean in intercrops: the 15N dilution method. *Plant and Soil 132* , 53 - 63.

Mazaheri, D., Madani, A., and Oveysi, M. (2006). Assessing the land equivalent ratio (LER) of two corn (Zea mays L.) varieties intercropping at various nitrogen levels in Karaj, Iran. *Journal of Central European Agriculture 7 No. 2* , 259 - 364.

Mbah, C.N. and Onweremadu, E.U. (2009). Effect of organic and mineral fertilizer inputs on soil and maize grain yield in an acid ultisol in Abakaliki-South Eastern Nigeria. *American-Eurasian Journal of Agronomy 2 (1)* , 7 - 12.

McCauley, A., Clain, J., and Jacobsen, J. (2009). *Commercial fertilizers and soil amendments. Nutrient management, a self-study course from MSU extension continuing education series.* Montana state, USA: Montana state university.

MINECOFIN. (2003). *Development indicators 2001.* Kigali, Rwanda: MINECOFIN.

MINECOFIN. (2008). *Rwanda development indicators 2006.* Kigali, Rwanda: MINECOFIN.

Morgado, L. B., and Willey, R. W. (2008). Optimum plant population for maize - bean intercropping system in the Brazilian semi - arid region. *Sci. Agric. (Piracicaba, Braz.) 65 No. 5* , 474 - 480.

Mori, A., and Hojito, M. (2011). Effect of combined application of manure and fertilizer on N2O fluxes from a grassland soil in Nasu, Japan. *Agriculture, Ecosystems and Environment, Article in press, Received 19 December 2010, received in revised form 10 July 2011, Accepted 25 July 2011* .

Mucheru-Muna, M., Mugendi, D. N., Pypers, P., Mugwe, J., Vanlauwe, B., Merckx, R., and Kung'u, K. B. (2011). Effect of organic inputs and mineral fertilizer on maize yield in a Ferrasol and a Nitisol soil in Central Kenya. In A. W. Bationo, *Innovations as Key to the green revolution in Africa - Vol. 1* (pp. 191 - 204). Springer science + Business media.

Mucheru-Muna, M., Mugendi, D., Kangai, R., Kung'u, J., Mugwe, J. and Micheni, A. (2003). Organic resources for soil fertility management in Eastern Kenya. In C. E. Savala, *Organic resource management in Kenya: Perspectives and guidelines* (pp. 26 - 33). Nairobi, Kenya: Forum for Organic Resource Management and Agricultural Technologies, FORMAT.

Mucheru-Muna, M., Mugendi, D., Mugwe, J., Kung'u, J., Merckx, R., and Vanlauwe, B. (2009). Soil mineral N dynamics in a maize crop following different soil fertility amendments in different soil fertility status in Sub-humid and Semi-arid regions in Central Kenya. *Research Journal of Agriculture and Biological Sciences 5(6)* , 978 - 993.

Mucheru-Muna, M., Pypers, P., Mugendi, D., Kung'u, J., Mugwe, J., Merckx, R, and Vanlauwe, B. (2010). A staggered maize-legume intercrop arrangement robustly increases crop yields and economic returns in the highlands of Central Kenya. *Field Crop Research 115* , 132 - 139.

Mugendi, D. N., Waswa, B. S., Mucheru-Muna, M. W., Kimetu, J. M., and Palm, C. (2011). Comparative analysis of the current and potential role of legumes in integrated soil fertility management in East Africa. In A. W. Bationo, *Fighting poverty in Sub-Saharan Africa: The multiple roles of legumes in integrated soil fertility management* (pp. 175 - 200). Springer science + Business media.

Mugendi, D., Mucheru-Muna, M., Mugwe, J., Kung'u, J., and Bationo, A. (2007). Improving food production using best-bet soil fertility technologies in the Central highlands of Kenya. In A. W. Bationo, *Advences in soil fertility management in Sub-Saharan Africa: Challenges and Opportunies* (pp. 345 - 352). Springer science + Business media.

Mugwe, J., Mugendi, D., Kung'u, J., and Mucheru-Muna, M. . (2007). Effect of plant biomass, manure and inorganic fertilizer on maize yield in the Central highlands of Kenya. *African Crop Science Journal, Vol. 15 No. 3* , 111 - 126.

Mugwe, J., Mugendi, D., Mucheru-Muna, M., Merckx, R., Chianu, J., and Vanlauwe, B. (2009). Determinants of the decision to adopt integrated soil fertility management practices by smallholder farmers in the Central highlands of Kenya. *Expl Agric 45* , 61 - 75.

Mukuralinda, A., Tenywa, J. S., Verchot, L., Obua, J., Nabahungu, N. L., and Chianu, J. N. (2010). Phosphorus uptake and maize response to organic and inorganic fertilizer inputs in Rubona, Southern Province of Rwanda. *Agroforest Syst 80* , 211 - 221.

Mulongoy, K. (2005). *Technical paper 2: Biological nitrogen fixation*. Retrieved from www.fao.org/Wairdocs/ILRI/x5546E/x5546e05.

Muneer, A., Panhwar, Memon, F. H., Mumtaz, A. K., and Soomro, M. I. (2004). Performance of maize in intercropping system with soybean under different planting patterns and nitrogen levels. *Journal of Applied Sciences 4 (2)* , 201 - 204.

Muoneke, C. O., Ogwuchel, M. A. O., and Kalu, B. A. (2007). Effect of maize planting density on the performance of maize/soybean intercropping system in a Guinea savannah agroecosystem. *African Journal of Agricultural Research 2 (12)* , 667 - 677.

Murwira, H. K., Mutuo, P., Nhamo, N., Marandu, A. E., Rabeson, R., Mwale, M., and Palm, C. A. (2002). Fertilizer equivalency value of organic materials of different quality. In B. D. Vanlauwe, *Integrated plant nutrient management in Sub-Saharan africa: From concept to practice* (pp. 113 - 122). Trowbridge, UK: CAB International.

Musoni, A., Kimani, P., Narla, R.D., Buruchara, R., and Kelly, J. (2010). Inheritance of fusarium wilts (Fusarium oxysporum F. sp. phaseoli) resistance in climbing beans. *African Journal of Agricultural Research 5 (5)* , 399 - 404.

Mutegi, E. M. (2007). *Complementary effects of organic and mineral fertilizers on maize production in the smallholder farms of Meru south District, Kenya. Msc thesis.* Nairobi, Kenya: Kenyatta University.

Nabahungu, N. L., and Visser, S. M. (2011). Farmers' knowledge and perception of agricultural wetland management in Rwanda. *Land Degradation & Development (2011)* , Pblished online in Wiley Online Library (wileyonlinelibrary.com). DOI: 10.1002/ldr.1133.

Nabahungu, N. L., Mowo, J. G., Uwiragiye, A., and Nsengumuremyi, E. (2011). Use of Tithonia biomass, maize residues and inorganic phosphate in climbing bean yield and soil properties in Rwanda. In A. W. Bationo, *Innovation as key to the green revolution in Africa. Vol. 2. Exploring the scientific facts* (pp. 335 - 342). Springer science + Business media.

Nair, P. K. (1993). *An introduction to agroforestry.* Dordrecht, The Netherlands: Kluwer Academic Publishers.

Negassa, W., Gebrekidan, H., and Friesen, D.K. (2005). Integrated use of farmyard manure and NP fertilizers for maize on farmers' fields. *Journal of Agriculture and Rural Development in the Tropics and Subtropics, Volume 106, No. 2* , 131 - 141.

Nguyen, M. T., Akiyoshi, K., Nakatsukasa, M., Saeki, Y., and Yokoyama, K. (2010). Multiple occupancy of nodules by nodulating rhizobia of field-grown soybeans with attendance of Sinorhizobium spp. *Soil Science and Plant Nutrition 56* , 382 - 389.

Nhamo, N., Murwira, H. K., and Giller, K. E. (2004). The relationship between Nitrogen mineralization patterns and quality indices of cattle manures from different smallholder farms in Zimbabwe. In A. (. Bationo, *Managing Nutrient Cycles to Sustain Soil Fertility in Sub-Saharan Africa* (pp. 299 - 318). Nairobi, Kenya: Academy Science Publishers, A Division of African Academy of Sciences.

Niels, V. (2009). *On-farm assessment of banana plant density in Rwanda. Masters' thesis.* Katholieke Universiteit Leuven.

Nyabyenda, P. (1992). *Le soja: Fiches descriptives des varietees diffusees.* Butare, Rwanda: Institut des Sciences Agronomic du Rwanda, ISAR.

Nyamangara, J., and Bergstrom, L. F. (2004). Effect of cattle manure and N fertilizer on nitrate leaching losses in smallholder maize production systems of Zimbabwe measured in field lysimeters. In A. (. Bationo, *Managing Nutrient Cycles to Sustain Soil Fertility in Sub-Saharan Africa* (pp. 317 - 328). Nairobi, Kenya: Academy Science Publishers, A Division of African Academy of Sciences.

Nyamangara, J., Mtambanengwe, F., and Musvoto, C. (2009). Carbon and Nitrogen mineralization from selected organic resources available to smallholder farmers for soil fertility improvement in Zimbabwe. *African Journal of Agricultural Research Vol. 4 (9)* , 870 - 877.

Nyamangara, J., Piha, M. I., and Giller, K. E. (2003). Effect of combined cattle manure and mineral nitrogen on maize N uptake and grain yield. *African Crop Science Journal, Vol. 11, No. 4* , 289 - 300.

Nziguheba, G., Merckx, R., Palm, C. A., and Mutuo, P. K. (2004). Combined use of Tithonia diversifolia and inorganic fertilizers for improving maize production in a phosphorus defficient soil in Western Kenya. In A. (. Bationo, *Managing Nutrient Cycles to Sustain Soil Fertility in Sub-Saharan Africa* (pp. 329 - 346). Nairobi, Kenya: Academy Science Publishers, A Division of African Academy of Sciences.

Obia, A. (2011). *Use of soil amendments as adaptation strategy for global climate change. Master dissertation.* Brussel, Belgium: Ghent University.

Ogoke, I. J., Carsky, R. J., Togun, A. O., and Dashiell, K. (2003). Effect of P fertilizer application on N balance of soybean crop in the Guinea savanna of Nigeria. *Agriculture, Ecosystems and Environment 100* , 153 - 159.

Okito, A., Alves, B. R. J., Urquiaga, S., and Boddey, R. M. (2004). Isotopic fractionation during N2 fixation by four tropical legumes. *Soil Biology & Biochemistry 36* , 1179 - 1190.

Opala, P. (2011). Comparative effects of lime and organic materials on selected soil chemical properties and nutrient uptake by maize in acid soil. *Scholars research library, Archves of applied science research 3 (1)* , 96 - 107.

Opala, P.A., Okalebo, J.R., and Othieno, C.O. (2012). Effect of organic and inorganic materials on soil acidity and phosphorus availability in a soil incubation study. *ISRN Agronomy, Volume 2012* , 1 - 10.

Osunde, A. O., and Bala, A. (2005). Nitrogen derived from promiscuous soybean in maize - based cropping systems in the moist savanna of Nigeria. *Nigerian Journal of Soil Science 15* , 109 - 115.

Osunde, A. O., Bala, A., Gwama, M. S., Tsado, P. A., Sanginga, N., and Okogun, J. A. (2003). Residual benefits of promiscuous soybean to maize (Zea mays L.) grown on farmers' fields around Minna in the southern Guinea savanna zone of Nigeria. *Agriculture, Ecosystems and Environment 100* , 209 - 220.

Pal, U. R., and Shehu, Y. (2001). Direct and residual contributions of symbiotic nitrogen fixation by legumes to the yield and nitrogen uptake of maize (Zea mays L.) in the Nigeria Savannah . *J. Agronomy & Crop Science 187* , 53 - 58.

Peoples, M. and Griffiths, J. (2009, June). *www.farmingahead.com.au*. Retrieved 10 29, 2012, from www.farmingahead.com.au: www.farmingahead.com.au

Peoples, M. B., Bergesen, F. J., Turner, G. L., Sampet, C., Rerkeasem, B., Bhormsiri, A., Nurhayati, D. P., Faizah, A. W., Sudin, M. N., Norhayati, M., and Herridge, D. F. (1991). Use of natural enrichment of 15N in plant available soil N for the measurement of symbiotic N2 fixation. In *Stable isotopes in plant nutrition. Soil fertility and environment studies* (pp. 117 - 170). Austleria: IAEA/FAO.

Peoples, M. B., Faizah, A. W., Rerkasem, B., and Herridge, D. F. (1989). *Methods for evaluating nitrogen fixation by nodulated legumes in the field.* ACIAR Monograph No. 11.

Peoples, M.B., Unkovich, M. J., and Heridge, D. F. (2009). Measuring symbiotic nitrogen fixation by legumes. In D. W. Emerich, *Nitrogen fixation in crop, Agronomy monograph no. 52* (pp. 125 - 170). American Society of Agronomy, Crop Science Society of America, and Soil Science Society of America.

Prasad, R. B., and Brook, R. M. (2005). Effect of varying maize densities on intercropped maize and soybean in Nepal. *Expl Agric 41* , 365 - 382.

Project, M. D. (2013, January Thursday,11). *Mekong Delta Agricultural Extension Project*. Retrieved January Thursday, 11, 2013, from www.ctu.edu.vn/institutes/mdi/extension/iot/rice: www.ctu.edu.vn

Pypers, P. (2006). *Isotopic approaches to characterize P availability and P acquisition by maize and legumes in highly weathered soils.* Katholieke Universiteit of Leuven, Belgium.

Pypers, P., Van Loon, L., Diels, J., Abaido, R., Smolders, E., and Merckx, R. (2006). Plant-available P for maize and cowpea in P-defficient soils from the Nigerian northern Guinnea savanna - comparison of E- and L- values. *Plant and Soil 283* , 251 - 264.

Pypers, P., Verstraete, S., Thi, C. P., Merckx, R. (2005). Changes in mineral nitrogen, phosphorus availability and salt-extractable aluminium following the application of green manure residues in two weathered soils of South Vietnam. *Soil Biology & Biochemistry 37* , 163 - 172.

Ramesh, P., Panwar, N. R., Singh, A. B., Ramana, S., and Rao, A. S. (2009). Impact of organic-manure combinations on the productivity and soil quality in different cropping systems in Central India . *J. Plant Nutr. Soil Sci. 172* , 577 - 585.

Rayar, A. J. (2000). *Sustainable agriculture in Sub-Saharan Africa. The role of soil productivity.* AJR publication-Chennai.

Reddy, M. R. (1991). Differential responses of soybean genotypes to excess manganese in an acidic soil. *Plant and soil 134* , 221 - 226.

Rufino, M. C., Tittonell, P., Van Wijk, M. T., Castellanos-Navarrete, A., Delve, R. J., De Ridder, N., and Giller, K. E. (2007). Manure as key resource within smallholder farming systems: Analysing farm-scale nutrient cycling efficiencies with the NUANCES framework. *Livestock Science 112* , 273 - 287.

Rutunga, V., and Neel, H. (2006). Yield trends in the long-term crop rotation with organic and inorganic fertilizers on Alisols in Mata (Rwanda). *Biotechnol. Agron. Soc. Environ. 10 (3)* , 217 - 228.

Rutunga, V., Steiner, K. G., Karanja, N. K., Gachene, C. K. K., and Nzabonihankuye, G. (1998). Continuous fertilization on non-humiferous acid oxisols in Rwanda 'Plateau central': soil chemical changes and plant production. *Biotechnol. Agron. Soc. Environ. 2 (2)* , 135 - 142.

Salvagotti, F., Cassman, K. G., Specht, J. E., Walters, D. T., Weiss, A., and Dobermann, A. R. (2008). *Nitrogen uptake, fixation and response to fertilizer N in soybeans: A review.* Nebraska - Linkorn: Agronmy faculty publications, University of Nebraska - Linkoln.

Sanchez, P. A., and Jama, B. A. (2002). Soil fertility replenishment takes off in East and Southern Africa. In B. D. Vanlauwe, *Integrated plant nutrient management in Sub-Saharan Africa: From concept to practice* (pp. 23 - 46). Trowbridge, UK: CAB International.

Sanginga, N., and Woomer, P. L. (eds). (2009). *Integrated soil fertility management in Africa: Principles, practices, and developmental process.* Nairobi, Kenya: TSBF-CIAT.

Sanginga, N., Dashiell, K. E., Diels, J., Vanlauwe, B., Lyasse, O., Carsky, R. J., Tarawali, S., Menkir, A., Schulz, S., Singh, B. B., Chikoye, D., Keatinge, D., and Ortiz, R. (2003). Sustainable resource management coupled to resilient germplasm to provide new intensive cereal-grain-legume-livestock systems in the dry savanna . *Agric. Ecosyst. Environ. 100* , 305 - 314.

Schulze, J. (2004). How are nitrogen fixation rates regulated in legumes? *J. Plant Nutr. Soil Sci. 167* , 125 - 137.

Simpson, B. B., and Molley, C. (1986). *Economic botany. Plants in our world.* USA: McGraw-Hill, Inc. .

Singh, A., Carsky, R. J., Lucas, E. O., and Dashiell, K. (2003). Soil N balance as affected by soybean maturity class in the Guinea savanna of Nigeria. *Agriculture, Ecosystems and Environment 100* , 231 - 240.

Smaling, E. M. A., Nandwa, S. M., and Janssen, B. H. (1997). Soil fertility is at stake! In R. J. Buresh, *Replenishing soil fertility in Africa* (pp. 47 - 61). Madison, WI: SSSA, Special Publication, Number 51, Soil Science Society of Africa, American Society of Agronomy.

Stark, J. M., Hart, S. C. (1996). Diffusion technique for preparing salt solution, Kjeldahl digests, and persulfate digest for nitrogen-15 analysis. *Soil Sci. Soc. Am. J. 60* , 1846 - 1855.

Ştefanic, G. and Gheorghiţă, N. . (2006). Soil fertility or soil quality? *Romanian agricultural research* , 26, 57 - 64.

Sugihara, S., Funakawa, S., Kilasara, M., and Kosaki, T. (2010). Dynamics of microbial biomass nitrogen in relation to plant nitrogen uptake during the crop growth period in a dry tropical cropland in Tanzania. *Soil Science and Plant Nutrition 56* , 105 - 114.

Sulieman, S. A., Muna, A. A., El Tahir, A. O., and Hago, T. E. M. (2009). Phosphorus supply and Phaseolus vulgaris performance grown in

Shanbat clay - alkaline soil and influenced by farmyard manure . *Australian Journal of Basic and Applied Sciences 3 (3)* , 2598 - 2606.

Svubure, O., Mpepereki, S., and Makonese, F. (2010). Sustainability of maize-based cropping systems in rural areas of Zimbabwe: an assessment of the residual soil fertility effects of grain legumes on maize (Zea mays [L.]) under field conditions. *International Journal of Engineering, Science and Technology, Vol. 2, No. 7* , 141 - 148.

Telalign, T., Haque, I., and Eduayi, E. A. (1991). *Soil, plant, water, fertilizer, animal manure and compost analysis manual.* Addis ababa, Ethiopia: Plant Science Division Working Document 13, ILCA.

Tittonell, P., Corbeels, M., van Wikj, M. T., Vanlauwe, B., and Giller, K. E. (2008). Combining organic and mineral fertilizers for integrated soil fertility management in smallholder farming systems of Kenya: Explorations using the crop-soil model FIELD. *Agronomy Journal, Volume 100* , Issue 5.

Triplett, E. W., Albrecht, K. A., and Oplinger, E. S. (1993). Crop rotation effects on populations of Bradyrhizobium japonicum and Bradyrhizobium meliloti. *Soil Biology & Biochemistry 25 (6)* , 781 - 784.

Tsubo, M., and Walker, F. (2004). Shade effects on Phaseolus vulgaris L. intercropped with Zea mays L. under well - watered conditions. *J. Agronomy & Crop Science 190* , 168 - 176.

Tsubo, M., Mukhala, E., Ogindo, H. O., and Walker, S. (2003). Productivity of maize-bean intercropping in a semi-arid region of South Africa. *Water SA, Vol. 29, No. 4* , 381 - 388.

Ullah, A., Bhatti, M. A., Gurmani, Z. A., and Imran, M. (2007). Studies on planting patterns of maize (Zea mays L.) facilitating legumes intercropping. *Journal of Agricultural Research 45 (2)* , 113 - 118.

Unkovich, M., Herridge, D., Peoples, M., Cadisch, G., Boddey, R., Giller, K. E., Alves, B., and Chalk, P. (2008). *Measuring plant-associated nitrogen fixation in agricultural systems.* ACIAR Monograph No. 136, 258 pp.

Urquiaga, S., Jantalia, C. P., Zotarelli, L., Araujo, E. S., Alves, B. J. R., Boddey, R. M., Cabezas, W. L., Dos Santos, H. P., and Torres, E. (2006). Nitrogen dynamics in soybean-based crop rotations under conventional and zero tillage in Brazil. In IAEA, *Managing practices for improving sustainable crop production in tropical acid soils. Results of a coordinated research* *project organized by the joint FAO/IAEA programme of nuclear techniques in food and agriculture. Proceedings series.* FAO/IAEA.

Van der Heijden, M. G. A., Bardgett, R. D., and van Straalen, N. M. (2008). The unseen majority: soil microbes as drivers of plant diversity and productivity in terrestrial ecosystems. *Ecology Letters 11* , 296 - 310.

Vanlauwe, A., Mukalama, J., Abaidoo, R. C., and Sanginga, N. (2011). Soybean varieties, developed in lowland West Africa, retain their promuscuity and dual-purpose nature under highland conditions in West Kenya. In A. W. Bationo, *Innovations as key to the green revolution in Africa, Vol. 1. Exploring the scientific facts* (pp. 133 - 144). Springer science + Business media.

Vanlauwe, B. (2004). Integrated soil fertility management research at TSBF: The framework, the principles, and their application. In A. (. Bationo, *Managing Nutrient Cycles to Sustain Soil Fertility in Sub-Saharan Africa* (pp. 25 - 42). Nairobi, Kenya: Academy Science Publishers, A Division of African Academy of Sciences.

Vanlauwe, B., and Giller, K. E. (2006). Popular myths around soil fertility management in Sub-Saharan Africa. *Agriculture, Ecosystems & Environment 116* , 34 - 46.

Vanlauwe, B., Bationo, A., Chianu, J., Giller, K. E., Merckx, R., Mokwunye, U., Ohiokpehai, O., Pypers, P., Tabo, R., Shepherd, K. D., Smaling, E. M. A., Woomer, P. L., and Sanginga, N. (2010). Integrated soil fertility management: Operational definition and consequences for implementation and dissemination. *Outlook on Agriculture, Vol. 39, No. 1* , 17 - 24.

Vanlauwe, B., Diels, J., Aihu, K., Iwuafor, E. N. O., Lyasse, O., Sanginga, N., and Merckx, R. (2002). Direct interactions between N fertilizer and organic matter: Evidence from trials with 15N-labelled fertilizer . In B. D. Vanlauwe, *Integrated plant nutrient management in Sub-Saharan Africa: From concept to practice* (pp. 173 - 184). Trowbridge, UK: CAB International.

Vanlauwe, B., Tittonell, P., and Mukalama, J. (2006). Within-farm soil fertility gradients affect response of maize to fertilizer application in Western Kenya. *Nutrient Cycling in Agroecosystems 76* , 171 - 182.

Verdoodt, A., Van Ranst, E. (2003). *Land evaluation for agricultural production in the tropics - A large-scale land suitability classification for Rwanda.* Ghent, Belgium: Laboratory of soil science, Ghent University.

Wang, Z. H., Li, S. X., and Malhi, S. S. . (2008). Review effects of fertilization and other agronomic measures on nutritional quality of crops. *Journal of the Science of Food and Agriculture 88* , 7 - 23.

Woomer, P. L., Lan'gat, M., and Tungani, J. O. (2004). Innovative maize-legume intercropping results in above and below-ground competitive advantages for understory legumes. *West African Journal of applied Ecology 6* , 85 - 94.

Yadegari, M., Rahmani, H. A., Noormohammadi, G., and Ayneband, A. (2010). Plant growth promoting rhizobacteria increase growth, yield and nitrogen fixation in Phaseolus vulgaris. *Journal of Plant Nutrition 33* , 1733 - 1743.

Yusuf, A. A., Abaidoo, R. C., Iwuafor, E. N. O., Olufajo, O. O., and Sanginga, N. (2009b). Rotation effects of grain legumes and fallow on maize yield, microbial biomass and chemical properties of an Alfisol in the Nigerian savanna. *Agriculture, Ecosystems & Environment 129* , 325 - 331.

Yusuf, A. A., Iwuafor, E. N. O., Abaidoo, R. C., Olufajo, O. O., and Sanginga, N. (2009). Effect of crop rotation and nitrogen fertilization on yield and nitrogen efficiency in maize in the northern Guinea savanna of Nigeria. *African Journal of Agricultural Research 4 (10)* , 913 - 921.

Zdor, R. E., and Pueppke, S. G. (1988). Early infection and competition for nodulation of soybean by Bradyrhizobium japonicum 123 and 138. *Applied and Environmental Microbiology 54 (8)* , 1996 - 2002.

Zhang, F., and Li, L. (2003). Using competitive and facilitative interactions in intercropping systems enhances crop productivity and nutrient-use efficiency. *Plant and Soil 248* , 305 - 312.

Zougmore, R., Mando, A., and Stroosnijder, L. (2010). Benefits of integrated soil fertility and water management in semi-arid West Africa: an example study in Burkina Faso. *Nutrient Cycling in Agroecosystems 88* , 17 - 27.

APPENDICES

Appendix 1: Initial chemical and physical properties of experimental soils (0 – 20 cm)

Parameter	Units	Mean	Range
organic C	(g kg^{-1})	19.4	8.55 – 32.2
total N	(g kg^{-1})	1.42	0.69 – 2.20
available P	(mg P kg^{-1})	6.22	3.00 – 14.3
pH(H_2O)		5.69	5.14 – 6.23
CEC	(cmol kg^{-1})	13.0	3.81 – 28.8
exch. K^+	(cmol kg^{-1})	0.44	0.13 – 1.04
exch. Mg^{2+}	(cmol kg^{-1})	2.29	0.60 – 5.92
exch. Ca^{2+}	(cmol kg^{-1})	6.72	1.11 – 17.4
clay	(g kg^{-1})	27	22 – 35
silt	(g kg^{-1})	6	1 – 17
sand	(g kg^{-1})	67	49 – 78

Appendix 2: Income per treatments during short rain seasons (2009 – 2011)

Treat	Legumes grain	Maize grain	Maize stover	Legume income	Maize grain income	Maize stover income
1	0	1982	5614	0	694	11
2	0	2517	6935	0	881	14
3	0	3482	7613	0	1219	15
4	0	3254	7009	0	1139	14
5	643	0	0	341	0	0
6	608	0	0	322	0	0
7	959	0	0	508	0	0
8	886	0	0	470	0	0
9	599	0	0	317	0	0
10	694	0	0	368	0	0
11	784	0	0	416	0	0
12	758	0	0	402	0	0
13	414	2609	7450	219	913	15
14	540	2338	5097	286	818	10

Key: 1 = Maize–maize/control, 2 = Maize–maize/FYM, 3 = Maize–maize/DAP, 4 = Maize–maize/½ DAP + ½ FYM, 5 = Common bean–maize/control, 6 = Common bean–maize/FYM, 7 = Common bean–maize/DAP, 8 = Common bean–maize/½ DAP + ½ FYM, 9 = Soybean–maize/Control, 10 = Soybean–maize/FYM, 11 = Soybean–maize/DAP, 12 = Soybean–maize/½ DAP + ½ FYM, 13 = 2:2 intercropping/½ DAP + ½ FYM, 14 = 2:1 intercropping/½ DAP + ½ FYM.

Appendix 3: Costs (US dollars ha-1) during short rains (2009 – 2011) (treatment 1 to 7)

	1	**2**	**3**	**4**	**5**	**6**	**7**
Seeds Total	7.68	7.68	7.68	7.68	57.63	57.63	57.63
Fertilizer	0	86.38	169.3	127.84	0	86.38	169.3
Row making	13.3	13.3	13.3	13.3	6.8	6.8	6.8
DAP application	0	0	4.45	4.45	0	0	14.96
FYM application	0	4.08	0	3.38	0	7.79	0
Input covering	0	0	2.8	3.5	0	0	8.51
Total fertilizer	**13.3**	**103.76**	**189.85**	**152.47**	**6.8**	**100.97**	**199.57**
Planting	5.58	5.58	5.58	5.58	15.52	15.52	15.52
Covering seeds	2.8	2.8	2.8	2.8	7.12	7.12	7.12
Thinning	5.56	5.86	5.74	5.91	7.95	5.62	7.37
Fist weeding	40.39	39.74	42.76	40.06	47.99	50.43	50.08
Harvesting legumes	0	0	0	0	15.52	14.05	16.61
Harvesting maize	88.1	102.2	125.7	119	0	0	0
Threshing maize	17	21.6	29.9	27.9	0	0	0
Total costs	**180**	**299**	**410**	**361**	**159**	**251**	**354**

Key: 1 = Maize – maize/control, 2 = Maize–maize/FYM, 3 = Maize–maize/DAP, 4 = Maize–maize/½ DAP + ½ FYM, 5 = Common bean–maize/control, 6 = Common bean–maize/FYM, 7 = Common bean–maize/DAP, 8 = Common bean–maize/½ DAP + ½ FYM, 9 = Soybean–maize/Control, 10 = Soybean–maize/FYM, 11 = Soybean–maize/DAP, 12 = Soybean–maize/½ DAP + ½ FYM, 13 = 2:2 intercropping/½ DAP + ½ FYM, 14 = 2:1 intercropping/½ DAP + ½ FYM.

Appendix 3: Costs (US dollars ha^{-1}) during short rains (2009 – 2011) (treatment 8 to 14)

	8	9	10	11	12	13	14
Seeds Total	57.63	38.47	38.47	38.47	38.47	38.36	45.78
Fertilizer	127.84	0	86.38	169.3	127.84	127.84	127.84
Row making	6.8	3.2	3.2	3.2	3.2	18.1	14.9
DAP application	8.01	0	0	3.68	2.65	11.04	7.6
FYM application	8.08	0	3.48	0	3.64	10.04	6.17
Input covering	9.81	0	0	5.97	2.99	6.5	7.51
Total fertilizer	**160.54**	**3.2**	**93.06**	**182.15**	**140.32**	**173.52**	**164.02**
Planting	15.52	8.45	8.45	8.45	8.45	21.23	16.07
Covering seeds	7.12	2.77	2.77	2.77	2.77	9.02	5.27
Thinning	6.63	6.7	6.7	7.55	6.95	10.32	11.57
Fist weeding	46.8	50.45	48.29	57.9	47.75	53.56	58.49
Harvesting legumes	17.2	11.42	13.79	14.88	13.27	16.78	13.37
Harvesting maize	0	0	0	0	0	104.3	93.6
Threshing maize	0	0	0	0	0	22.4	20.1
Total costs	**311**	**121**	**212**	**312**	**258**	**449**	**428**

Key: 1 = Maize–maize/control, 2 = Maize–maize/FYM, 3 = Maize–maize/DAP, 4 = Maize–maize/½ DAP + ½ FYM, 5 = Common bean–maize/control, 6 = Common bean–maize/FYM, 7 = Common bean–maize/DAP, 8 = Common bean–maize/½ DAP + ½ FYM, 9 = Soybean–maize/Control, 10 = Soybean–maize/FYM, 11 = Soybean–maize/DAP, 12 = Soybean–maize/½ DAP + ½ FYM, 13 = 2:2 intercropping/½ DAP + ½ FYM, 14 = 2:1 intercropping/½ DAP + ½ FYM.

Appendix 4: Income per treatment during long rains (2009 – 2011)

Treat	Legumes grain	Maize grain	Maize stover	Legume income	Maize income	Maize stover income
1	0	2531	7657	0	886	15
2	0	3014	8567	0	1055	17
3	0	3283	9101	0	1149	18
4	0	3259	9151	0	1141	18
5	0	2929	8524	0	1025	17
6	0	3313	8944	0	1160	18
7	0	3467	9319	0	1213	19
8	0	3824	10676	0	1338	21
9	0	3146	7842	0	1101	16
10	0	3206	9349	0	1122	19
11	0	3538	9690	0	1238	19
12	0	4142	10721	0	1450	21
13	566	3137	10700	300	1098	21
14	944	2231	7700	500	781	15

Appendix 5: Costs (US dollars ha-1) during long rains (2009 – 2011) (treatment 1 to 8)

	1	2	3	4	5	6	7	8
Seeds Total	7.68	7.68	7.68	7.68	7.68	7.68	7.68	7.68
Fertilizer	0	86.38	169.3	127.84	0	86.38	169.3	127.84
Row making	13.3	13.3	13.3	13.3	13.3	13.3	13.3	13.3
DAP application	0	0	5.88	5.88	0	0	5.88	5.88
FYM application	0	5.41	0	5.27	0	5.41	0	5.27
Input covering	0	0	2.8	3.51	0	0	2.8	3.51
Total fertilizer	**13.3**	**103.76**	**189.85**	**152.47**	**6.8**	**100.97**	**199.57**	**160.54**
Planting	5.59	5.59	5.59	5.59	5.59	5.59	5.59	5.59
Covering seeds	2.8	2.8	2.8	2.8	2.8	2.8	2.8	2.8
Thinning	4.31	1.23	4.3	2.22	4.44	3.21	3.24	3.87
Fist weeding	37.4	29.4	34.3	28.4	34.3	33.2	34	26.5
Harvesting legumes	0	0	0	0	0	0	0	0
Harvesting maize	105.1	106.5	114.2	112.8	101.5	108.9	116.5	123.5
Threshing maize	21.8	25.9	28.2	28	25.2	28.5	29.8	32.9
Total costs	**198**	**283**	**387**	**340**	**188**	**291**	**399**	**363**

Key: 1 = Maize–maize/control, 2 = Maize–maize/FYM, 3 = Maize–maize/DAP, 4 = Maize–maize/½ DAP + ½ FYM, 5 = Common bean–maize/control, 6 = Common bean–maize/FYM, 7 = Common bean–maize/DAP, 8 = Common bean–maize/½ DAP + ½ FYM, 9 = Soybean–maize/Control, 10 = Soybean–maize/FYM, 11 = Soybean–maize/DAP, 12 = Soybean–maize/½ DAP + ½ FYM, 13 = 2:2 intercropping/½ DAP + ½ FYM, 14 = 2:1 intercropping/½ DAP + ½ FYM.

Appendix 5: Costs (US dollars ha^{-1}) during long rains (2009 – 2011) (treatment 9 to 14)

	9	10	11	12	13	14
Seeds Total	7.68	7.68	7.68	7.68	38.36	45.78
Fertilizer	0	86.38	169.3	127.84	127.84	127.84
Row making	13.3	13.3	13.3	13.3	15.98	14.67
DAP application	0	0	5.88	5.88	7.57	4.64
FYM application	0	5.41	0	5.27	7.19	3.89
Input covering	0	0	2.8	3.51	6.5	7.51
Total fertilizer	**3.2**	**93.06**	**182.15**	**140.32**	**173.52**	**164.02**
Planting	5.59	5.59	5.59	5.59	24.58	18.53
Covering seeds	2.8	2.8	2.8	2.8	10.49	6.09
Thinning	4.42	2.94	3.44	6.28	4.83	3.54
Fist weeding	30.4	27.9	34.1	27.4	53.6	44.7
Harvesting legumes	0	0	0	0	21.27	17.59
Harvesting maize	113.5	114.3	124.3	132	113.7	87.8
Threshing maize	27.1	27.6	30.4	35.6	27	19.2
Total costs	**195**	**282**	**390**	**358**	**467**	**407**

Key: 1 = Maize–maize/control, 2 = Maize–maize/FYM, 3 = Maize–maize/DAP, 4 = Maize–maize/½ DAP + ½ FYM, 5 = Common bean–maize/control, 6 = Common bean–maize/FYM, 7 = Common bean–maize/DAP, 8 = Common bean–maize/½ DAP + ½ FYM, 9 = Soybean–maize/Control, 10 = Soybean–maize/FYM, 11 = Soybean–maize/DAP, 12 = Soybean–maize/½ DAP + ½ FYM, 13 = 2:2 intercropping/½ DAP + ½ FYM, 14 = 2:1 intercropping/½ DAP + ½ FYM.

Appendix 6: Analytical methods

pH determination

A sample of 10 g of soil was put in a 60 ml plastic bottle and 25 ml of distilled water was added with a dispenser. The mixture was stirred for 10 minutes, allowed to stand for 30 minutes and stirred again for 2 minutes. The soil was allowed to settle for 30 seconds and then the electrode immersed into 60 ml bottle with soil and pH reading was recorded after the reading stabilizes (about 30 seconds to 1 minute). The glass electrode was then removed from the bottle and rinsed with distilled water before further use.

Total soil organic carbon

About 1 g of soil sample, ground to pass 0.2 mm mesh was weighed into labelled digestion tubes and 2 ml deionised water added. Ten ml of 5% K_2CrO_7 solution was added into both standard and sample tubes. After this 5 ml concentrated H_2SO_4 was slowly added from an appendorf pipette. The acid was added 1 ml at a time while swirling on a voltex mixer. The suspensions were then digested at 150^oC for 30 minutes and then allowed to cool. After cooling, 50 ml 0.4% barium chloride solution was added and mixed thoroughly. The solution was allowed to stand overnight, so as to leave a clear supernatant solution. The following day, concentration of each standard sample was read at 600 nm on the spectrometer. This was done after determining the absorbance values for the standards so as to check on linearity of the standard curve and proper functioning of the spectrometer. The spectrometer was then calibrated in concentration mode, setting the calibration with the 15 ml C standard. Then blanks and samples were read in the concentration mode.

Determination of exchangeable calcium and magnesium

About 5 g of soil was extracted with 25 ml of 1 M KCl. The soil and KCl in the bottle were stirred for 10 minutes. The extract for analysis was then filtered through Whatman No. 5 filter paper into a clean 60 ml bottle. 1 ml of the extract or standard and 9 ml of deionised water were dispensed into a clean 60 ml and 10 ml of 1% lanthum solution added. Calcium and magnesium were determined on a frame spectrophotometer.

Determination of exchangeable potassium

Approximately 25 g of dry soil was extracted with 25 ml of 0.5 M $NaHCO_3$ + 0.01 M EDTA, pH 8.5 (modified Olsen) using 1:10 soil solution ratio. The slurry was stirred for 10 minutes and then filtered through Whatman No. 5 filter paper into clean bottles. Two ml of sample and 8 ml of deionised water were dispensed into clean 60 ml bottles and swirled gently to mix. Exchangeable K^+ was then analysed by flame spectrometer.

Determination of total soil nitrogen

A dry soil sample (0.4 g) ground to pass through 0.3 mm was weighed into a labelled digestion tube and 1.8 g of K_2SO_4 added. 7.5 ml of soil digestion mixture (Selenium powder, concentrated sulphuric acid and salicylic acid) was then added and left to stand overnight. The contents were then heated at 100^oC for two hours after which 3 ml of hydrogen peroxide (H_2O_2) was put before heating for another 4 hours at 360^oC. The contents were stoppered and left to stand so that a clear solution could be obtained for analysis. Five ml of reagent N1 (68 g sodium salicyclate, 50 g sodium citrate, 50 g sodium titrate, 0.24 g sodium nitroprusside mixed with deionised water to make 2 litres) was added to 0.2 ml of the digested solution, mixed well and then left for one hour for colour development. The sample concentration was then read at 655 nm using a spectrophotometer.

Appendix 7: Calculations

1. SOIL SAMPLES

- **Soil moisture content**

$$\%\ \text{Moisture content} = \frac{\text{Sample fresh dry weight} - \text{Sample dry weight} * 100\%}{\text{Sample dry weight}}$$

- **Exchangeable acidity**

Exchangeable acidity (soil volume basis)

$$\text{EAME100M} = (\text{EATITRAT} - \text{EABLANK}) \frac{(\text{NNaOH})}{0.01}$$

Where: EAME100M = Exchangeable acidity (me/100mL soil)

EATITRAT = titration volume for sample (mL)

EABLANK = titration volume for blank (mL)

NNaOH = Normality of NaOH

Exchangeable acidity (soil mass basis)

EAME100G - EAME100M = <u>(EASOILVOL)</u>

EASOILWT

Where: EAME100G = Exchangeable acidity (me/100g soil)

EASOILVOL = Volume of extracted soil (mL)

EASOILWT = Weight of dry soil extracted (g)

- **Extractable soil Ammonium**

Ammonium – N concentration (dry soil basis):

$$EXANMGKG = \frac{(EXACONC - EXABLANK)\ (100 + (EXNSLWT - EXNDSWT)}{EXNDSWT}$$

Where: EXANMGKG = Ammonium concentration in soil (mg N/kg)

EXACONC = Ammonium concentration for sample (mg N/L)

EXABLANK = Ammonium concentration for blank (mg N/L)

EXNDSWT = Dry weight of extracted soil (g)

Ammonium – N content of soil (kg N/ha) (EXANKGHA):

$$EXANKGHA = \frac{EXANMGKG\ (BD)\ SD}{10}$$

Where: BD = Soil bulk density (g/cm^3)

SD = Depth of soil layer (cm)

- **Extractable Nitrate**

1. Dry weight of extracted soil (g) (EXNSDSWT)

$$\frac{(EXNSLWT)\ 100}{(100 + EXNGWC)}$$

Where: EXNSLWT = Field – moisture weight of extracted soil (g)

EXNGWC = Gravimetric soil water content (%)

2. Nitrate – N concentration (dry soil basis):

$$EXNNMGKG = \frac{((EXNCONC - EXNBLANK)\ (100 + (EXNSLWT - EXNDSWT))}{EXNDSWT}$$

Where: EXNNMGKG = Nitrate concentration in soil (mg N/kg)

EXNCONC = Nitrate concentration for sample (mg N/L)

EXNBLANK = Nitrate concentration for blank (mg N/L)

3. Nitrate – N content of soil (kg N/ha)

$$EXNNKGHA = \frac{EXNNMGKG\ (BD)\ SD}{10}$$

Where: BD = Bulk density (g/cm^3)

SD = Depth of soil layer (cm)

- **Total Nitrogen**

N concentration in soil (SNPER) (%): $\frac{((SNCONC - SNBLANK)\ SNVOL)\ 0.0001}{SNSOLWT}$

Where: SNCONC = N concentration in soil digest (mg/L)

SNBLANK = N concentration in blank digest (mg/L)

SNVOL = Total volume of diluted digest (mL)

SNSOLWT = Soil/plant sample weight (g)

- **Total Phosphorus**

The values read from the instrument are in me/100 mL of soil. The mean blank reading must be subtracted from the sample readings to obtain net concentration values.

P concentration in soil (%); $\frac{((SPCONC - SPBLANK)\ SNVOL)}{SNSOLWT}\ 0.0001$

Where: SNCONC = P concentration in soil digest (mg/L)

SPBLANK = P concentration in blank digest (mg/L)

- **Exchangeable Potassium**

The values read from the instrument are in me/100 mL of soil. The mean blank reading must be subtracted from the sample readings to obtain net concentration values.

a) Exchangeable K (soil volume basis):

EXK100M: EXKCONC – EXKBLANK

Where: EXK100M = Exchangeable K (me/100 mL soil)

EXKCONC = Concentration of K in sample (instrument reading for sample, in me/100 mL soil)

EXKBLANK = Concentration of K in blank (instrument reading for blank, in me/100 mL soil)

b) Exchangeable K (soil mass basis)

$$\text{EXK100M} = \frac{\text{EXK100M (EXKSOLVL)}}{\text{EXKSOLWT}}$$

Where: EXK100G = Exchangeable K (me/100g soil)

EXKSOLVL = Volume of extracted soil (mL)

- **Exchangeable Calcium and magnesium**

The values read from the instrument are in me/100 mL of soil. The mean blank reading must be subtracted from the sample readings to obtain net concentration values.

1) Exchangeable Ca and Mg (soil volume basis)

EXCA100M = EXCACONC – EXCABLANK

EXMG100M = EXMGCONC – EXMGBLANK

Where: EXCA100M, EXMG100M = Exchangeable Ca and Mg (me/100 mL soil)

EXCACONC, EXMGCONC = Concentration of Ca and Mg in sample (instrument for sample, in me/100 mL soil)

EXCABLANK, EXMGBLANK = Concentration of Ca and Mg in blank (instrument for blank, in me/100 mL soil)

2) Exchangeable Ca and Mg (soil mass basis)

$$\text{EXCA100G} = \frac{\text{EXCA100M (EASOLVOL)}}{\text{EASOILWT}}$$

$$\text{EXMG100G} = \frac{\text{EXMG100G (EASOLVOL)}}{\text{EASOILWT}}$$

Where: EXCA100G, EXMG100G = Exchangeable Ca, Mg, respectively (me/100 g soil)

EASOLVOL = Volume of extracted soil (mL)

EASOILWT = Weight of dry soil extracted (g)

- **Total organic Carbon in soils: colorimetric method**

The mean blank must be subtracted from sample concentration values to give a value for corrected concentration.

Total soil organic Carbon (%) (SCPER): $\frac{(\text{SCCONC} - \text{SCBLANK})\ (0.1)}{\text{SCSOLWT}}$

Where: SCCONC = Carbon content of sample (mg C)

SCBLANK = Carbon content of blank (mg C)

SCSOLWT = Dry weight of soil sample (g)

2. PLANT SAMPLES

Nitrogen

$$\text{PNPER} = \frac{(\text{PNCONC} - \text{PNBLANK})\ (\text{PNVOL})\ 0.0001}{\text{PNWT}}$$

Where: PNPER = N concentration in plant tissue (%)

PNCONC = N concentration in plant digest

PNBLANK = N concentration in blank digest

PNVOL = Total volume of diluted digest (mL)

PNWT = Plant sample weight (g)

Phosphorus

$$\text{PPPER} = \frac{(\text{PPCONC} - \text{PPBLANK})\ (\text{PNVOL})\ 0.0001}{\text{PNWT}}$$

Where: PPPER = P concentration in plant tissue (%)

PPCONC = P concentration in plant digest

PPBLANK = P concentration in blank digest

PNVOL = Total volume of diluted digest (mL)

PNWT = Plant sample weight (g)

Potassium

$$\text{PKPER} = \frac{(\text{PKCONC} - \text{PKBLANK})\ (\text{PNVOL})\ (\text{KDF})\ 0.0001}{\text{PNWT}}$$

Where: PKPER = K concentration in plant tissue (%)

PKCONC = K concentration in plant digest

PKBLANK = K concentration in blank digest

PNVOL = Total volume of diluted digest (mL)

PNWT = Plant sample weight (g)

KDF = K dilution factor (usually = 5)

Calcium

$$PCA = \frac{(PCACONC - PCABLANK)\ (PNVOL)\ 0.001}{PNWT}$$

Where: PCA = Ca concentration in plant tissue (%)

PCACONC = Ca concentration in plant digest (mg/L)

PCABLANK = Ca concentration in blank digest (mg/L)

PNVOL = Final volume of diluted plant digest (mL)

PNWT = Weight of plant tissue digest (g)

Magnesium

$$PMG = \frac{(PMGCONC - PMGBLANK)\ (PNVOL)\ 0.001}{PNWT}$$

Where: PMG = Mg concentration in plant tissue (%)

PMGCONC = Mg concentration in plant digest (mg/L)

PMGBLANK = Mg concentration in blank digest (mg/L)

PNVOL = Final volume of diluted plant digest (mL)

PNWT = Weight of plant tissue digested (g)

Source: Dorich and Nelson (1984); Anderson and Ingram (1993)

Appendix 8: Interpreting soil data

Evaluation of pH in soils (after Landon, 1991)

Rating	**pH (H_2O)**
Extremely acidic	4.0 – 4.4
Very strongly acidic	4.5 – 5.0
Strongly acidic	5.1 – 5.5
Moderately acidic	5.6 – 6.0

Evaluation of N and C in soil (after Telalign *et al.*, 1991)

Rating	**Total N**	**Organic C**
	……………………………% ……………………………	
High	> 0.25	> 3.0
Moderate	0.12 – 0.25	1.5 – 3.0
Low	0.05 – 0.12	0.5 – 1.5
Very low	< 0.05	< 0.5

Evaluation of extractable P in soil (after Landon, 1991)

Rating	**Extractable P (cmol/kg)**
Acutely deficient	< 3.0
Deficient	3.1 – 6.5
Marginal	6.6 – 12
Adequate	13 – 22
Rich	> 22

Evaluation of exchangeable cations in soil (after Telalign *et al.*, 1991)

Rating	**K**	**Mg**	**Ca**
		.. (Cmol/kg)	
Very high	> 0.3	> 0.18	> 2.4
High	0.175 – 0.3	0.08 – 0.18	1.6 – 2.4
Medium	0.1 – 0.175	0.04 – 0.08	1.0 – 1.6
Low	0.05 – 0.1	0.02 – 0.04	0.5 – 1.0
Very low	< 0.05	< 0.02	< 0.5