2021-07

Assessing intensification options of common bean cultivation to improve food security on smallholder farms in the Northern Highlands of Tanzania

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NM-AIST

https://doi.org/10.58694/20.500.12479/1333

ASSESSING INTENSIFICATION OPTIONS OF COMMON BEAN CULTIVATION TO IMPROVE FOOD SECURITY ON SMALLHOLDER FARMS IN THE NORTHERN HIGHLANDS OF TANZANIA

Eliakira Kisetu Nassary

A Thesis Submitted in Fulfilment of the Requirements for the Degree of Doctor of Philosophy in Life Sciences of the Nelson Mandela African Institution of Science and Technology

Arusha, Tanzania

July, 2021

ABSTRACT

Complementarities of common bean (*Phaseolus vulgaris* L.) with non-legume food crops and their significances to the agricultural systems are underexploited. Based on the description of this study, eight options were assessed for the sustainable intensification of common bean cultivation (through manipulations of intercropping and rotation) against the monocultures of maize (*Zea mays* L.), and the improved and local varieties of common bean in the northern highlands of Tanzania. The factors assessed were the cropping seasons/years (S) (2015 to 2017), agro-ecological zones (A) above sea level (lower 843 m, middle 1051 m, upper 1743 m), cropping systems (C) (sole, intercrop, rotation), and bean varieties (V) (improved *Lyamungu 90* and local *Mkanamna*) and their interactions. Results indicated that S, A, C, and S×A, S×C, S×A×C were significant and bean grain yields increased in intercrops ranging from 1.5 to 2.9 t ha^{-1} with land equivalent ratio (LER) of 1.58. Intercropping over five cropping seasons indicated that with S×V grain yields increased from 0.2 to 3.5 t ha^{-1} in bean and from 2.3 to 2.6 t ha^{-1} in maize with LERs of 1.48 and 1.55. In rotations, higher bean grain yields were attributed to S (3.3 t ha^{-1}), C (3.4 t ha^{-1}), and V (2.7 t ha^{-1}) and for maize were in C (2.9 t ha^{-1}) and S (2.6 t ha^{-1}). In conclusion, out of eight assessed options, this study found two main useful options for improving food security on smallholder farms in the northern highlands of Tanzania. The options were continuous cultivation of the improved and/or local varieties of common bean in intercrops with the maize throughout two rainy seasons of the year (long and short). Another option was cultivation of the improved and/or local varieties of common bean intercropped with maize in the long rainy season and rotating of these intercrops with the maize cultivated in the short rainy seasons. Importantly, the improved bean variety *Lyamungu 90* was heavier in weight, using the same number of seeds, than the local bean variety *Mkanamna*, which provided additional factors to be considered to improve income where weight is the acceptable standard in the market.

DECLARATION

I, Eliakira Kisetu Nassary, do hereby declare to the Senate of the Nelson Mandela African Institution of Science and Technology that this thesis is my own original work, and that it has neither been submitted nor being concurrently submitted for degree award in any other institution.

Eliakira Kisetu Nassary **Candidate Name**	**Signature**	**Date**
Prof. Patrick Alois Ndakidemi **Supervisor Name**	**Signature**	**Date**
Dr. Frederick Baijukya **Supervisor Name**	**Signature**	**Date**

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CERTIFICATION

The undersigned certify that they have read the thesis entitled "Assessing intensification options of common bean cultivation to improve food security on smallholder farms in the northern highlands of Tanzania" and found it to be acceptable for examination in fulfilment of the Award of Doctor of Philosophy in Life Sciences majoring in Sustainable Agriculture of the Nelson Mandela African Institution of Science and Technology.

Prof. Patrick Alois Ndakidemi
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Dr. Frederick Baijukya
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ACKNOWLEDGEMENTS

All acclamations and appreciations are for Almighty God, who is the Creator of the Universe, the Cherisher and Sustainer of the world, Lord of all things, Master of the Day of Judgment and Hath Power over all things; Most Gracious, Most Merciful.

I thank the Bill & Melinda Gates Foundation for funding this research through N2Africa Project: Putting Nitrogen Fixation to Work for Smallholder Farmers in Africa (www.N2Africa.org) tenable at the Wageningen University and Research (WUR), the Netherlands (Grant number OPP1020032). I am also grateful to acknowledge additional financial support from the International Institute of Tropical Agriculture (IITA) through the Graduate Research Internship (IITA Fellowship 114 22 031). Sincere appreciations are to my supervisors Dr. Frederick Baijukya and Prof. Patrick A. Ndakidemi for their stimulating and relentless guidance and constructive criticisms throughout this study. The acknowledgements of the help I received from them as my supervisory team are made with both pleasure and emphasis. They have been instrumental and always remained a positive factor even in the worst moments of tear shedding, sorrows, tiredness and depressions. I am profound of their unreserved cordial assistance and insistence on nothing less than excellence at every opportune time.

I am highly indebted to my Employer the Sokoine University of Agriculture (SUA) represented by its top management the Deputy Vice Chancellor Academics (Prof. Peter Gillah) and later Prof. Maulid Walad Mwatawala, and the Principal Administrate Officer I (RAC) (Ms. Josephine Lwiza). They granted me study leave and accorded their guidance during hard times I perceived this PhD study as a "*hook*" on my neck. My mentor Prof. Jerome Mrema, and Heads of Department Prof. Ernest Marwa, Dr. Nyambilila Amuri, and Dr. Hamis Juma Tindwa from the Department of Soil and Geological Sciences, SUA, are highly acknodelged for their endless contribution to my PhD life. Prof. Carol Njau, Drs. Ernest Mbega, Neema Kassim, Francis Moyo, Erasto Mlyuka, Pavithravani Venkataramana**,** Efraim Kosia, Angela Mkindi, Michael Haule, Elkana Hezron Misana and Mr. Greyson Johnson Mwasomola from the NM-AIST are also instrumentally unforgettable to my shelf life. You the NM-AIST staff had a potential contribution to ensure the scholarly of this work. Endless best wishes from Hon. Prof. Joyce Ndalichako the Minister for the Ministry of Education, Science and Technology were always a reference of comfort to me. Kind appreciation is to my fellow students Jacob Bulenga Lisuma (at NM-AIST), and Dennis Erro Tippe, Daniel Brain Akakpo, Ojo Comfort Tinuade, Ashenafi Hailu Gunnabo and Pastori Mrosso (at WUR) for their endless encouragements in the Netherlands and in Tanzania.

Finally, but not by importance, special appreciation is to my family Pulkeria Benedict Massawe (wife) and my sons Doveson and Prosper for their endurably hard time they underwent while I was away for my studies. My lovely son (Prosper), you have been a graduate Diploma to my PhD on 28th August 2018 when God brought you to the world. My sincere appreciations are to Ms. Evanesta Unambwe Mbise, Happiness Unambwe Mbise, Ms. Salma Salim Mkiramwini and Eva Thuijsman for their extra social care they accorded me during the entire period of my studies.

DEDICATION

This work is strictly dedicated to my lovely sister (late) Upendo Kisetu Nassary who passed away in July 2016 while I was attending her at the Kilimanjaro Christian Medical Centre (KCMC) during critical times of data collection for my PhD studies. I also dedicate the same work to my lovely parents Kisetu Izack Nassary (father) and Vumilia Larisho Pallangyo (mother) for their role as parents and tireless encouragements, assistance and paved the way for which I have followed and surpass.

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LIST OF ABBREVIATIONS AND SYMBOLS

AEZs	Agro-Ecological Zones
ANOVA	Analysis of Variance
ATP	Adenosine Triphosphate
BNF	Biological Nitrogen Fixation
CV	Coefficient of Variation
d.f.	Degrees of Freedom
GenSTAT	General Statistics
LER	Land Equivalent Ratio
LSD	Least Significance Difference
P	Probability
PLER	Partial Land Equivalent Ratio
r	Correlation
RCBD	Randomized Complex Block Design
S.E.D.	Standard Errors of Differences of Means
SARI	Agricultural Research Institute
SOC	Soil Organic Carbon
SSA	Sub-Saharan Africa
TSP	Triple Sulfer Phosphate
Tukey’s-HSD	Tukey’s-Honest Significance Difference

CHAPTER ONE

INTRODUCTION

1.1 Background of the Problem

Sustainable intensification of agricultural systems is important in the present and future world's food demand (Raimi *et al*., 2017; Loboguerrero *et al*., 2019). Intensification may increase food production whereas sustainability ensures a continuous supply of food (Pretty *et al*., 2011). The increase in the world's population by 2050 is projected to be around 9.1 billion (34% higher than today) and food production will need to increase by 70% (Stagnari *et al*., 2017; Loboguerrero *et al*., 2019). This projection indicates that more food is to be produced using less land while other resources including water and energy will become the limiting factors (Food and Agriculture Organization of the United Nations [FAO], 2009). There are still some promising advances in agricultural science and technology that have contributed to remarkable increases in food production and global the growth in agriculture has been 2.5–3 times over the last 50 years (FAO, 2011; Christou *et al*., 2013). Further, the methods of global food production must change to minimize the impact on the environment and support the world's capacity to produce food in the future including contribution to climate change, soil degradation, water scarcity and destruction of biodiversity (Foresight, 2011; Food Chain Evaluation Consortium, 2014). The impact of food production on the environment defines the land, methods deployed and availability of water and soil resources. There are trade-offs between environmental factors while there are no appropriate methods of ensuring environmental sustainability (FAO, 2014).

An increase in food production and availability without much impact on the environment is an important element of environmental sustainability (Foley *et al*., 2011; Pretty *et al*., 2011; Vanlauwe *et al*., 2011). The sustainable food system is composed of the environment, the people and processes by which agricultural and farmed products are produced, processed and brought to consumers without compromising the health of the ecosystems and vital cultures that provide food (FAO, 2016). Farming systems in densely populated areas are defined by environments, altitude, precipitation during the crop growing season, latitude and soil pH on one side, and biological significance to the crop species on the other (Abera *et al*., 2005; Hillocks *et al*., 2006; Funakawa *et al*., 2012; Ronner *et al*., 2018; Nassary *et al*., 2020). Keba (2018) indicated that environmental heterogeneity contributed much to the variations in crop performance and suggested a need for experimentation and testing in diverse environments in the evaluation of various crop genotypes. According to Tittonell *et al*. (2008), the potential crop growth is site-specific, determined by variety and climate but its actual yields are influenced by the interactions of local growth limiting and reducing factors.

Apart from other crops, grain legumes such as common bean (*Phaseolus vulgaris* L.), peas (*Pisum sativum* L.), pigeon pea (*Cajanus cajan* (L.) Millsp.), groundnut (*Arachis hypogaea* L.), chickpea (*Cicer arietinum* L.), soybean (*Glycine max* L.), and cowpea (*Vigna unguiculata* L.) are commonly grown by smallholder farmers worldwide (Food and Agriculture Organization Corporate Statistical Database [FAOSTAT], 2014; Venance *et al*., 2016; Nassary *et al*., 2020). Depending on the cropping systems, the average grain yields of these crops are 0.5–1.5 t ha^{-1} (Ndakidemi *et al*., 2006; Xavery *et al*., 2006; Baijukya *et al*., 2016), relative to the potential grain yield of 1.5–3.5 t ha^{-1} of high yielding improved varieties (Ronner & Giller, 2013; Baijukya *et al*., 2016; Nassary *et al*., 2020). Common bean fetches 2 to 2.5 times higher prices, on a weight basis than cereal crops like maize (*Zea mays* L.) and, therefore, is an important component crop of maize intercrop and/or rotation (Mutungamiri *et al*., 2001; Chipomho *et al*., 2015), or as an understory in banana-coffee based farming systems (Franke *et al*., 2016). Common bean improves soil fertility through the fixation of atmospheric nitrogen (N_2) in symbiosis with rhizobia (Hardarson *et al*., 1993; Graham & Vance, 2003) and decomposition of its residues (Kermah *et al*., 2018; Nassary *et al*., 2020). Under optimal conditions of common bean cultivation up to 72% of N derived from fixation has been obtained and in longer growing seasons these are up to 125 kg N ha^{-1} (Hardarson *et al*., 1993). Nevertheless, farmers are also aware of soil fertility improvement through affordable options such as improved fallow, agroforestry, crop rotation, intercropping and transfer of biomass (Mowo *et al*., 2006; Iannetta *et al*., 2013).

Maize is the most important cereal crop for food and cash in Sub-Saharan Africa (SSA), Asia and Latin America (Ranum *et al*., 2014). Maize is produced throughout the world, with the United States, China, and Brazil being the top three producing countries (Ranum *et al*., 2014). Maize accounts for 30 to 50% of low-income household expenditures and the crop contains starch (72%), protein (10%), fat (4%), and energy density of 365 Kcal/100 g (Nuss & Tanumihardjo, 2010). Of the worldwide maize consumption as food, Africa consumes most (30%) of its maize production and the highest (21%) consumption is in SSA (FAOSTAT, 2012). However, the global consumption of maize is expected to increase by 16% by 2027 as animal feed and for human consumption due to the expanding livestock sector and population growth (Organisation for Economic Co-operation Development and the Food and Agriculture Organization [OECD/FAO], 2018).

Intercropping of different species of food crops overcomes risks associated with the complete failure of one of the component crops (Vanlauwe *et al*., 2014; Nassary *et al*., 2020). The farmers' primary objective in maize and common bean intercropping is to optimize the productivity of maize while a secondary objective is to produce higher bean grain yields (Rusinamhodzi *et al*., 2012; Kermah *et al*., 2017). Intercropping aims to match efficient crop demands to the available growth resources and return from labour (Lithourgidis *et al*., 2011). The advantages derived from intercrops arise from positive interactions in facilitation and complementarity as crops in mixtures differ in requirements and acquisition of water, light, and nutrients (Hauggaard-Nielsen *et al*., 2001; Brooker *et al*., 2015). Common bean is a short duration crop (2.5–3 months), a characteristic that also permits its production during short rains (Baijukya *et al*., 2016; Nassary *et al*., 2020).

1.2 Statement of the Problem

Food insecurity is a serious problem for smallholder farmers where the production of food crops is mostly for subsistence (Vanlauwe *et al*., 2014). Intercropping of cereals and grain legumes is commonly practiced in developing countries (Lithourgidis *et al*., 2011). Crops growing in mixtures complement each other by making efficient utilization of growth resources such as light, water, and nutrients since they differ in height, canopy architecture, ability to rooting, nutrient and water requirements (Brooker *et al*., 2015). Through resource complementarities, intercrops are reported to improve food security by the production of greater yields per resource endowment (Giller, 2001; Brooker *et al*., 2015). The drawbacks of intercropping are suppression of growth and yields of a legume by the dominant cereal crop and high labour demand for field operations (Baijukya *et al*., 2016). Other challenges of intercropping include the selection of compatible crops to be cultivated together, sowing densities of the component crops, and time of introducing a legume crop in the system relative to the cereal crop (Lithourgidis *et al*., 2011).

The common practice of mixed cropping on smallholder farms where farmers consider maize as the main crop and common bean as the minor crop involves the broadcasting of common bean seed to the maize plants during sowing or at weeding (Baijukya *et al*., 2016). With this broadcasting practice, there is always no proper sowing pattern and spacing of the common bean and the total population of the crops in a mixture is never known. Literature shows that the densities of plants determine the overall productivity of the cereal and grain legume intercrops (Giller, 2001). Investing on sustainable intensification of intercrops could provide approaches that offer new techniques to better manage and monitor globally complex systems of sustainable food production on smallholder farms (Nassary *et al*., 2020).

Rotation of cereals/maize with grain legumes/common bean is another important element of sustainable intensification in highly populated areas due to a reduction in the readily available cultivated land (Pretty *et al*., 2011). However, there is limited information about the appropriate options by which these rotations may be practiced in a given cropping season (short or long rainy seasons) and the varieties of common bean (local or improved) cultivated by smallholder farmers (Baijukya *et al*., 2016; Nassary *et al*., 2020). Considering the agronomic importance of cultivating common bean including residual effects on the subsequent non-N_2 fixing crops, it is important to understand the benefits derived from different varieties of common bean on the system productivity. Apart from the continuous use of local varieties of common bean, there are still options for the inclusion of improved varieties, which are high yielding (Baijukya *et al*., 2016). The local and improved varieties of common bean can be compared for their benefits on the subsequent maize crop and the overall return to the farmer on smallholder systems. Therefore, this study focused on assessing the productivity of maize sown with the determinate (improved) and indeterminate (local) varieties of the common bean by understanding whether the monocultures of maize could be substituted by the intercrops and/or rotations with common bean and close the gap associated with low yields of these crops and food security on smallholder farms.

1.3 Rationale of the Study

Options for the intensification of agricultural systems (e.g. rotations and intercropping) where the common bean is included in a maize-based system should be designed based on the altitude (agro-ecology), cropping seasons (long and short), and varieties of common bean (local and improved) and their sowing densities. The sustainable intensification of common bean cultivation is reported to be an important part of ensuring food security to the smallholder farmers (Giller *et al*., 2013; Layek *et al*., 2018). It is also believed that investing on sustainable intensification of common bean cultivation will be a recent study that improves the foundation of knowledge on the benefits derived from rotations and intercrops of grain legumes in the tropical highlands (Yusuf *et al*., 2009; Thierfelder *et al*., 2012; Franke *et al*., 2018). The symbiotic N_2-fixation by grain legumes is dependent on the varieties/cultivars, environments/altitudes, management/cropping systems, and socio-economic factors, and/or their interactions (Chekanai *et al*., 2018; Van Vugt *et al*., 2018). The higher yields of different common bean varieties across altitudes are reported to be associated with a broader spectrum of tolerances to the environmental factors (Annichiarico, 2002). However, variability in grain yields of the beans within and across altitudes is significantly influenced by the interactions of varieties and the altitudes (Mushi, 1994; Gebeyehu & Assefa, 2003).

Intercropping and rotations with grain legumes have been indicated to sequester carbon (C), store N, and enrich the biodiversity (Peoples *et al*., 2009; Gan *et al*., 2011). Intensification of common bean is important in reducing the dependency on synthetic mineral nitrogen (N) fertilizer for the maize crop as the bean has the ability to fix atmospheric N through symbiotic association with the rhizobia (Giller, 2001; Nieder & Benbi, 2008; Giller *et al*., 2013). For sustainable intensification, it is important to understand the yields and land utilization benefits to be derived from common bean cultivated as part of an intercrop with maize based on the altitudes and the varieties of the bean during the main cropping seasons. In addition, continuous intercropping of common bean and maize in the highlands experiencing bimodal rains (short and long seasons) can offer new insights on the options towards the assurance of food security (Kermah *et al*., 2017). Therefore, it is important to evaluate the yields and land utilization benefits of intercropping different varieties of common bean with maize continuously in the same altitude where bimodal rains are experienced. Compared with the residues of cereals, the residues of grain legumes are rich in N with a narrow C/N ratio (Giller, 2001; Franke *et al*., 2018). Understanding the yields of maize and common bean cultivated in rotations and/or any one of these crops cultivated in rotations with the intercrops of both can be an important element of looking more options for sustainable intensification.

Smallholder farmers in most parts of the northern highlands of Tanzania consider common bean as a complement crop to a prioritized food maize crop (Ndakidemi *et al*., 2006). Farmers are interested in higher yields of maize than common bean but the cultivation is usually associated with low inputs (seeds and fertilizers) endowment. Despite the fact that farmers in Tanzania practice rotational cropping and mixed cropping of common bean and maize across altitudes, the practices are locally conducted, probably, for their own good reasons including unpredictable factors such as higher prices of seeds and fertilizers in the local market, rainfall, and outbreak of diseases and insect pests (Baijukya *et al*., 2016). Rotational cropping, for example, involves the cultivation of maize during the long rainy season and the common bean during the short rainy season but in small portions of the arable land. Further, the cultivation of common bean and maize in association involves the broadcasting of the bean seed during sowing of maize seed or during weeding in the maize plants where the bean seed is incorporated into the soil.

The practice of broadcasting bean seed does not provide a clear pattern and/or the sowing spacing between plants growing together, hence a mixed system rather than a commonly known intercropping. In a mixed cropping technique, two or more crop species are cultivated simultaneously during a cropping season in the same piece of land, and this aims at decreasing the risk of complete crop failure, due to unfavourable weather conditions (Li *et al*., 2019). The system also restores soil fertility, as the products and remains of one plant facilitate the growth of the other and vice versa. The crops sown in mixtures do not follow any planting pattern and hence the population of the mixture cannot be easily estimated (Giller, 2001; Malezieux *et al*., 2009; Li *et al*., 2019). On the other hand, intercropping like mixed cropping involves sowing of two or more crops at the same time in a certain piece of land, but in a definite row pattern, to increase the productivity of the crops (Lithourgidis *et al*., 2011; Brooker *et al*., 2015). Intercropping ensures optimum utilization of the plant growth resources such as nutrients, light, and water as well as space where the crops grow (Brooker *et al*., 2015).

Further, although farmers in the northern highlands of Tanzania strive to use the improved maize seed, they usually use the local varieties of common bean that are low yielding (Baijukya *et al*., 2016). The use of improved maize seed also requires a high investment in other inputs like N-containing fertilizers, which are not affordable to the smallholder farmers (Giller, 2001). Farming and pastoralist communities dominate the lower altitude of the northern highlands of Tanzania (Nassary *et al*., 2020). Pastoralists do not integrate crop production in their sources of food despite the increasing impact of climate change on the aspect of food security. The co-existence of the two communities in the lower altitude increases conflicts as livestock are grazed to the food crops in fields. Therefore, this study was designed to strengthen the awareness and the importance of intensification of agricultural systems for food security in the entire community in the lower altitude. The farmers' knowledge of the dependency of rains and the use of local varieties was studied along with the improved varieties of common bean and maize. Other important factors assessed include sowing of maize and common bean in rotations and/or intercropping, seasons, and altitudes as they offer new options that can increase food security as an important output of sustainable intensification.

Literature synthesis shows that soil pH influences the physical, chemical, and biological properties and processes that affect the growth and overall yields of the plant (Dhillon *et al*., 2018; Neina, 2019; Meena *et al*., 2020). Cropping systems and the types of crop species in the field are responsible in the changes in soil pH due to the agro-inputs used (such as synthetic fertilizers, pesticides). The production of phytosiderophores (organic substances such as nicotinamine, mugeniec acid, and avenic acid) by the graminaceous species (e.g. maize plant) under iron (Fe) and zinc (Zn) deficiency increase their uptake by plants (Dotaniya *et al*., 2013; Brooker *et al*., 2015). Oxidation of Fe^{2+} to Fe^{3+} as well as the release of a proton (H^+) from these organic acids increases soil acidity by the reduction of soil pH. The dynamics of soil pH control transformations of soil organic carbon (SOC), total nitrogen (N), and available phosphorus (P) in tropical cropping systems (Giller, 2001; Neina, 2019; Purwanto & Alam, 2020). Therefore, given these facts plus the costs related to total routine soil characterization, it was important to characterize the soils for the soil pH, SOC, total N, and available P at the end of field experiment, which involved both rotations and/or intercropping in order to establish the significances of these cropping systems to the soil fertility and health.

Apart from assessing the performance of crops as a measure of the productivity of the intercrops, another useful indicator is the Land Equivalent Ratio (LER), which measures the benefits derived from intercropping of crops in using land resources compared with their sole cropping (Brooker *et al*., 2015; Yu *et al*., 2016; Jalilian *et al*., 2017). The LER of a multispecies system is the area needed to produce the same outputs as one unit of land with a pattern of sole cropping (Yu *et al*., 2016). When the LER is equal to 1.0, the crop species cultivated as intercrops compete equally on the same growth-limiting resources (Jalilian *et al*., 2017). The LER greater than 1.0 shows an advantage of the crops in an intercrop or demonstrates an interspecific competition lower than interspecific facilitation and the crop species in intercrops result in greater land-use efficiency. Mutual antagonism of the crop species in the intercrops is detected when the LER is less than 1.0 hence no intercropping advantage indicating that interspecific facilitation is lower than the interspecific competition (Wahla *et al*., 2009). Therefore, apart from crop performance and soil fertility indices, the LER was determined in order to assess the land use benefits associated with the intercrops of maize and the improved and/or local varieties of common bean in the northern highlands of Tanzania.

1.4 Research Objectives

1.4.1 General objective

To intensify common bean cultivation on maize-based cropping systems through rotations and/or intercropping to improve food security on smallholder farms in the northern highlands of Tanzania.

1.4.2 Specific Objectives

(i) To assess common bean performance and land utilization benefits derived from intercropping with maize during long rainy seasons across three altitudes in the northern highlands of Tanzania.

(ii) To assess common bean and maize performance, soil fertility, and land utilization benefits derived from the intercrops of these crops evaluated over the continuous long and short rainy seasons in the middle altitude of the northern highlands of Tanzania.

(iii) To assess common bean and maize performance and soil fertility benefits of rotations of these crops over different cropping seasons (long and short) in the middle altitude of the northern highlands of Tanzania.

1.5 Research Questions

(i) What is the performance of local and improved varieties of the common bean when cultivated in intercrop with the maize crop across three altitudes over long rainy seasons?

(ii) What are the land use benefits of local and improved varieties of the common bean when cultivated in intercrop with the maize crop across three altitudes over long rainy seasons?

(iii) What is the performance of local and improved varieties of the common bean when cultivated in intercrop with the maize crop in the middle altitude?

(iv) What is the performance of a maize crop when cultivated in intercrop with local and improved varieties of the common bean in the middle altitude?

(v) What are the land use benefits of local and improved varieties of the common bean when cultivated in intercrop with the maize crop in the middle altitude?

(vi) What is the status of soil fertility after five cropping seasons of intercropping maize and common bean crops in the middle altitude?

(vii) What is the performance of local and improved varieties of the common bean when cultivated in rotations with the maize crop in the middle altitude?

(viii) What is the performance of local and improved varieties of the common bean when cultivated in rotations with their intercrops with the maize crop in the middle altitude?

(ix) What is the performance of a maize crop when cultivated in rotations with local and/or improved varieties of the common bean in the middle altitude?

(x) What is the performance of a maize crop when cultivated in rotation with its intercrop with the local and/or improved varieties of the common bean in the middle altitude?

(xi) What is the status of soil fertility after cropping seasons of rotational options of a maize crop and varieties of the common bean in the middle altitude?

1.6 Significance of the Study

This study was significant since it aimed at improving food security and diversifying the sources of income on smallholder farms through rotations and/or intercropping of common bean with maize as the affordable practices in Tanzania. Common bean is the most important source of protein and its grains have a market value higher than that of maize grains. In addition, common bean improves soil health through N_2-fixation and enhancement of nutrients other than N for the companion or subsequent non-N_2-fixing maize crop. The residues of common bean and maize being important fodder to livestock and can be sold to generate income, those of common bean can also improve soil fertility by releasing nutrient N upon decomposition. The new information/facts found in this study, which were not there in the literature, depended on the cropping systems of maize and common bean in the northern highlands of Tanzania. Firstly, there were no intercropping experiments where two varieties of common bean (improved and local varieties) were cultivated in intercrops with maize over long periods thereby taping both long and short rainy seasons on smallholder farms especially in the tropical highlands. Secondly, no experiments where the intercrops of maize and common bean (improved and/or local varieties) have been cultivated during long rainy season and rotated with the maize cultivated in the short rainy season. Thirdly, there has not been any study before that compared the global market benefits (value) in weight basis reflected in the seeds of the improved bean variety (e.g. the *Lyamungu 90*) relative to the local bean variety (e.g. the *Mkanamna*) under ordinary cultivation settings of the smallholder farmers in Tanzania or elsewhere in tropics.

This study was conducted at different altitudes (lower, middle, higher), different cropping seasons (2015 to 2017) including long and short rainy seasons, and two bean varieties (improved and local). Therefore, the analysis of soils in the experimental fields was necessary to evaluate the impact of these experiments on the physical and chemical properties of the soils. However, a complete routine characterization of the soils was not possible due to the limitations of time and funds. This limitation prompted routine soil analysis to be done only in soils from intercropping and rotational experiments collected in the middle altitude where the tests involved the soil pH, SOC, total N, and available P based on the information found in the literature search. The present study has specifically:

(i) Generated results on the significance of the altitudes, cropping seasons, and cropping systems on the intensification of common bean cultivation in the northern highlands of Tanzania.

(ii) Indicated that the cultivation of common bean in intercrop with maize is more productive than their monocultures in terms of yields and land use.

(iii) Shown that the intensification of common bean in the northern highlands of Tanzania is independent of the bean varieties.

(iv) Indicated that in situations where the intercrops of maize and common bean are rotated with one of these crops is more productive than a traditionally known rotation of one crop with another.

(v) Indicated that the adoption of improved bean variety *Lyamungu 90* is worth noting for marketing due to higher grain weight apart from volume against the local bean variety *Mkanamna*.

(vi) Resulted in the production of four manuscripts published in reputable journals.

(vii) Contributed to the production of this thesis for possible Award of a PhD degree.

1.7 Delineation of the Study

This study focused on assessing the productivity of maize sown with the determinate (improved) and indeterminate (local) varieties of the common bean by understanding whether the monocultures of maize could be substituted by the intercrops and/or rotations with common bean and close the gap associated with low yields of these crops and food security on smallholder farms. This study was conducted at different altitudes (lower, middle, higher), different cropping seasons (2015 to 2017) including long and short rainy seasons, and two bean varieties (improved and local). Therefore, the analysis of soils in the experimental fields was necessary to evaluate the impact of these experiments on the physical and chemical properties of the soils. However, a complete routine characterization of the soils was not possible due to the limitations of time and funds. This limitation prompted routine soil analysis to be done only in soils from intercropping and rotational experiments collected in the middle altitude where the tests involved the soil pH, SOC, total N, and available P based on the information found in the literature search.

CHAPTER TWO

LITERATURE REVIEW

2.1 Conceptual Framework

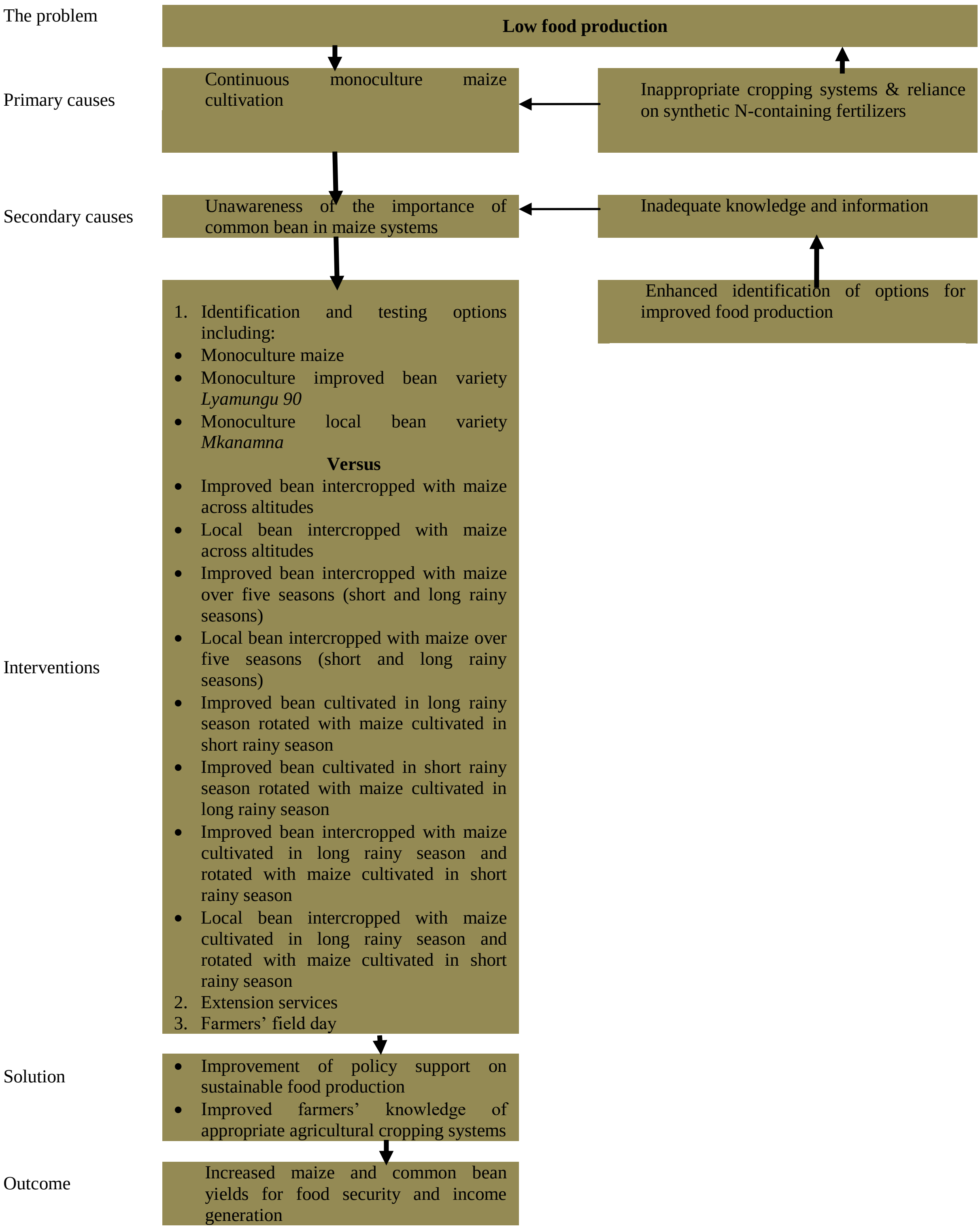

Figure 1: Conceptual Framework

2.2 Agricultural Production of Food Crops

This chapter addresses important dimensions for the sustainable intensification of grain legumes to optimize food security on smallholder farms. Agriculture produces food and generates income for the smallholders worldwide including Sub-Saharan Africa (SSA) and it employs over 70% of the labour force (Pretty *et al*., 2011). Most of the food production by smallholder farmers is for subsistence attributed to the small land owned and cultivated which vary from less than 1 to 3 ha (Sarris *et al*., 2006; Vanlauwe *et al*., 2014). The main food crops produced by smallholder farmers are maize (*Zea mays* L.), rice (*Oryza sativa* L.), wheat (*Triticum aestivum* L.), sorghum (*Sorghum bicolor* L.), finger millet (*Eleusine coracana* L.), cassava (*Manihot esculenta* L.), grain legumes, potatoes (*Solanum tuberosum sp Ipomoea batatas* and *Solanum tuberosum*), and bananas (*Musa sp*) comprising over 80% of the total area cultivated (Sarris *et al*., 2006).

Production of food crops on smallholder farms is always below potentials due to the effects of altitudes, crop management options, and cultivar/variety of the crops cultivated (Lyimo *et al*., 2014; Nyaligwa *et al*., 2017). Variations in climatic conditions and the major soil types are large and partly due to topography (Pretty, 2008; Vanlauwe *et al*., 2017). Management options including poor farming systems are often due to lack of access to resources such as little use of inorganic fertilizers, and continuous cultivation of cereals crops with the commonly practiced rotations and/or intercrops (Pretty *et al*., 2011). Lack of nutrients means that farmers cannot get the yield benefits that better varieties can provide (Tittonell & Giller, 2013). There are other constraints related to poor access to market information and low prices of crops in local markets, outbreaks of diseases and pests, both insects and invasive weeds (Carter & Zimmerman, 2000). Another important constraint to crop production in smallholder farms is low purchasing power of smallholder farmers for fertilizers to meet nutrients demand of the crop and this is associated with high prices, availability and accessibility of fertilizers (Giller, 2001).

Grain legumes are produced by smallholder farmers as food and provide an important source of protein (38%) and 14% of daily calorific requirements, vitamins, nutrients including iron (Fe), zinc (Zn), phosphorus (P), calcium (Ca), copper (Cu), potassium (K), and magnesium (Mg) and complex carbohydrates to both human beings and livestock (Vance *et al*., 2002; Xavery *et al*., 2006; Considine *et al*., 2017; Stagnari *et al*., 2017). In SSA, for instance, grain legumes are produced by over 75% of rural farming households mainly for subsistence and little surplus is sold to generate cash income (Considine *et al*., 2017). Improvement of soil fertility through biological symbiosis of grain legumes with rhizobium under favourable conditions and upon incorporation of residues into soils has been widely reported (Giller *et al*., 1991; Leidi & Rodriguez-Navarro, 2000). Despite their importance, yields of these legumes have remained below their potential of 3.5 t ha^{-1}(Smithson *et al*., 1993; Giller *et al*., 1994; Hillocks *et al*., 2006).

The population growth worldwide is estimated to reach around 9 billion by 2050 and SSA leads in this increase (Stagnari *et al*., 2017; Loboguerrero *et al*., 2019). Global food demand is also expected to increase concomitantly (Loboguerrero *et al*., 2019) thus, a need for intensification of agricultural systems and its sustainability (Raimi *et al*., 2017). Intensification will ensure increase in food production on smallholder farmers by exploiting small pieces of lands owned (Pretty, 2008; Pretty *et al*., 2011). Pretty *et al*. (2011) and Pretty and rucha (2014) defined agricultural intensification such as: (a) Ptimizing yields per land area, (b) Intensify plant population (i.e. more crops at once) per land or other inputs in a season (water), and (c) Increasing value for land with respect to crops cultivated. However, intensification of agricultural systems cannot necessarily ensure food security as the practice needs to be considered under a sustainable basis (Pretty *et al*., 2011; Bedoussac *et al*., 2015; Stagnari *et al*., 2017). The definition of sustainable intensification is given by many studies as a practice, which involves increasing land productivity (Pretty, 2008; Giller *et al*., 2011; Pretty *et al*., 2011). However, sustainable intensification of agricultural systems should not confront the role of land and other land use types (Godfray *et al*., 2010; Vanlauwe *et al*., 2014).

Sustainable intensification of grain legumes as an option to food security on smallholder farms may be invested in the highly populated regions, which are dominated by small owned lands for cultivation (Devendra, 2012; Rusinamhodzi *et al*., 2012; Ronner & Giller, 2013; Bybee-Finley & Ryan, 2018; Dong *et al*., 2018). Grain legumes are often intercropped with bananas, coffee (*Coffea sp*), sorghum and maize. These legumes are less grown as sole crops during short rainy seasons in regions, which experience bimodal rainfall pattern (Giller *et al*., 1998; Hillocks *et al*., 2006; Ndakidemi *et al*., 2006; Ronner & Giller, 2013). In addition, the inclusion of these grain legumes during short rainy season adopts rotational cropping with cereal crops such as maize (*Zea mays* L.), grown often during the long rainy season. The importance of maize and grain legumes such as common bean (*Phaseolus vulgaris* L.) as food and cash crops on smallholder farms cannot be compromised (Ndakidemi *et al*., 2006) hence a need for sustainable intensification for food security and scaling-up to agri-business entrepreneurship (Hillocks *et al*., 2006; Venance *et al*., 2016). Sustainable intensification in grain legumes will improve systems productivity in the farming settings and ensure food base for the households (Pretty, 2008; Pretty *et al*., 2011; Raimi *et al*., 2017). Therefore, the objective of this review was to identify options for sustainable food production through intensification of grain legumes producing systems including intercropping and/or rotations with food cereal crops. To do that the literature on various annual food crops commonly involved in intercrops and/or as part of a rotation on smallholder farms was reviewed. The review also examined principles underlying socio-economic and environmental importance, and the mechanisms involved to achieve the benefits from these practices mostly undertaken by smallholder farmers in different parts of the world. The topic on the role of grain legumes intensification in improving food security under changing climate is included. In addition, concerns on gender equity in the production of various crops in these farming systems were raised.

2.3 Intercropping as an Element of Sustainable Agricultural Intensification

Intercropping involves growing of two or more crops simultaneously during the same cropping season but overall profitability is derived from sustainable intensification (Brooker *et al*., 2015). Intercropping is considered sustainable only when it enhances food production from the component crops and does not have large negative impact to the natural resources in the environment during field operations and after harvesting of both crops (Lithourgidis *et al*., 2011; Micheni *et al*., 2015). Therefore, there is a need of understanding the ways by which food cereal crops and various varieties/cultivars of grain legumes can interact and result into additional benefits on diverse farming systems of smallholder farmers.

2.3.1 Benefits Derived from Intercropping Cereals and Grain Legumes

(i) Food Productivity and Associated Benefits of Intercrops

Intercropping cereals with grain legumes has often recorded overall systems advantage compared with sole cropping of each crop (Zhang *et al*., 2015). Intercrops are reported to give greater combined yields and monetary returns than their corresponding sole crops (Seran & Brintha, 2010). Smallholder farmers practise cereal-legume intercropping in order to mitigate risks of complete crop failure in monocropping (Kermah *et al*., 2017). Sun *et al*. (2014) indicated that maize cultivated in intercrop with alfalfa optimized their niche complementarity through efficient use of growth resources. Intercropping maize with grain legumes is more advantageous over their respective sole crops when are grown on poor soils for both absolute yield and economic return (Rusinamhodzi *et al*., 2012; Midega *et al*., 2014; Kermah *et al*., 2017).

The benefits derived from intercrops can be evaluated depending on the purpose and in most cases on relative, absolute, monetary and nutritional units of measurements (Willey, 1985). The overall intercropping system productivity was shown earlier by Dahmardeh *et al*. (2010) who found greater land equivalent ratio (LER) in all intercropping systems with modified planting densities of component crops (Fig. 2). The values above line X of Fig. 2 indicate that crop *a* is more competitive than crop *b* when were sown in intercrops. Below line X the crop *b* has higher competitive advantage over crop *a* when are intercropped. At CRa is 2 means that crop *a* is twice as much as competitive as crop *b*. Likewise, when the CRb is 2 means that crop *b* has twice competitive advantage over crop *a*. In addition, Zhang *et al*. (2015) found that intercrops of maize and soybean gave higher LER (1.3), total N fixed (258 kg ha^{-1}), and economic return of 3408 USD per ha. The partial LERs of the component crops in maize-bean intercrop depicted more efficiently used land than sole cropping and attributed this observation to the better utilization of growth resources. Therefore, understanding of food and economic benefits derived from improved and local varieties of crops cultivated in intercrops with maize would increase awareness to appropriate system combination of these crops and optimize food productivity in smallholder farms.

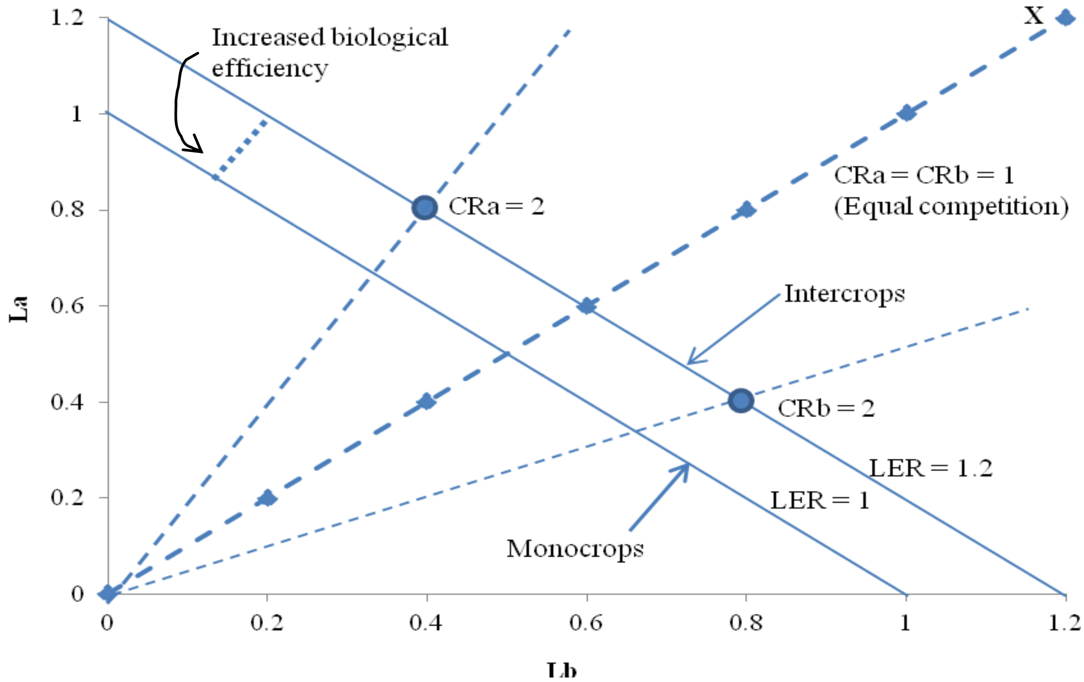

Figure 2: Competitive ratios of two different crops when sown in intercrops compared with their sole crops. Key: La and Lb are land equivalent ratios of crops *a* and *b*, respectively; LER is the land equivalent ratio; CRa and CRb are the competitive ratios of crops *a* and *b*, respectively (Willey, 1985)

(ii) Resource Facilitation, Complementarity, Sharing and Utilization in Intercrops

Intercropping of cereal-legume improves utilization of plant growth resources (Willey, 1979; Jensen, 1996). Intercropping optimizes crop productivity in a unit land area where the crops are grown depending on the seasons of the year, resource inputs, and appropriateness of the planting density of each crop species. Willey (1979) and Chowdhury and Rosario (1994) indicated that higher uptake of nutrients and utilization of other growth factors by the intercropped component crops are the primary benefits gained from intercropping. Temporal and spatial arrangements of intercrops can be chosen to enhance the complementarity of resources such as space, light, water and nutrients. The spatial arrangement needs to be carefully selected to improve radiation interception through maximization of ground cover (Li *et al*., 2014).

Enhanced productivity of intercrops compared with their sole crops is shown to improve utilization of limited resources through complementarity and facilitation (Hinsinger, 2001; Tilman *et al*., 2001; Li *et al*., 2014). According to Hinsinger *et al*. (2011) and Li *et al*. (2014), there is always a decrease in interspecific competition between intercrops thereby increasing their complementarities for the growth resources. This is attributed to differences in utilization of these resources in space, time, and forms; for example, the cereals in association with legumes complement each other for N use. Cereals and legumes compete for the soil N but the legume can also obtain additional N from N_2–fixation. Niche complementarity between intercrops is determined by root (deep and shallow) and canopy (tall and short) architecture, which allow exploitation of light and soil resources (Hinsinger, 2001; Hauggaard-Nielsen & Jensen, 2005; Li *et al*., 2014).

Productivity of intercrops is achieved with less competition within species than competition between contrasting species for the limited resources (Zhang *et al*., 2015). The competition between cereals and legumes enhances atmospheric N_2 fixation by a legume in symbiosis with rhizobium (Corre-Hellou *et al*., 2006). Inter-specific competition causes complementarity for N in an intercrop where N-fixing legume is included (Brooker *et al*., 2015; Zhang *et al*., 2015). In intercrops of maize and common bean there is an increase in mycorrhizal colonization as well as higher shoot N concentration in the maize (Dawo *et al*., 2008; Brooker *et al*., 2015). According to Connolly *et al*. (2001) and Latati *et al*. (2016), there is positive interaction in cereal-legume intercrops although the resulted yield increase in a cereal crop was due to other non-N enhancing factors. The facilitation for resources between component intercrops has also been realized in situations where the cereal crop improves availability of Fe for the legume and the later enhances N and P uptake by the former (Zhang & Li, 2003; Li *et al*., 2016).

Facilitation (Fig. 3; Table 2) is the positive interaction between intercrops and it is well explained by situations where growth and survival of intercrops are interdependent (Brooker *et al*., 2015). The facilitation of P acquisition for both component crops when one is P-mobilizing and another is non-P-mobilizing. The P-mobilizing species may mobilize sparingly soluble inorganic P in soil through carboxylates or protons or organic P by acid phosphatises enzymes. These substances hydrolyze soil organic P into soluble inorganic P, which may be shared by both plant species. There is also facilitation of acquisition of minerals Fe and Zn by a dicotyledonous (e.g. common bean) or non-graminaceous monocotyledonous. In the non-Fe-/or Zn- mobilizing plant species and in graminaceous monocotyledonous (e.g. maize) the Fe and Zn acquisition is facilitated by the Fe-/Zn- mobilizing species (Brooker *et al*., 2015). Phytoavailability and acquisition of micronutrients such as Zn, Fe, and Cu on alkaline or calcareous soils is a good example of a facilitative interaction. Plants such as maize and beans release acids and enzymes (phosphatases) that enhance availability of P in the soil while a legume bean also facilitates N availability through N_2-fixation (Dotaniya *et al*., 2013; Brooker *et al*., 2015). Aluminium (Al) and manganese (Mn) associated toxicities to plants are reduced through root secretions of proton in the rhizosphere (Ryan *et al*., 2011). On the other hand, plants adapted to soils higher in pH (mildly alkaline) such as maize increase the availability of P and possibly of Fe, Zn, Mn and Cu through their root secretions (Zhang *et al*., 2010).

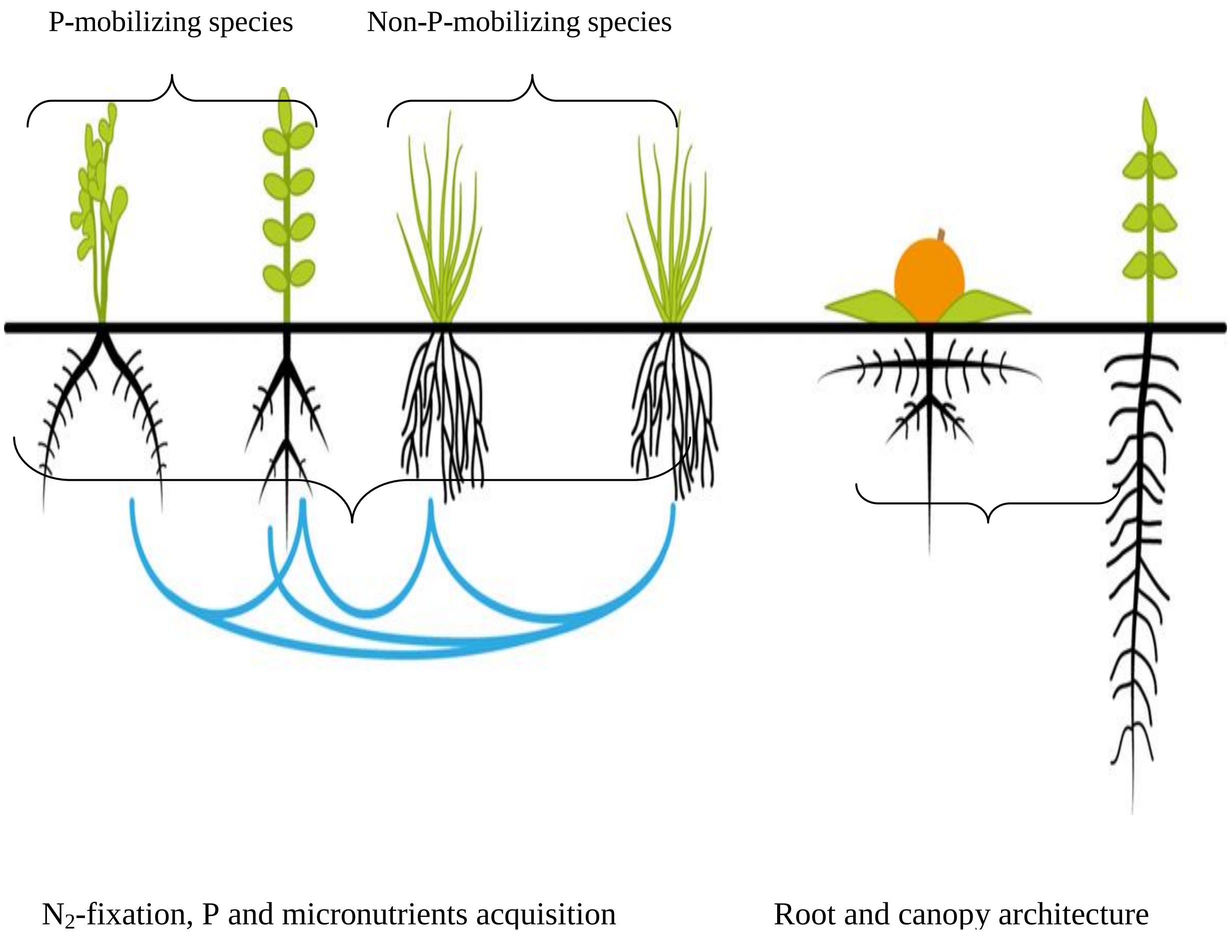

Figure 3: Facilitation of growth resources, sharing and niche complementarity enable polyculture systems to yield more than their corresponding monocultures (Brooker *et al*., 2015)

Table 1: Acquisition, sharing and utilization of growth resources (space, light, water and nutrients) between component crops in intercrops

Character	Contribution of intercrops	References
Resource Facilitation	1. Protection against mineral toxicities in saline, sodic or metalliferous soils 2. Attraction of beneficial organisms such as natural enemies and pollinators 3. Deterrence of pests and pathogens 4. Suppression of weeds	Li *et al*. (2014) and Brooker *et al*. (2015)
Benefits	Nitrogen UE; Phosphorus UE; Micronutrients UE	
Resource Sharing	Mycorrhizal fungi connections 1. Leaf litter 2. Root turnover	Babikova *et al*. (2013)
Benefits	1. Water (WUE) 2. Carbon (RUE) 3. Minerals (MUE)	
Complementarity between plant species	Traits: 1. Root architecture 2. Canopy architecture	
Benefits	Root architecture: 1. Humidity (WUE) 2. Temperature (WUE) 3. Light harvesting (LUE) 4. Weed competition (RUE)	
	Canopy architecture: 1. Hydraulic lift (WUE) 2. Minerals acquisition (MUE) 4. Reduced leaching (WUE & MUE)	

UE = use efficiency

Phytosiderophores, the anti-binding agents such as nicotinamine, mugineic acids (MAs) and avenic acid (Dotaniya *et al*., 2013) dissolve micronutrients Mn, Zn, Cu, and Fe, in soils and enhance their solubility for crop utilization (Zhang *et al*., 2010). According to Li *et al*. (2014), the Fe^{3+} phytosiderophore deoxymugineic acid released by maize or another cereal in intercrop is mostly absorbed directly by dicotyledonous crops. Sharing of the resources between component crops in intercrops is also highly documented (Brooker *et al*., 2015; Li *et al*., 2016). Therefore, there is a need of evaluating interactions between species of crops cultivated in intercrops as different crop species and/or varieties/cultivars may have different properties, which may influence their coexistence.

(iii) Control of Insects and Diseases by Intercrops

Crops in mixtures may have a small niche for insect pests that are specific to certain plant species and therefore, might not proliferate (Appendix 1). Foliage beetle incidence is significantly reduced by 15% in mixed bean varieties and/or in intercrops with other crops compared with when each bean variety is sown alone (Wortmann *et al*., 1998; Hillocks *et al*., 2006; Obanyi *et al*., 2017). Abdullah and Fouad (2016) found that the population of the aphids decreased significantly in faba bean + fenugreek intercrop than faba bean + onion or sole faba bean crop.

The reduced pest abundance in mixed cropping systems compared with monocrops has been attributed to efficacy and abundance of natural enemies and in differences in food or resource concentration that limits the insect pests to locate the host plants (Ogenga-Latigo *et al*., 1992). Mulumba *et al*. (2012) found that the damages caused by insect pest and disease and their incidence on crops decreased with higher levels of diversity in production systems in four contrasting agro-ecologies in Uganda. According to Ssekandi *et al*. (2016), damage of resistant varieties of common bean caused by bean fly in intercrops was reduced using different cropping patterns compared with when the same varieties were sown as sole crops. Intercropping enhances the abundance of predators and parasites of pests and diseases as the modified environments can delay spread of pathogens and the introduction of diseases (Seran & Brintha, 2010). Understanding the dynamics of insect pests and diseases of common bean and maize when grown in intercrops in the field is crucial for prevention and control by smallholder farmers. Evaluation of the interactions between contrasting varieties of common bean and maize intercrops and their effects on occurrence, prevalence, and severity of these reducing factors on crop productivity is also important in the farmers' field settings.

In phenomenological studies comparing disease in monocultures and intercrops, primarily due to foliar fungi, intercropping reduce diseases. The important sources of these diseases and the various studies involved as references are presented in Appendix 2. According to Boudreau (2013), the mechanisms by which intercrops affect disease dynamics include alteration of wind, rain and vector dispersal; modification of microclimate, especially temperature and moisture; changes in host morphology and physiology; and direct pathogen inhibition. Chen *et al*. (2007) reported a 26 to 49% reduction in wheat powdery mildew when wheat was sown in association with faba bean. The rate of disease progress and delayed epidemic onset was observed in common bacterial blight of bean caused by *Xanthomonas campestris* pv phaseoli in several additive patterns of maize and sorghum intercrops with beans (Fininsa, 1996).

Intercropping of cereals and legumes are reported to suppress competition from weeds. Kwiecinska-Poppe *et al*. (2009) found that many broadleaf weeds were suppressed by the intercrops and their biomass was reduced. Previous studies have revealed that intercrops compete with weeds for the light capture, space, water and nutrients (Wanic *et al*., 2005), and given good canopy created by intensified cropping systems sprouting and the establishment of weeds are suppressed.

Allelopathic compounds released by intercrops interfere with weeds occurrence and establishment (Ndakidemi & Dakora, 2003; Kwiecinska-Poppe *et al*., 2009; Makoi & Ndakidemi, 2012; Shahzad *et al*., 2016a, b). Maize-bean intercrops have been reported to reduce weed biomass by 50-66% when bean population was varied (Seran & Brintha, 2010). A study that evaluates allelochemicals from contrasting species of crops cultivated in intercrops is required since different crop species may release different allelochemicals with allelopathic properties useful in the natural control of associated weed species to one or more crops. It is important to examine how different varieties of grain legumes when cultivated in intercrops with cereals can be helpful in the suppression of weeds in order to avoid costs that would be incurred from chemicals and the likely negative environmental and health impacts of these chemicals.

(v) Soil Erosion Control by Intercrops

Soil erosion is caused by water and wind, which degrades land and its productivity potential as physical and chemical characteristics are negatively affected (Dregne, 2002). Soil erosion is determined by various factors but important ones include amount of rainfall, erodibility of the soil, topography of the area, cropping systems and the existing land conservation measures (Adekalu *et al*., 2006). The measures that control or reduce soil erosion are helpful in sustaining soil fertility and its overall productivity. Canopies of plants for the crops sown in intercrops prevent the action of raindrops from hitting and destructing structure of the bare soil thereby checking for surface runoff, rapid underground seepage, development of rills and gullies on land (Adekalu *et al*., 2006). Dense vegetation covers and/or use of green manure in intercrops prevent or reduced impact of rain drop to the soil surface, reduce surface runoff and prevent sweeping of detached soil particles (Dogliotti *et al*., 2005). Sowing of maize + cowpea (1:1), intercrop reduced surface runoff as well as loses of surface soil compared with sowing maize alone (Sharma *et al*., 2017). This is attributed to the good ground cover created by the overlapping canopies of both crops in the intercrop.

Intercropping taller plants such as maize and shorter grain legumes like the common bean, the taller plants act as a wind barrier for the shorter crops, which both improve the ability of the soil to resist erosion by wind or runoff (Reddy & Reddi, 2007). It is, therefore, important to study how crops differing in species and/or in varieties when are cultivated in intercrops would prevent impact of soil erosion on land degradation and maintain suitability of the soil for sustainable crop production.

2.3.2 Disadvantages of Intercropping

The component crops in intercropping may produce less total individual yield compared with their sole crops due to incompatibility and/or high interspecific competition and lack of niche complementarity between them (Brooker *et al*., 2015). There is high labour demand for field operations during sowing, weeding, spraying and harvesting, since mechanization is not possible in intercrops. For instance, in most cases sowing of crops in association the main crop will not reach as high yield as in a monoculture due to competition among component plants for light, soil nutrients and water (Willey, 1979). Reduction in yield may be economically significant if the main crop has a high market value than its associate crop. The canopy cover of intercrops may result in a microclimate with a higher relative humidity conducive to disease outbreak, especially of fungal pathogens, which however, happens within the same cropping season when the plants are in the field (Li *et al*., 2014). The selection of the appropriate crop species to be included in the intercrops and the time of sowing one crop relative to the other or simultaneously is also a big challenge in intercropping. Therefore, it is important to design intercrops to avoid these potential disadvantages.

2.4 Crop Rotation as an Element of Agricultural Intensification

Crop rotation involves a practice of cultivating two or more crop species in the same piece of land but after one has been harvested i.e. in sequence or a definite sequence of crops grown in successive cropping seasons. The sequence of rotating the crops in the same piece of land with differing cropping seasons is repetitive. The practice unveils its profitability by improving the productivity of the subsequent crop through improving soil fertility, minimization of diseases and pests. The study by Yusuf *et al*. (2009) indicates that crop rotation usually performs better than both monoculture and intercropping. Decomposition of plant residues in cultivated fields is also an important source of soil N used by plants, with the exception of those having the ability to fix atmospheric N_2. Cereal yield decline under intensive continuous cultivation with little or no use of inorganic N-containing fertilizers has been attributed to soils depleted of fertility (Papastylianou, 2004). The productivity of cereal crops on such soils can be improved sustainably by including it as part of a rotation with N_2-fixing legumes (Gathumbi *et al*., 2002).

The benefits derived from cereals and legumes cultivated in rotations as well as the associated trade-offs from these practices are important to be examined, understood, and established.

2.4.1 Crop Rotation Improves Soil Fertility

Inclusion of grain legumes on rotational cropping has been benefiting subsequent cereal crops. The benefits derived from crop rotation have been due to both 'N-effects' and 'non-N-effects', also termed as 'other rotational effects' (Franke *et al*., 2018; Kermah *et al*., 2018). According to Franke *et al*. (2018), 'N-effects' explain the improvement in N nutrition for the subsequent non-legume crop as well as reduced N fertilizer requirements as it is facilitated by the legumes included in rotation. The N balance of a legume crop in the field becomes close to zero or even negative in situations where most of the fixed N_2 is removed at crop harvest, escalating availability of more N for the subsequent crop (Chen *et al*., 2014). The N-effects depend on the initial amount of N-fertilizer applied to the subsequent crop in soils with low N (Giller, 2001). On the other hand, the 'non-N-effects' of legumes refers to the effects of biotic and abiotic factors determining crop growth and development. The biotic factors include the occurrence of insect pests, weeds and diseases. In addition, the abiotic factors include changes in soil moisture as well as plant nutrients other than N, changes in soil pH, or changes in soil organic matter and soil structure (Chan & Heenan, 1996; Rusinamhodzi *et al*., 2012; Shahzad *et al*., 2016c; Franke *et al*., 2018). The positive effects realized from rotations of legumes on the productivity of subsequent cereal have been attributed to the additional residual N from BNF and high decomposition of legumes residues due to lower C/N ratio (Sanginga *et al*., 2001). On the other hand, P and K distribution to the soil surface for easy plant uptake from beyond the root zone is one of the advantages of including deep-rooted cover crops in rotations (Marschner, 1990). It is important to know the ways sustainability of soil productivity optimizes crop performance as an influence of rotational cultivations of cereals with grain legumes.

2.4.2 Crop Rotation Disrupts Disease Cycle and Suppresses Weeds

Manipulation of cropping systems improves weed control options and requires a better understanding of the spatial and temporal dynamics of weeds and their likely seed banks (Bastiaans *et al*., 2008; Belde *et al*., 2008). According to Bastiaans *et al*. (2008), applicability, reliability, acceptability, efficacy and the adoption of most non-chemical strategies of controlling weeds are dependent on combinations of various measures resulting in systems complexity. Rotational cropping systems of various crops where legumes are included negatively affect weed population, biomass, seed production, and seed bank. Crop rotations altered seed bank density and species composition more in annual grass weeds than in broadleaf weeds (Koochecki *et al*., 2009). According to Koochecki *et al*. (2009), weed seed bank was reduced in rotations, which involved cropping of crops with different growth durations. The inclusion of plants with allelopathic effects in rotational systems has also shown a promising and sustainable option for weed control in agricultural systems (Ndakidemi & Dakora, 2003; Ndakidemi, 2006; Makoi & Ndakidemi, 2012).

Striga infestation was reduced by 35% in the legume-maize rotation and the reduction was doubled when the rotation was repeated (Kureh *et al*., 2006). Comparing soybean and cowpea in rotations with maize, Kureh *et al*. (2006) found that the former was better than the latter in reducing *Striga* infestation. The reason for the differences observed between the two legumes could be attributed to the higher ability of soybean in fixing atmospheric N, but both improving soil fertility, which does not favour germination and survival of *Striga* (Gworgwor & Weber, 1991; Ikie *et al.*, 2007; Gacheru & Rao, 2011). It is, therefore, important to understand how the rotational cultivations of cereals with different legumes can be the feasible option towards weed control in cropping systems.

2.5 Nitrogen Budgets in Grain Legume Cropping Systems

The cereal-legume cropping systems have gained prominence in increasing yields of maize as a major crop relative to sole maize cropping (Sanginga *et al*., 2001). The increased maize yields in legume-associated systems are due to N contributed by the legumes through biological N_2 fixation to improve soil fertility (Giller, 2001). The sustained benefits with large N applications like 60–120 kg N ha^{-1} equal to cereal grain yield of 0.32 t ha^{-1} or 59% of the response have been reported to indicate the importance of non-N effects (Franke *et al*., 2018). There are also, however, non-N benefits such as the reduced impact of pests and diseases, increased soil microbial biomass and activity and improved soil properties (Giller, 2001; Franke *et al*., 2018; Kermah *et al*., 2018).

The amount of N input from biological N_2 fixation (BNF) is reported to be as high as 360 kg N ha^{-1} (Giller, 2001). The N contributions from non-symbiotic such as free-living/associative organisms are relatively low ranging from 10–160 kg N ha^{-1} (Roger & Ladha, 1992; Urquiaga *et al*., 1989). Peoples *et al*. (1989; 2009) depicted those environmental conditions such as temperature, water availability, soil pH, and soil bulk density, the level of availability of mineral nutrients in the soil, pests, and diseases of legumes may affect nodulation and/or N_2 fixation. Soil low in mineral N favours effective legume-rhizobia symbiosis. In contrast, a legume growing on soils higher in mineral-N content is likely to compensate for poor N_2

fixation by scavenging N from the soil. In both intercrops and rotations of cereals with legumes, it is expected that there is improvement of soil fertility through N_2–fixation as well as microbial activities and soil structure (Giller, 2001).

The translocation, fates, and distribution of N in legumes influence soil fertility and productivity of the next crop. The residues of legumes contain some of the N that they have fixed, and this becomes available to subsequent crops if are retained back in the field after harvest although part of it remains in the plant system (Carranca *et al*., 2015). The N-fixed, which remains in soil/plant parts in the same field, have economic importance of reducing N-fertilizers needed in subsequent crops. Maingi *et al*. (2001) found a slight increase and maintenance of total N (%) levels in maize-common bean intercropped fields after one cropping season compared with the pure maize fields where N declined in the soil.

N_2-fixation is affected by the factors that affect the host plant during its growth and development such as water, temperature, pH, nutrients, and light. Rondon *et al*. (2006) found that greater boron (B) and molybdenum (Mo) availability from bio-char increased Biological Nitrogen Fixation (BNF) in common bean. The greater K, Ca, and P availability, lower N availability, higher pH levels, and Al saturation decreased BNF in common bean (Rondon *et al*., 2006). It is reported that higher levels of P increase symbiotic N_2-fixation in common bean at low N (Leidi & Rodriguez-Navarro, 2000). Giller *et al*. (1998) found that P- fertilizer at 26 kg P ha^{-1} increased the number of root nodules and seed yields of *Phaseolus* bean on farmers' fields in the West Usambara Mountains in northern Tanzania. There has been realized improvement in seed yields by addition of P or N fertilizers in Kilimanjaro and Arusha regions (Giller *et al*., 1998).

Selection of common bean varieties to be cultivated by farmers is important since they differ in their abilities to fix and utilize atmospheric N to optimize yield and improve soil fertility (Manrique *et al*., 1993). Phosphorus is also a very important macronutrient during N_2-fixation acting as a source of energy when Adenosine Triphosphate (ATP) is converted to adenosine diphosphate (ADP) as N_2 is reduced to NH_3 (Equation 1) as the overall reaction of BNF (Armstrong *et al*., 1999; Giller, 2001). Inadequate P in soil restricts root growth, the process of photosynthesis, translocation of sugars, and other functions, which directly or indirectly influence N fixation by legume plants.

$$N_2 + 8H^+ + + 8e^- \rightarrow 2NH_3 + H_2 \quad (1)$$

The released H_2 stimulates the growth of hydrogen-fixing bacteria in the rhizosphere, and these compete successfully for living space with other rhizosphere organisms, including many pathogens (Armstrong *et al*., 1999).

Effectiveness of nodulation is the best studied at or near to 50% flowering but immediately before pod formation. In each individual plant, the number of nodules and presence or absence of crown nodulation will be noted. Nodule number and nodule mass or nodule weight per unit dry weight of the whole plant or root system are often used in trial comparisons. Similar comparison information can be obtained by visually scoring nodulation on a scale of 0–5 by considering nodule number, size, colour, distribution, and longevity of the nodule population (Peoples *et al*., 1989).

The pink/brown colour of the nodule is caused by a protein leghaemoglobin containing both micronutrient iron (Fe) and it is responsible for binding of oxygen (Armstrong *et al*., 1999). This creates a low oxygen environment within the nodule, which allows rhizobium bacteria to live and to fix N_2. The practice involves carefully digging-up plants at random across a crop while ensuring the root system and nodules are recovered and scoring each plant using predetermined classification criteria. A mean nodule score of 4–5 excellent nodulation and potential for N_2 fixation, 3–4 good nodulation and potential for fixation, 2–3 fair nodulation but N_2 fixation may not be sufficient to supply the N demand of the crop, 0–2 poor nodulation, little or no N_2–fixation (Peoples *et al*., 1989). Knowledge of nodulation characteristics in legumes is important as it provides an indication of N_2–fixing legume at certain stages of plant growth. This also provides an insight of the time for sowing a component crop in an intercrop relative to their growing cycles and/or the likely amount of residual N_2–fixed for the subsequent crop in the same land.

2.6 Quantifying the Amount of N_2–Fixed by the Legumes

The widely acceptable methods of quantifying the amount of N_2–fixed by a legume are enrichment (^{15}N-enriched) and natural abundance (δ^{15}N) (Unkovich *et al*., 2008). The ^{15}N-enriched method is useful where N-containing materials e.g. N-carrying fertilizers and organic substrates have been added into the experimental ecosystem while δ^{15}N method is applicable in environments where no inclusion of N-containing materials (Giller, 2001; Unkovich *et al*., 2010). The δ^{15}N method uses small differences between the $^{15}N/^{14}N$ ratio of the N-source being examined and the $^{15}N/^{14}N$ ratio of N already existing in the system to follow the N-source through the soil, water, and plants. The advantage of the δ^{15}N approach is that, in principle, it can be used in any ecosystem, but it has analytical, assumptions and interpretative limitations (Unkovich *et al*., 2010).

Natural abundance method uses N_2–fixing legume and a no N_2–fixing reference plant growing together with the N_2–fixing legume. Cadisch *et al*. (2000) found that $\delta^{15}N$ method was less sensitive between the reference and N_2-fixing plant compared to the ^{15}N-enrichment method but signals for the same precautions as for the ^{15}N-enrichment method because of the N_2–fixing legume and the reference plant and accounting for ^{15}N variation within the plant. According to Unkovich *et al*. (2010), the ^{15}N content of the plant lies between the ^{15}N signature of the plant-available soil N (%Ndfa of zero) and a value close to 0.3663 atom% ^{15}N (%Ndfa of 100%). Carranca *et al*. (2015) reported that whole legume plant i.e. top plant and visible roots and nodules should be involved in N_2–fixation studies in order to avoid underestimating the role of legumes for soil N fertility. Grain yields in legumes are a useful parameter in estimating biomass yield by taking into account harvest index and root/shoot ratio. Data on N concentrations in seeds, straw, and roots of the main species allows quantification of the amount of N accumulated in the plant. Fustec *et al*. (2010) indicated that deposition of N in the root zone from dead cells, root exudates, and shed fragments of roots, and the amount of N derived from biological fixation are important in considering the amount of N in the plant.

Several formulae for calculating the amount of N_2–fixed by a legume have been put in place but they depend on the method employed (Cadisch *et al*., 2000; Giller, 2001; Unkovich *et al*., 2010). The natural abundance method relies on the different natural abundance of ^{15}N in soil N and atmospheric N. The ^{15}N abundance in a non-N_2–fixing (reference) plant, which is all derived from the soil, is larger than that of a N_2–fixing plant, which derives some of its N from atmospheric N through symbiotic nitrogen fixation (Shearer & Kohl, 1986). The reference plant is a non-N_2-fixing but useful in measuring the ^{15}N-enrichment of the available soil N (Giller, 2001). The total N is then analyzed for ^{15}N, and the percentage of N derived from the atmosphere (%Ndfa) by the legume is calculated using the Equation 2:

$$\%\mathrm{Ndfa} = \left(1 - \frac{\mathrm{atom\%}\ 15_N\ \mathrm{excess\ from}\ N_2 - \mathrm{fixing\ plant}}{\mathrm{atom\%}15_N\ \mathrm{excess\ from\ a\ reference\ plant}}\right) \times 100 \qquad (2)$$

Boddey *et al*. (1995) deduced a computational equation for %Ndfa based on the whole plants i.e. the whole plant $\delta^{15}N$ by considering the weight of seed and stover/straws (Equation 3).

$$\%15_N\mathrm{dfa}_{whole\ plant} = \left(\frac{(\mathrm{total\ seed\ N} \times \delta 15_{N\,seed}) - (\mathrm{total\ straw\ N} \times \delta 15_{N\,straw})}{\mathrm{total\ seed\ N} + \mathrm{total\ straw\ N}}\right) \times 100 \quad (3)$$

The natural ^{15}N abundance is expressed as delta $\delta^{15}N$ in parts per thousand or per mill (‰) ^{15}N excess over a standard (Equation 4).

$$\delta 15_N(‰) = \left(\frac{\text{atom\% } 15_N \text{ sample} - \text{atom\% } 15_N \text{ standard}}{\text{atom\% } 15_N \text{ standard}}\right) \times 1000 \qquad (4)$$

A slightly different expression for $\delta^{15}N$ (‰) uses the R-values of the isotope ratios (Equation 5).

$$\delta 15_N(‰) = \left(\frac{R_{sample} - R_{standard}}{R_{standard}}\right) \times 1000 \qquad (5)$$

Where $\delta^{15}N$ (‰) is the isotope ratio of the sample relative to the atmospheric air standard and $R_{-sample}$ and $R_{-standard}$ is the molar ratios of ^{15}N to ^{14}N from the atmosphere. According to Giller (2001), the value of R is calculated as indicated in Equation 6.

$$R = \frac{15_N + 14_N}{14_N + 14_N} \qquad (6)$$

The proportion of ^{15}N atoms in the atmospheric N_2 is constant, around 0.3663 atom% ^{15}N and Ojiem *et al*., (2007) indicated that the $\delta^{15}N$ of the atmosphere is zero. However, the majority of N_2 transformed in the soil is in the ^{15}N isotopic form of N. The amount of N_2–fixed can be calculated (Cadisch *et al*., 2000; Somado & Kuehne, 2006) as in Equation 7.

$$\text{Amount of } N_2 \text{ fixed} = \left(\frac{\text{\%Ndfa} \times \text{total N from } N_2 - \text{fixing crop}}{100}\right) \qquad (7)$$

The amount of N_2–fixed by a legume crop can also be calculated from measures of DM and N content (%N) in more simplified formula (Hauggaard-Nielsen *et al*., 2009) as in Equation 8.

$$\text{Amount of } N_2 \text{ fixed} = \left(\frac{\text{\%Ndfa}}{100}\right) \times DM \times \left(\frac{\text{\%N}}{100}\right) \qquad (8)$$

Where *DM* is the dry weight of shoot

In the case of annual field crops, e.g. common bean, the %N from N_2–fixation calculated using the equation of Shearer and Kohl (1986), Peoples *et al*. (1997) and Ojiem *et al*. (2007) as in Equation 9.

$$\%\text{N from N}_2\text{fixation} = \left(\frac{\delta 15_{N_{\text{reference plant}}} - \delta 15_{N_{N_2\text{fixing plant}}}}{\delta 15_{N_{\text{reference plant}}} - B} \right) \times 100 \qquad (9)$$

Where *B* is the $\delta^{15}N$ of the growing legume deriving its entire N from N_2–fixation in an N-free medium and the *B*-value measured in common bean is -1.00 (Peoples *et al*., 2002; Ojiem *et al*., 2007). This value is obtained by taking the average of $\delta^{15}N$ measurements of a total of randomly selected bean genotypes and recombinant inbred lines from a cross between low symbiotic N_2–fixing genotype and high symbiotic N_2–fixing genotype grown in a greenhouse (Peoples *et al*., 2002). The N (%) obtained in equation 8 is converted into land area (kg N ha^{-1}) basis of N contributed by an N_2–fixing legume. It is important to quantify the amounts of N_2–fixed by grain legumes by referring to non-N_2–fixing plants such as C4-plants such as cereals (e.g. maize) as are growing together with legumes but cereals do not have closely related growth habits (acquisition of growth factors) with these legumes. It is therefore, practical to choose a reference plant with the same growth habit and duration as the test legume. The use of C3-plants (e.g. broadleaved weeds as reference plants) growing together with both maize and legume crops in the same land is important as these C3-plants have some similarities in growth habit with the test legume. Ojiem *et al*. (2007) indicated that the inclusion of C4-plants underestimated quantities of N_2–fixed relative to the use of C3-plants as reference. It is important to understand the appropriate method of quantifying the amount of N_2–fixed by legumes in cereal-legume cropping systems under field conditions and the associated N economy in the soil. The ^{15}N natural abundance method is superior to the ^{15}N–enrichment method because there is no application of N-containing fertilizer. The non-N_2–fixing reference plants need to be well matched with the N_2–fixing legumes.

The amount of N in soil due to fixation by a legume is also quantified in order to understand residual N that would be available for the subsequent crop. However, it is unlikely that N in soil would change over one cropping season as a contribution of including a legume. However, total N in soil before and after experimentation (given a long-term), soil sampling depth and bulk density are important in estimating the amount of mineral N (NH_4^+ and NO_3^-) in soil (Giller, 2001; Cresswell & Hamilton, 2002; Casanova *et al*., 2016). Therefore, it is important to quantify the amounts of N_2–fixed by grain legumes and added to the soil in order to understand the availability of N to the subsequent crop when cultivated in the same land and its overall influence on soil health.

2.7 Role of Grain Legumes Intensification in Improving Food Security under Changing Climate

Grain legumes are the important crops in sustaining natural resources, improvement of food security, improving nutrition and health status, and reduction of poverty (Dar *et al*., 2012; Loboguerrero *et al*., 2019). Smallholder farmers diversify and intensify grain legumes with tubers, cereals, and root crops through rotations and intercrops. With the impact of climate change, there are chances that some crops may fail in a season but diversification of different crop species ensures food security for the family's livelihood (Bedoussac *et al*., 2015). Grain legumes like other legumes also play role in breaking cycles of weed, pest and disease of other subsequent crops, and provide soil cover (Franke *et al*., 2018; Loboguerrero *et al*., 2019).

Climate change is explained by the increase in temperatures and rainfall, which affect association among crop species, weeds, disease pathogens, and pests (Saina *et al*., 2013; Myers *et al*., 2017; Stagnari *et al*., 2017). Grain legumes such as common bean and soybean and cereals including rice and wheat operate with a C-3 photosynthetic pathway. The growth of C3 crops is more stimulated by increases in CO_2 due to climate change than a C-4 photosynthetic pathway crops such as sugarcane, sorghum, and maize (Leakey *et al*., 2009; Considine *et al*., 2017). It has been reported that the changes in climate since 1980 have reduced global food production (Myers *et al*., 2017). However, there is no evidence that the production of common bean, soybeans and rice has been affected by the trends of climate change (Lobell *et al*., 2011; Saina *et al*., 2013; Myers *et al*., 2017). This is an important area of concern that common bean would play role in sustaining food security on smallholder farms. Lipiec *et al*. (2013) indicated that plants with C-3 pathways are more sensitive to higher temperatures during photosynthesis compared with the plants characterized by C-4 pathways.

Accessibility as well as availability of food both physically and economically at all times ensures food security where the people are sufficiently provided with dietary safe and nutritious food (Ericksen, 2008; Saina *et al*., 2013; Loboguerrero *et al*., 2019). Grain legumes including common bean are locally produced and/or available at farmer's level, safe and healthy, provide dietary proteins and vitamins, and acceptable at all households on smallholder farms (Hillocks *et al*., 2006; Ndakidemi *et al*., 2006; Ronner & Giller, 2013). However, production of these grain legumes and their dependence as an important source of food security should be considered consciously along with the influence of changes in climatic trends (Bishop *et al*., 2017; Considine *et al*., 2017) although there is no direct evidence reported. Therefore, it is important that options are designed for adaptation and mitigation of the impact of climate change on crops considered for food security. Some of the available options include intensification of cropping systems using improved varieties, sowing based on the on-set of rains, improvement of irrigation and water use efficiency, diversification of the farming systems, and adoption of crop rotations and intercropping (Ericksen, 2008; Devendra, 2012; Loboguerrero *et al*., 2019). Grain legumes are important in improvement and sustainability of soil quality, which dedicates production of food crops. Depending on the legume species, climatic conditions, and variation in soil properties grain legumes differently influence rhizospheric levels of soil N supply, soil organic carbon (SOC) and availability of P (Stagnari *et al*., 2017).

2.8 Soil Health and Fertility Status and Associated Environmental Benefits of Intercrops or Rotations

Intercrops and rotations, which involve grain legumes, improve soil health by reducing amount of N losses (Sanderson *et al*., 2013; Lemaire *et al*., 2014). The SOC and N contents sequestration rates are reported to increase in intercropped and/or rotated wheat, maize, and faba beans (*Vicia faba* L.) compared with the quantities of SOC measured in the monocultures of these crops (Cong *et al*., 2014).

Inclusion of different crop species during or in successive cropping seasons in the same piece of land is reported to increase the diversity of soil microbes such as rhizobacteria and arbuscular mycorrhizal fungi (Cong *et al*., 2014; Bybee-Finley & Ryan, 2018). The practices also increase microbial activities with the additional benefits of influencing nutrient availability in soils and facilitate their uptakes for the component and/or subsequent crops (Cong *et al*., 2014; Vukicevich *et al*., 2016). Due to the ability of grain legume to fix atmospheric N in symbiosis with the rhizobium, the cereal-legume based systems have self-regulatory abilities on the amounts of soil total N (Chapman *et al*., 1996; Vukicevich *et al*., 2016). These self-regulating mechanisms reduce the fates of denitrification and leaching of NO_3^- through reduction of the reactive N in the soil. This in turn, reduces the problems associated with emissions of greenhouse gases and water quality in cropping systems (Tang *et al*., 2017).

2.9 Socio-Economic Implications of Intercrops and Rotations

Despite that the benefits derived from intercropping and/or rotations would outperform sole cultivations of each crop either during the season (monocropping) or throughout the cropping seasons (monoculture), there are also some economic implications of these systems (Ndakidemi *et al*., 2006; Kermah *et al*., 2017). The demand of labour for field operations such as sowing, weeding, spraying, and harvesting may be higher in intercropping compared with monocropping and this increases operational costs due time consumed and might affect the rate of adoption of the practice by farmers (Ndiritu *et al*., 2014; Kermah *et al*., 2017). However, costs related to large seed quantities are reduced under intercrops due to relatively low seeding rate at sowing (Kermah *et al*., 2017). In addition, component crops complement each other in the season in cases one of them fails to complete its maturity cycle, probably, due to bad climatic conditions, poor soil fertility, diseases, and pests (Trenbath, 1993). Similarly, in crop rotation although costs related to field operations might not be as higher as those incurred in intercrops, the practice often involves one crop in a cropping season (Kermah *et al*., 2017; Shahzad *et al*., 2017). In situations where this sole cultivated crop fails to complete its life cycle, farmers relying on it for food and income will suffer from food insecurity. With this in mind, it is likely that farmers may prefer continuous intercropping of contrasting plant species as an alternative to avoid risks of one crop failure in a season.

Gender preference in farming activities intersects most of the socio-economic aspects to be considered in intensification of crop production and sustainability of food security in smallholder settings. For example, cereals and the only highly commercialized grain legumes are often considered as crops for male whereas less commercialized grain and vegetable legumes are regarded as crops for women (Bationo *et al*., 2011). Women are the most important group, which affects the execution of agricultural activities and the outcomes unveiled since women are obedient and fully involved in field operations, processing and storage, and trading where applicable. However, women are less entitled to property ownership including access to and control of production assets such as land and the funds earned from farming activities and constitute an inferior group in decision making (Wakhungu, 2010).

It is a major concern that women are given priority and great consideration in decision making on designing appropriate practices to be adopted for sustainable intensification of systems productivity as this will increase awareness for gender equity in food security. Me-Nsope and Larkins (2016) indicated that farmers' adoption/cultivation of legume-cereal was highly affected by the gender element. Where only men are involved in marketing of farm products, the sales do not translate into improvements of the household's food security (Me-Nsope & Larkins, 2016). Development efforts towards food security through farming need to consider interventions on gender equity such that women are involved at every stage. According to Rubin *et al*. (2009), systems productivity and access to commodities from farming, funds from sales, human resources, time, information, and skills are affected by the gender equity. This suggests that there should be co-sharing of decision making, execution of the idea or activity and benefits derived from farming for both men and women right from the household level. It is important that farmers' perception is evaluated based on the options for sustainable intensification of common bean cultivation through rotations and/or intercropping while considering gender equity and its sensitization.

CHAPTER THREE

MATERIALS AND METHODS

3.1 Study Area

The site selection for this study was based on the study conducted by Ronner & Giller (2013) and the findings of a baseline survey conducted in November and December 2014. Hai district in Kilimanjaro Region was the geographic focus of this study to meet the objectives of N_2Africa Project in Tanzania of putting nitrogen fixation to work for smallholder farmers in Africa. The different farming practices in the district are the mixed cropping of maize and common bean during the short rainy season and the mixed cropping of maize, common bean, banana, and coffee during the long rainy season in the higher altitude. In the middle and lower altitudes, the farming practices include sole bean cultivation during the short rainy season and the mixed cropping of maize and common bean during the long rainy season. Vegetables are also produced during the short rainy season through supplemental irrigation in the lower and middle altitudes. Indoor (zero) grazing of cattle and goats is practiced in the higher and middle altitudes while pastoralist (free) grazing of cattle, goats, sheep and donkeys is practiced in the lower altitude.

The coverage of the study was based on a transect of altitudes ranging from lower to the upper sub-agro-ecological zones (AEZs). The district is located between latitudes $02^0$30’ and $03^0$29’ South and between longitudes $30^0$30’ and $37^0$10’ East (Fig. 4). The land use types in the district are highly variable depending on the altitude with high heterogeneity although grazing is mostly concentrated in the lower zone (Fig. 5). Agriculture constitutes the largest type of land use by 46% and the mountain and snow land covers only 13% part of the district (Hai District Profile, 2011). About 87% of the population in the district are smallholders in farming and livestock husbandry (Hai District Profile, 2011; Funakawa *et al*., 2012). The climate of the district is classified as Tropical Savannah but it varies considerably because of the influence of Mt. Kilimanjaro. Rainfall is bimodal that is long rainy season (*Masika*), which starts in March and ends in June and short rainy season (*Vuli*), which starts in October and ends in December (Munishi *et al.,* 2015). However, short rainy season in the higher altitude is different from other altitudes because it starts in July through January (Funakawa *et al*., 2012).

Hai district is categorized into three AEZs: (a) Higher zone – lies between 1660 and 1800 m above sea level and receives average annual rainfall of 1750 to 2000 mm. (b) Middle zone – lies between 900 and 1350 m above sea level and receives average annual rainfall of 1250 to 1750 mm. (c) Lower zone – found below 900 m above sea level and receives average annual rainfall of 500 to 1250 mm (Hai District Profile, 2011). The mean annual rainfall during cropping seasons in the district has been ranging from 92 to 346 mm since 2009 (Munishi *et al*., 2015), which compares relatively similar to the rainfall data recorded in the present study. The three major AEZs have distinct crops, cropping systems and these zones still interact closely in terms of nutrients movement because of the slope, which steeps up the Mount Kilimanjaro and down-slope surface runoff (Funakawa *et al*., 2012; Munishi *et al.*, 2015).

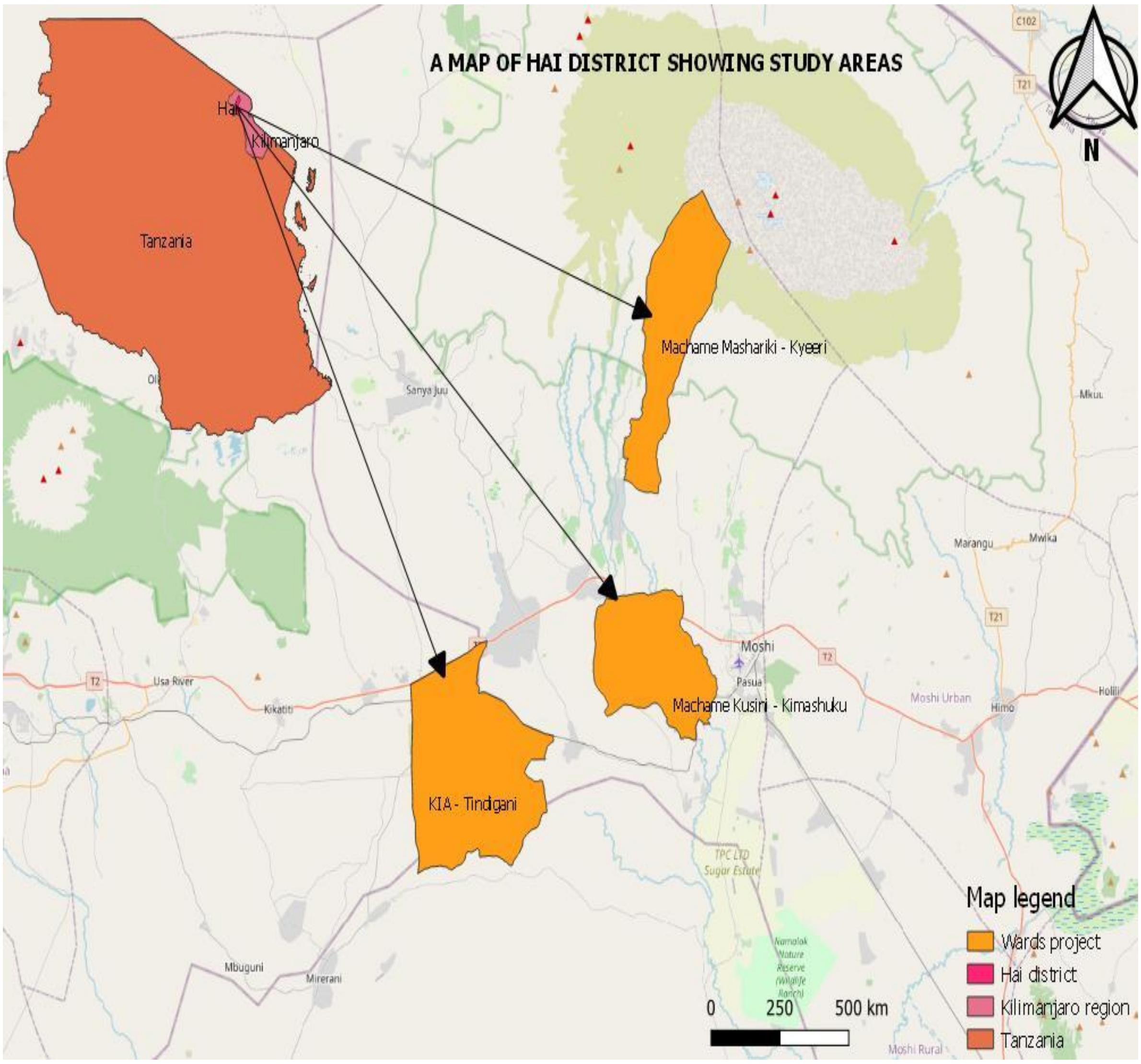

Figure 4: Map of Hai District showing study areas (Tindigani-Masama, Kimashuku, Kyeeri) (Primary own work, 2015)

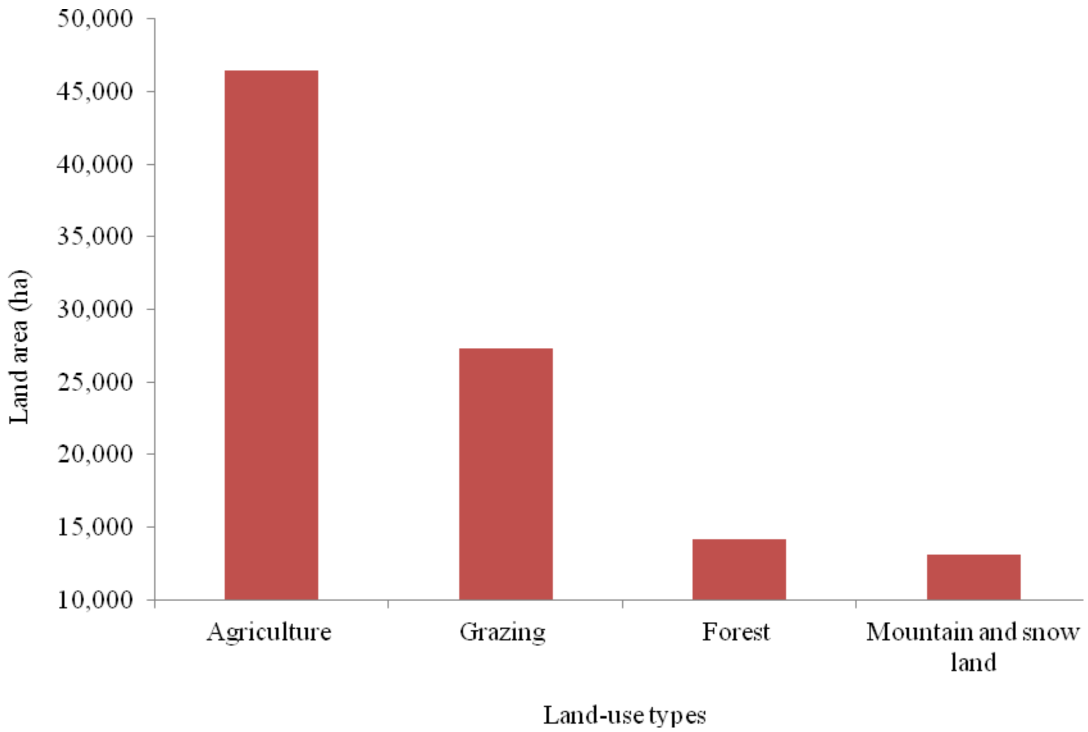

Figure 5: Distribution of different land uses in Hai district of the northern highlands of Tanzania (Hai District Profile, 2011)

3.2 Specific Objective One

3.2.1 Experimental Design and Treatments

The experiment involved intercropping of the two varieties of common bean (improved and local) was repeated for two cropping seasons (2015 and 2016 long rainy seasons) in three agro-ecologies namely lower (743 m above sea level), middle (1051 m above sea level), and higher (1743 m above sea level) attitudes (Table 3). A randomized complete block design (RCBD) was employed where intercrops of common bean varieties were tested against their monocultures. The sources of variability used for blocking were the soil colour, type of sprouting vegetation, and signs/gullies of surface runoff. Orientation of the blocks in the experimental field was along the contours across the slopes.

Table 2: Treatments layout used in the field experiments in three agro-ecological zones

2015 long rainy season	2016 long rainy season
M	M
IB	IB
LB	LB
M + IB	M + IB
M + LB	M + LB

Key: M =Maize, IB =improved bean, LB =local bean

3.2.2 Seeds and Sowing

Hybrid maize seed Dekalb brand DK8031, DKC8053, and DKC9089 were used as adapted in the lower, middle, and higher agro-ecological zones, respectively (Lyimo *et al*., 2014). The improved bean variety *Lyamungu 90* was obtained from Selian Agricultural Research Institute (SARI) in Arusha, Tanzania and the local bean *Mkanamna* was sourced from Lawate and Kwasadala local markets (Plate 1). The choice of these bean varieties was because farmers in the area prefer the local bean *Mkanamna* in dishes due to good flavour and it does not cause gaseous effect in stomach when consumed but also the only improved bean which is often grown is *Lyamungu 90* (Ronner & Giller, 2013; Baijukya *et al*., 2016). All seeds were subjected to germination tests, which were greater than 98%. The experimental fields were 55 m × 15.8 m in size and each plot was 5 m × 3.2 m with four replicates in all sites and at every experiment hence total of 20 plots for five treatments in each zone. Maize and bean seeds were sown simultaneously in experimental fields in the season but in definite patterns contrary to the farmers' practice of broadcasting bean seeds during sowing or weeding of maize. The planting density is indicated in Table 4. At sowing, triple superphosphate (TSP, 46% P_2O_5) fertilizer was applied in each planting hole at a rate equivalent to 25 kg P ha^{-1} because in all agro-ecological zones soil available P extracted by the Bray-1-Kurtz method was less than 7 mg P kg^{-1} soil. When maize plants were 21 days in age after sowing, fertilizer urea (46% N) was applied by banding at a rate equivalent to 120 kg N ha^{-1} (Mowo *et al*., 1993).

Table 3: An indication of the sowing density of maize and common bean seeds

Crop	Cropping	Sowing space (cm)	Plants/ hole	Plants/row	No. rows/plot	Plants/plot	Plants/ ha equiv
Maize	Sole	80 × 30	1	17	5	85	41 666
Maize	Intercrop	80 × 30	1	17	5	85	41 666
Bean	Sole	40 × 10	1	51	9	459	2 86 875
Bean	Intercrop	80 × 10	1	51	4	204	1 27 500

Plate 1: Bean varieties used in the present study

3.2.3 Data Collection

The tools used were quadrat frame to measure ground coverage, metal tape-measure for plant height, weighing and digital balances for total biomass and grain yields, machete for harvesting maize and chopping trashes, carry bags for carrying soil and plant samples, and mat for spreading and quartering of samples into composites. The data collected are: (a) Growth characteristics including ground coverage and plant height on weekly basis starting from six weeks after sowing until no further change; and (b) Grain yield and yield components: total biomass, number of pods per bean plant, number of seeds per pod, weight of 100-seed and grain yields.

The data collected were the growth characteristics of plants including plant height and leaf canopy coverage on ground were measured at weekly intervals when the plants were 42 days from sowing until there was no further increase in these variables. Plants of the inner rows in each plot were identified and marked with coloured strings for which the variables were measured. In monoculture cultivated common bean, only plants in the inner seven rows (total of 35 plants) were randomly selected and marked and the measurements recorded. However, in common bean intercropped with maize, plants from two inner most rows (total of 15 plants) were randomly selected and measurements taken.

In maize, eleven plants from the inner three rows were marked and used for the study. In all plots, neighbouring three plants in each row were left as buffer zone to reduce edge and/or neighbour effects caused by potentially strong interaction between treatments in competition for light, water or nutrients and this ensures validity of results. In taking data for common bean at harvest, plants were harvested and weighed for total weight (stover + grains), threshed and grains weighed for yield determination. Of the harvested plants, ten plants were randomly selected and counting of pods was done in each plant before threshing. Counting of seeds in each pod was done after threshing of pods. The measurement of data in maize at harvest followed the same procedures as for common bean. The data from maize crop at harvest were also collected in all AEZs to be used in determination of the land equivalent ratio (LER) as a measure of the land utilization advantage of common bean in intercrop with maize relative to its sole cropping. Therefore, the biological efficiency and productivity of the common bean in intercrops with maize were compared by the partial (individual crop's) land equivalent ratios (LERs) and the total LER using the formula of Willey (1979):

$$LER = PLER_{maize} + PLER_{common\ bean} \quad (10)$$

With,

$$\text{PLER}_{\text{common bean}} = \frac{\text{Yield of common bean in intercrop}}{\text{Yield of common bean in monoculture}} \quad (11)$$

$$\text{PLER}_{\text{maize}} = \frac{\text{Yield of maize in intercrop}}{\text{Yield of maize in monoculture}} \quad (12)$$

Where PLER is the partial land equivalent ratio of maize or common bean.

3.2.4 Statistical Analyses

The fixed main effects were the cropping seasons, agro-ecological zones, and cropping systems whereas replicate blocks were treated as random effect. The influence of plant growth characteristics on bean grain yields under each cropping system and the agro-ecological zone was evaluated by correlation analysis. Plant height, ground coverage percent, and yield components (pods, seeds, 100-seed dry weight, and total biomass) were used to test the significance of correlations with grain yields depending on cropping systems of common bean. Results of correlation analyses in the first cropping season of the experiment provided an insight of an altitude with many variables (growth and yield components) of common beans affecting grain yields from intercropping with maize that could be tested through more trials. Means of treatments across replicates were used for calculating correlations as the literature indicates that in maize and bean intercrops, the bean is the most negatively affected by competition in the association. The significant effects of treatments were isolated by a post-hoc Tukey's-HSD test at a threshold of 5% using GenStat Discovery Edition 4. A 3–WAY ANOVA was used for the analysis of data collected in common bean and maize, and the factor effects model (Equation 13) was:

$$Y_{ijk} = \mu + \alpha_i + \beta_j + \gamma_k + (\alpha\beta)_{ij} + (\alpha\gamma)_{ik} + (\beta\gamma)_{jk} + (\alpha\beta\gamma)_{ijk} + \varepsilon_{ijk} \qquad (13)$$

where, *Yijk* is the observation in the *ijkth* factors; μ is the overall (grand) mean; α_i, β_j, γ_k are the main effects of the factors cropping seasons (S), agro-ecological zones (A), and cropping systems (C), respectively; $(\alpha\beta)_{ij}$, $(\alpha\gamma)_{ik}$, $(\beta\gamma)_{jk}$ are the two-way (first order) interactions between the factors; $(\alpha\beta\gamma)_{ijk}$ is the three-way (second order) interaction effects of the factors S, A, and C; εijk is the random error associated with the observation in the *ijkth* factors.

The Pearson's correlation coefficients between bean grain yield and other measured variables were estimated in the same bean crops.

A 2–WAY ANOVA was used for the LER and the factor effects model (Equation 14) was:

$$Y_{ij} = \mu + \alpha_i + \beta_j + (\alpha\beta)_{ij} + \varepsilon_{ij} \qquad (14)$$

where, *Yij* is the observation in the *ijth* factors; μ is the overall (grand) mean; α_i, β_j are the main effects of the factors agro-ecological zones (A) and bean varieties (V), respectively; $(\alpha\beta)_{ij}$ are the two-way interaction effects between the factors A and V; εij is the random error associated with the observation in the *ijth* factors.

3.3 Specific Objective Two

3.3.1 Experimental Design and Treatments

Maize was intercropped with the two varieties of common bean (improved and local) repeated for five cropping seasons (2015 to 2016 long and short and 2017 long rainy seasons) in the middle (1051 m above sea level) attitude (Table 5). These experiments were meant for three years, involving long and short rainy seasons of each year from 2015. However, there were no cultivation experiments during the short rainy season in 2017 due to the limitations of time and funds since the budget allocated for this research was for five cropping seasons only. The design and field variability considered were the same as those in section 3.2.1 and the intercrops of maize and common bean were tested against their sole cropping. The treatments were replicated four times, which made total of 20 experimental plots. The maize seed Dekalb brand DKC8053 was used and the sowing densities of maize and common bean were as shown in Table 4. Crop management in the field and the type and means of data collection were the same as those described in Section 3.2.3.

Table 4: Treatments layout used in the field experiments in the middle agro-ecological zone

Years of cropping, rainy seasons, and treatments				
2015		2016		2017
Long	**Short**	**Long**	**Short**	**Long**
M	M	M	M	M
IB	IB	IB	IB	IB
LB	LB	LB	LB	LB
M + IB	M + IB	M + IB	M + IB	M + IB
M + LB	M + LB	M + LB	M + LB	M + LB

M =Maize, IB =improved bean, LB =local bean

It was important that the reaction of soils (soil pH) is determined at the end of experiments since pH drives the chemistry and overall fertility status of soils. Therefore, soil samples were collected from five spots in each experimental plot and quartered to one composite sample per each plot. The composite soil samples were characterized for the soil pH, soil organic carbon (SOC), total nitrogen (N), and available phosphorus (P). The characterization of all soil samples for the mentioned parameters was done following standard procudres described by Okalebo *et al*. (2002).

3.3.2 Statistical Analyses

The fixed main effects for the common bean were the cropping seasons, bean varieties, and cropping systems and the replicate blocks were treated as random effect. The influence of plant growth characteristics on bean grain yields under each cropping system and the bean varieties was evaluated by correlation analysis. Plant height, ground coverage percent, and yield components (pods, seeds, 100-seed weight, and total biomass) were used to test the significance of correlations with grain yields depending on the cropping systems of common bean. The effects of significant treatments were isolated by a post-hoc Tukey's-HSD test at a threshold of 5% using GenStat Discovery Edition 4. A 3–WAY ANOVA was used for the data collected in common bean where the factor effects model (Equation 15) was:

$$Y_{ijk} = \mu + \alpha_i + \beta_j + \gamma_k + (\alpha\beta)_{ij} + (\alpha\gamma)_{ik} + (\beta\gamma)_{jk} + (\alpha\beta\gamma)_{ijk} + \varepsilon_{ijk} \qquad (15)$$

where, *Yijk* is the observation in the *ijkth* factors; μ is the overall (grand) mean; α_i, β_j, γ_k are the main effects of the factors cropping seasons (S), bean varieties (V), and cropping systems (C), respectively; $(\alpha\beta)_{ij}$, $(\alpha\gamma)_{ik}$, $(\beta\gamma)_{jk}$ are the two-way (first order) interactions between the factors; $(\alpha\beta\gamma)_{ijk}$ is the three-way (second order) interaction effects of the factors S, V, and C; εijk is the random error associated with the observation in the *ijkth* factors.

The Pearson's correlation coefficients between bean grain yield and other measured variables in the same bean crops were estimated.

A 2–WAY ANOVA was used for the data collected in maize and for the calculated LER and the factor effects model (Equation 16) was:

$$Y_{ij} = \mu + \alpha_i + \beta_j + (\alpha\beta)_{ij} + \varepsilon_{ij} \qquad (16)$$

where, *Yij* is the observation in the *ijth* factors; μ is the overall (grand) mean; α_i, β_j are the main effects of the factors cropping seasons (S) and cropping systems (C) for maize and/or bean varieties (V) for the LER; $(\alpha\beta)_{ij}$ are the two-way interaction effects between the factors S and C and/or V; εij is the random error associated with the observation in the *ijth* factors.

The soil data collected at the end of the intercropping experiments were subjected to the statistical analysis of variance (ANOVA). A one-way ANOVA was performed to compare the levels of the selected fertility contributing parameters in the soils of the intercrops against the monocultures of maize and the two varieties of common bean. The factor effects model (Equation 17) was:

$$Y_i = \mu + \alpha_i + \varepsilon_i \qquad (17)$$

where, *Yi* is the observation (amount of a nutrient) in the *ith* cropping system, μ is the overall (grand) mean, α_i is the effect of the *ith* cropping system relative to the mean, and εi is the random error associated with the observation in the *ith* cropping system. The tests were done at a 95% level of confidence (P =0.05). To identify the differences in means between the cropping systems, the post hoc Turkey's tests were performed.

3.4 Specific Objective Three

3.4.1 Experimental Design and Treatments

This experiment involved the long and short rainy seasons (normal cropping calendar) from 2015 to 2017. A randomized complete block design (RCBD) of assigning treatments to the experimental plots was used. Table 6 presents a summary of treatments used in each cropping season. In each long rainy season, the treatments were: (a) Monocultures: (i) three levels of maize (M); (ii) improved bean (IB); (iii) local bean (LB); and (b) intercrops: (i) maize with improved bean (M+IB); (ii) maize with local bean (M+LB). Since rotational effects were the main objectives of this section of study, the strategy was met by introducing a sequence of rotations in the first short rainy season but the design was based on the very first long rainy season of 2015. Therefore, the treatments in each short rainy season were: (a) five levels of monoculture maize (M); (b) two levels of the monoculture-improved bean (IB); and (c) two levels of monoculture local bean (LB). All treatments and/or some in their respective levels in each cropping season were in four replications making total of 28 experimental plots. The experiments in the 2015 long rainy season were the establishment of the study; so, the basis of the treatments shown in Table 6 were not expected to be IB (long) + LB (short), or LB (long) + LB (short). The maize variety Dekalb brand DK8031 was used throughout the experiment. Both bean varieties were included in all cropping seasons as also smallholder farmers often do not have the exact choice of a certain bean type to be cultivated in rotation (as a monocrop) or as part of an intercrop with maize. Therefore, it was important in this study to test the performance of rotations with maize and varieties of common bean under each cropping season (long and short). The data collected are as described in Section 3.2.3.

Table 5: Treatments layout used in the field experiments in the middle agro-ecological zone for rotations between maize and common bean

Years of cropping, rainy seasons and treatments				
2015		**2016**		**2017**
Long	**Short**	**Long**	**Short**	**Long**
M	M	M	M	M
IB	IB	IB	IB	IB
LB	LB	LB	LB	LB
IB	M	IB	M	IB
LB	M	LB	M	LB
M + IB	M	M + IB	M	M + IB
M + LB	M	M + LB	M	M + LB

Key: M =Maize, IB =improved bean, LB =local bean

The soil samples were collected from five spots of each experimental plot and a composite sample was made out of them at the end of the field experiments that involved rotations of common bean and maize in the middle altitude Kimashuku site. The composite soil samples were characterized for the soil pH, SOC, total N, and available P as described under Section 3.3.1.

3.4.2 Statistical analyses

To isolate the effects of significant treatments, F-test was used at a threshold of 5%. In analyzing the data from common beans cultivated during long rainy seasons, the fixed effects were the cropping seasons (years), cropping systems, and bean varieties but in short rainy season (single) the fixed effects were the cropping systems and bean varieties whereas the replicates were treated as random factors. Analysis of the data collected from maize cultivated during the long and/or short rainy seasons involved treating cropping seasons and cropping systems as the fixed effects while the replicates were treated as random factors. For the beans in a short rainy season, the main effects were the cropping systems and bean varieties. Maize was evaluated in both long and short seasons using cropping seasons and cropping systems as the fixed effects. The data was coded as bean-maize rotation and maize-bean rotation as testing of both could indicate an important question and hypotheses, that there could be a difference between lengths of rainy season and rotation (and interactions between year and rotation). This involved considering special contrasts or as beans and maize nested within monoculture and beans rotated/mixture times season was expected to yield more insight in the data and its interpretation. The use of season as the fixed effect is based on the observed variations of rainfall, its distribution, and intensity in a specific season, which might not always be the same. Further, as the experiment was performed in a single location for five cropping seasons, the main effects and their interactions with location are confounded. Shapiro-Wilk test for the normality of residuals and Bartlett's test for the homogeneity of variances were performed in situations where the main effects were not significant. The significance of effects is independent of the check of model assumptions. The mixed model approach is only valid if assumptions are fulfilled. In addition, multiple linear regression analysis was performed for grain yield as a response variate and the fitted terms being 100-seed weight, total biomass, seeds per pod, and ground coverage and plant height at weeks six and eight to test the relationships between grain yield and these variables. GenStat Discovery Edition 4 was used for all statistical analyses. A 3–WAY ANOVA was used for the data collected in common bean during the long rainy seasons where the factor effects model (Equation 18) was:

$$Y_{ijk} = \mu + \alpha_i + \beta_j + \gamma_k + (\alpha\beta)_{ij} + (\alpha\gamma)_{ik} + (\beta\gamma)_{jk} + (\alpha\beta\gamma)_{ijk} + \varepsilon_{ijk} \qquad (18)$$

where, *Yijk* is the observation in the *ijkth* factors; μ is the overall (grand) mean; α_i, β_j, γ_k are the main effects of the factors cropping seasons (S), bean varieties (V), and cropping systems (C), respectively; $(\alpha\beta)_{ij}$, $(\alpha\gamma)_{ik}$, $(\beta\gamma)_{jk}$ are the two-way (first order) interactions between the factors; $(\alpha\beta\gamma)_{ijk}$ is the three-way (second order) interaction effects of the factors S, V, and C; εijk is the random error associated with the observation in the *ijkth* factors.

A 2–WAY ANOVA was used for the data of common bean collected during the short rainy season and the factor effects model (Equation 19) was:

$$Y_{ij} = \mu + \alpha_i + \beta_j + (\alpha\beta)_{ij} + \varepsilon_{ij} \qquad (19)$$

where, *Yij* is the observation in the *ijth* factors; μ is the overall (grand) mean; α_i, β_j are the main effects of the factors cropping systems (C) and bean varieties (V); $(\alpha\beta)_{ij}$ are the two-way interaction effects between the factors C and V; εij is the random error associated with the observation in the *ijth* factors.

In addition, a 2–WAY ANOVA was used for the data collected in maize during the long and the short rainy seasons where the factor effects model (Equation 20) was:

$$Y_{ij} = \mu + \alpha_i + \beta_j + (\alpha\beta)_{ij} + \varepsilon_{ij} \qquad (20)$$

where, *Yij* is the observation in the *ijth* factors; μ is the overall (grand) mean; α_i, β_j are the main effects of the factors cropping seasons (S) and cropping systems (C); $(\alpha\beta)_{ij}$ are the two-way interaction effects between the factors S and C; *εij* is the random error associated with the observation in the *ijth* factors.

The soil data collected at the end of the rotational cropping experiments were subjected to the statistical analysis of variance (ANOVA). A one-way ANOVA was performed to compare the levels of different soil fertility contributing parameters in the soils of the rotations against the monocultures of maize and the two varieties of common bean. The factor effects model (Equation 21) was:

$$Y_i = \mu + \alpha_i + \varepsilon_i \qquad (21)$$

where, *Yi* is the observation (amount of a nutrient) in the *ith* cropping system, μ is the overall (grand) mean, α_i is the effect of the *ith* cropping system relative to the mean, and *εi* is the random error associated with the observation in the *ith* cropping system. The tests were done at a 95% level of confidence (*P* =0.05). To identify the differences in means between the cropping systems, the post hoc Turkey's tests were performed.

3.5 Soil Tests Before Establishment of the Experiments

The soil tests before experiments included pH, soil organic carbon (SOC), bulk density, total nitrogen (N), available phosphorus (P), exchangeable potassium (K), calcium (Ca), magnesium (Mg), and sodium (Na), micronutrients such as zinc (Zn), iron (Fe), manganese (Mn), and copper (Cu), and texture (Moberg, 2000; Okalebo *et al.*, 2002). The physical and chemical properties of the soils of the middle zone are as presented in Table 7. Due to the limitations of funds to carry out analysis of the soils from all three altitudes where the study was conducted, it is important that other studies or researchers consider this gap as an important area for further investigation.

Table 6: Properties of the soil collected from cultivated field in the middle zone

Measured variable	SI–Unit	Value	Rating category
$pH_{(H2O)}$		6.02	Medium acid (5.6–6.0)
Available phosphorus (P)	mg kg^{-1}	28.6	High (> 25)
Exchangeable bases:	$cmol_{(+)}$ kg^{-1}		
- Potassium (K)		0.27	Low (0.20–0.40)
- Sodium (Na)		0.62	Medium (0.31–0.70)
- Calcium (Ca)		8	Very high (> 5.0)
- Magnesium (Mg)		0.53	Low (0.3–1.0)
Total nitrogen (N)	%	0.12	Low (0.1–0.2)
Organic carbon	%	1.79	Very low (<2)
Organic matter	%	3.09	Medium (3–7)
C/N ratio		15:01	Medium (10–15)
Micronutrients:	mg kg^{-1}		
- Zinc (Zn)		1.42	High (> 1)
- Iron (Fe)		38.33	High (> 4.5)
- Manganese (Mn)		35.22	High (> 1)
- Copper (Cu)		0.18	Low (deficient) (0–0.4)

The column for rating category is based on ratings given by Landon (1991)

3.6 Rainfall Description In the Experimental Sites

3.6.1 Rainfall during the 2015 and 2016 Cropping Long Rainy Seasons

During the first experimentation in 2015 long rainy cropping season, there was high investment on irrigation of crops in the field in the lower zone compared with the middle and higher zone. The performance and overall yield of common bean was satisfactorily promising for adoption by the smallholder farmers. Further, there was high theft of maize cobs at early and after maturity by the Maasai residents and cattle were grazed in some parts of the experimental fields due to drought and shortage of grasses for nomadic pastoralists in the lower zone. However, the stolen maize cobs where from the plants in border rows but some plant stalks were left hence assumed to have continued prevent the data collected from being confounded by the externalities. During the second cropping in the 2016 long rainy season, there was a delay in rain and later the rain was little in a short period (Fig. 6).

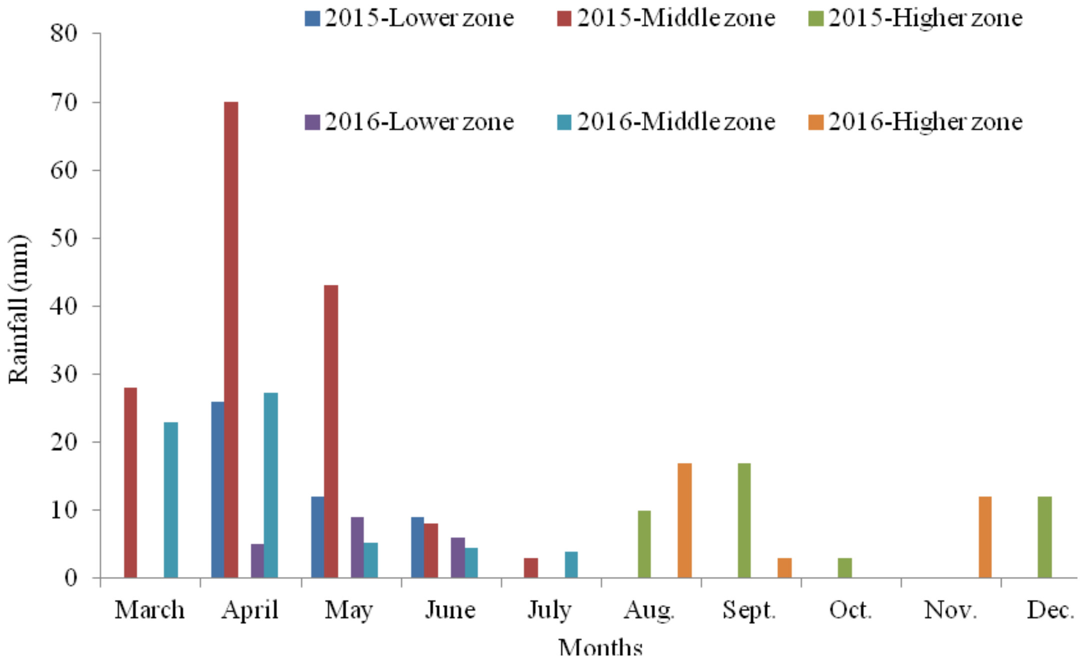

Figure 6: Rainfall trends in the lower, middle, and higher zones at the cropping period during the 2015 and 2016 long rainy seasons

3.6.2 Rainfall in the Middle Zone During the 2015, 2016 and 2017 Cropping Seasons

There were continuous experiments of rotations and intercropping of maize with common bean established in the middle agro-ecological zone. Water for supplemental irrigation during both short and long cropping seasons was possible due to the flowing irrigation canals from the higher slops of Mt. Kilimanjaro. Figure 7 presents rainfall data collected during the 2015-2017 long and 2015 and 2016 short rainy seasons throughout the crop growing periods. During the 2015 and 2016 short rainy seasons, rainfall was supplemented with irrigation throughout the growth stages of common bean and maize plants.

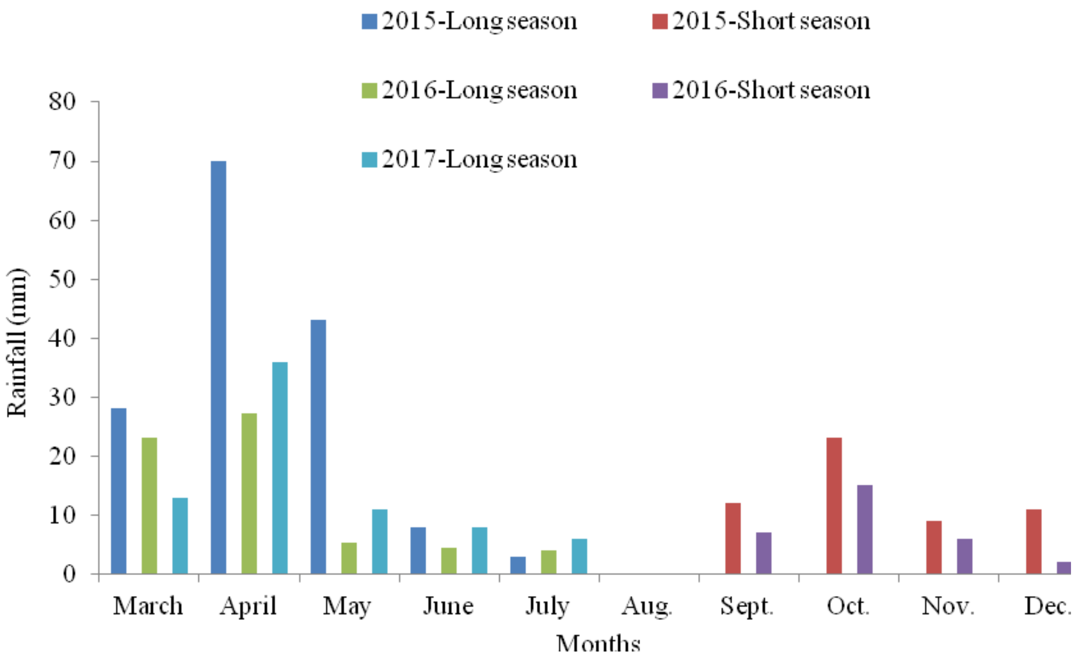

Figure 7: Rainfall trends in the middle zone at the cropping periods of 2015 to 2016 rainy seasons

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 Results

4.1.1 Effects of Cropping Seasons, Agro-ecological Zones and Cropping Systems on Bean Performance

The main effects of the cropping seasons and variations of agro-ecological zones were only significant on the number of pods per bean plant but not on other measured variables. The main effect of cropping systems was significant on the measured bean grain yield and the attributes of yield. The significantly higher bean grain yield (2.94 to 2.97 t ha^{-1}) was obtained in sole cropped bean compared with grain yield (1.94 to 2.13 t ha^{-1}) obtained in bean intercropped with maize. Results also indicated that total biomass followed a similar trend of grain yield where the significantly high biomass yield (7.4 t ha^{-1}) was obtained in sole cropped beans relative to the biomass yield (5.0 t ha^{-1}) obtained in beans intercropped with maize (Table 8).

Table 7: Grain yields, total biomass, number of pods per bean plant, number of seeds per pod, and weight of 100-seeds of common bean as affected by the cropping seasons, agro-ecological zones, cropping systems and their interactions

Factors	Sub-factors	Measured variables in common bean				
		Grain yield (t ha^{-1})	Biomass (t ha^{-1})	Pods per plant	Seeds per pod	100-seed wt (g)
Seasons/years (S)	2015	2.45[a]	5.52[a]	12[a]	3[a]	37.3 [a]
	2016	2.54[a]	5.63[a]	4[b]	2[a]	33.28[a]
Agro-ecological zones (A)	Lower agro-zone	2.22[a]	4.82[a]	6[b]	3[ab]	33.01[a]
	Middle agro-zone	2.64[a]	6.27[a]	7[b]	3[ab]	37.78[a]
	Upper agro-zone	2.63[a]	5.63[a]	12[a]	2[b]	35.09[a]
Cropping systems (C)	Monoculture local bean	2.97[a]	7.44[a]	13[a]	3[a]	25.83[c]
	Monoculture improved bean	2.94[a]	5.54[ab]	5[c]	2[b]	49.66[a]
	Intercropped local bean	2.13[b]	4.98[b]	10[b]	3[a]	23.52[c]
	Intercropped improved bean	1.94[b]	4.34[b]	5[c]	2[b]	42.16[b]
3 -WAY ANOVA (F-stat.)						
S		0.16 (*P* =0.717)	0.04 (*P* =0.858)	126.14 (*P* =0.002)	0.001 (*P* =0.976)	7.65 (*P* =0.070)
A		1.73 (*P* =0.219)	1.00 (*P* =0.395)	22.75 (*P* <0.001)	3.90 (*P* =0.050)	2.45 (*P* =0.128)
C		12.19 (*P* <0.001)	5.77 (*P* =0.002)	31.23 (*P* <0.001)	5.00 (*P* =0.004)	70.14 (*P* <0.001)
S×A		11.12 (*P* =0.002)	10.97 (*P* =0.002)	37.15 (*P* <0.001)	0.87 (*P* =0.443)	6.96 (*P* =0.010)
S×C		3.64 (*P* =0.018)	1.80 (*P* =0.159)	6.02 (*P* =0.001)	0.96 (*P* =0.417)	3.17 (*P* =0.031)
A×C		1.33 (*P* =0.261)	0.93 (*P* =0.481)	3.97 (*P* =0.002)	1.91 (*P* =0.095)	2.98 (*P* =0.014)
S×A×C		4.11 (*P* =0.002)	2.58 (*P* =0.028)	5.51 (*P* =0.002)	2.49 (*P* =0.034)	3.61 (*P* =0.004)

The means in a column for each of the measured variables bearing different letter(s) differ significantly

The interaction effects between cropping seasons and agro-ecological zones, cropping seasons and cropping systems and the interactions among cropping seasons, agro-ecologies and cropping systems were significant on bean grain yield. Results showed that continuous intercropping of a local bean with maize over two cropping seasons (2015 and 2016) resulted in the increase of bean grain yields by 53% (1.5 to 2.13 t ha^{-1}) in the lower altitude, 15% (2.0 to 2.3 t ha^{-1}) in the middle altitude, and 61% (1.8 to 2.9 t ha^{-1}) in the upper altitude. In addition, using intercrops of the improved bean with maize against the local bean variety had grain yield advantage of 162% and 52% in the lower and upper altitudes but with a yield drop by 86% in the middle altitude (Table 8). The interactions of cropping seasons and agro-ecological zones were also significant on other measured variables except for the number of seeds recorded in a pod. Further, the interaction effects between cropping seasons and cropping systems on one side and between agro-ecological zones and cropping systems on the other were significant on the number of pods per bean plant and 100-seed weight. Results indicated that the interactions of cropping seasons, agro-ecological zones and cropping systems were significant on all measured variables (Table 8). Appendix 3 presents grain yields of maize as affected by the agro-ecological zones, seasons of cropping, systems of cropping with the bean, and the interactions of these factors. The yield data related to cropping systems was used in the calculation of the LER.

The predictors of the suitability of a certain agro-ecological zone for sustainable intercropping of improved and local varieties of common bean with maize indicated varying results. In the lower zone, intercropping of improved bean variety with maize had a significant relationship between bean grain yield and the number of pods per bean plant and the total biomass (r =0.71; P =0.0485). In the middle zone, the significant relationships of grain yields were obtained with total biomass and 100-seed weight (r =0.78; P =0.0212) and with the number of pods per plant (r =0.83; P =0.0131) in improved bean variety intercropped with maize. Improved bean intercropped with maize in the upper zone recorded a significant relationship between bean grain yield and total biomass (r =0.80; P =0.0166). On the other hand, the local bean variety when intercropped with maize in the middle zone had significant relationships between bean grain yield and the number of pods per bean plant (r =0.78; P =0.0223). In the upper zone, the local bean intercropped with maize indicated a significant relationship between total biomass and bean grain yield (r =0.75; P =0.0300) and the number of pods per bean plant (r =0.81; P =0.0155).

The partial and total land equivalent ratios (LER) were used to verify the effectiveness of intensifying intercrops of both improved and local bean varieties with maize on smallholder farms. The partial land equivalent ratio of beans (PLER-bean) was significantly affected by the variation in agro-ecological zones (*P* =0.040) and by the differences in common bean varieties used (*P* =0.039) when intercropped with maize. There was no significant interaction effect of agro-ecological zones and common bean varieties on the PLER-bean (Table 9). The partial land equivalent ratio of maize (PLER-maize) and the total LER of intercropped bean and maize were not significantly affected by the agro-ecological zones, common bean varieties and/or their interactions. Intercrops of the local bean with maize produced total LER (1.57) larger than the intercrops of improved bean with maize (1.48), which averaged to a PLER of 1.53.

Table 8: Partial and total land equivalent ratios (PLER and LER) of maize and two varieties of common bean measured in different agro-ecological zones

Factors	Treatments		Measured variables in common bean		
			PLER-bean	PLER-m	LER-Total
Agro-ecological zones (S)	Lower zone		0.67[a]	0.72[a]	1.38[a]
	Middle zone		0.80[ab]	0.78[a]	1.58[a]
	Upper zone		0.84[b]	0.76[a]	1.61[a]
		S.E.D.	0.054	0.09	0.12
		P-value	0.040	0.793	0.21
		CV (%)	9.9	17.4	11.1
Bean varieties (V)	Improved bean		0.73[a]	0.75[a]	1.48[a]
	Local bean		0.81[b]	0.76[a]	1.57[a]
		S.E.D.	0.0368	0.08	0.08
		P-value	0.039	0.998	0.297
		CV (%)	5.6	14.5	5.8
2 -WAY ANOVA (F-stat.)					
S			5.77*	0.24ns	2.05ns
V			5.86*	0.001ns	1.23ns
S×V			0.44ns	2.05ns	2.6ns

LER is the land equivalent ratio, and PLER-bean and PLER-m are partial LER of beans and maize, respectively; S.E.D. = standard errors of differences of means; CV = coefficient of variation. The means in a column for each measured LER bearing different letter(s) for each assessed treatment in a specific category of factors differ significantly; * and ns are <0.05 and not significant respectively

4.1.2 Evaluating Intercrops of Maize and Common Bean over Five Cropping Seasons

(i) Effects of Cropping Seasons, Cropping Systems and Bean Varieties on Performance of Common Bean

Results of common bean performance are presented in Table 10. There was no significant effect of cropping seasons, cropping systems and common bean varieties interaction on total biomass, number of pods per common bean plant, number of seeds per pod, 100-seed weight, and bean grain yield. There was significant (P <0.001) effect of cropping seasons on bean total biomass and bean grain yield, 100-seed weight (P =0.005) and number of pods per bean plant (P =0.013). The 2015 long rainy season outperformed other cropping seasons for the bean total biomass (11 t ha^{-1}), number of pods per bean plant (9) and bean grain yield (3.0 t ha^{-1}). The 100-seed weight was higher in both 2015 (35.1 g) and 2016 (40.4 g) long rainy seasons compared with the 2015 short (28.6 g) and the 2016 long (29.5 g) rainy seasons (Table 10).

The effect of common bean varieties was significant (P <0.001) on total biomass, number of pods per bean plant, and the number of seeds per pod but not significant (P =0.842) on bean grain yields. The local bean variety *Mkanamna* outperformed the improved bean variety *Lyamungu 90* in total biomass (5.8 t ha^{-1}), number of pods per bean plant (8), number of seeds per pod (3), and bean grain yield (1.63 t ha^{-1}). Cropping systems were significant (P =0.019) on total biomass of common bean (Table 10). The interaction between cropping seasons and common bean varieties was significant on bean grain yield (P <0.001) and 100-seed weight (P =0.001). Significantly (P =0.001) higher 100-seed weights of 54.4 and 49.1 g in improved bean variety *Lyamungu 90* were obtained during the 2015 and 2016 long rainy seasons, respectively compared with 100-seed weights obtained in 2015 and 2016 short rainy seasons (Table 10). Significantly (P <0.001) higher bean grain yields of 3.5 and 2.2 t ha^{-1} were obtained in improved bean variety *Lyamungu 90* compared with 2.5 and 1.9 t ha^{-1} in local bean variety *Mkanamna* during the 2015 long and short rainy seasons. The lowest grain yields in both improved and local bean varieties were recorded during 2016 and 2017 long rainy seasons (Table 10).

Cropping seasons and cropping systems interaction was significant (P <0.001) on bean grain yield and total biomass (P =0.014). The total bean biomass (13.7 t ha^{-1}) obtained in monoculture beans during 2015 long rainy season was significantly (P =0.014) higher than that obtained in other cropping seasons. Total biomass of bean obtained from intercropping and monoculture during 2015 (3.9 t ha^{-1}) short and 2016 (3.3 t ha^{-1}) long rainy seasons was not statistically different (Table 10). On the other hand, significantly (P <0.001) higher bean grain yield was 3.2 t ha^{-1} in monoculture and 2.8 t ha^{-1} in intercropping during 2015 long rainy season compared with grain yields obtained in other cropping seasons. The lowest bean grain yields were 0.9 t ha^{-1} in intercropped bean during 2016 long rainy season and 0.2 t ha^{-1} in monoculture bean during 2017 long rainy season (Table 10). The effects of bean varieties and cropping systems interaction was significant (P =0.012) on the number of pods per individual bean plant. The higher number of pods per bean plant was ten in monoculture local bean. The lowest number of pods per bean plant was four in improved bean in monoculture and/or intercrop with maize (Table 10).

Table 9: Grain yield and yield components measured in common bean as affected by the cropping seasons, cropping systems, varieties of common bean and their interactions

Factors	Treatments	Measured variables in common bean				
		Total biomass (t ha^{-1})	Pods per plant	Seeds per pod	100-seed wt (g)	Yield (t ha^{-1})
Cropping seasons (S)	2015 – Long rainy season	11.0^{c}	9.0^{b}	2.7^{a}	35.1^{bc}	3.0^{d}
	2015 – Short rainy season	4.9^{b}	4.2^{a}	2.3^{a}	28.6^{a}	2.0^{c}
	2016 – Long rainy season	3.0^{ab}	5.4^{a}	3.1^{a}	40.4^{c}	1.3^{b}
	2017 – Long rainy season	0.5^{a}	4.8^{a}	2.3^{a}	29.5^{ab}	0.2^{a}
Cropping systems (C)	Monoculture	4.03^{a}	6.8^{a}	2.5^{a}	33.63^{a}	1.7^{a}
	Intercropping	5.65^{b}	4.9^{a}	2.6^{a}	33.19^{a}	1.6^{a}
Common bean varieties (V)	Improved bean *Lyamungu 90*	3.9^{a}	3.8^{a}	2.0^{a}	44.27^{b}	1.60^{a}
	Local bean *Mkanamna*	5.8^{b}	7.9^{b}	3.2^{b}	22.55^{a}	1.63^{b}
3 -WAY ANOVA (F-stat.)						
S		33.68***	6.37*	1.41ns	8.59**	61.29***
C		7.28*	4.26ns	0.09ns	0.08ns	1.92ns
V		17.69***	37.38***	17.1***	260.45***	0.04*
S×C		2.03ns	0.76ns	0.11ns	0.16ns	12.1***
S×V		2.19ns	0.31ns	1.3ns	7.44**	8.62***
C×V		5.43*	7.53*	0.001ns	0.71ns	0.16ns
S×C×V		1.17ns	2.06ns	0.62ns	0.13ns	0.68ns

The means in a column for each measured variables bearing different letter(s) for each assessed treatment in a specific category of factors differ significantly; ns, *, **, *** are ≤0.05, <0.01, <0.001, and not significant, respectively

Improved bean variety *Lyamungu 90* in monoculture had positive and significant correlation between total biomass and bean grain yield (*r* =0.85***; *P* =0.0001). Bean grain yield also correlated positively and significantly with ground coverage by leaf canopy at week 6 after sowing (*r* =0.70**; *P* =0.0035). There was positive and significant correlation (*r* =0.59*; *P* =0.0195) between bean grain yield and number of pods per bean plant (Table 11). In addition, positive and significant correlations between bean grain yield with total biomass (*r* =0.81***; *P* =0.0001) and number of pods per bean plant (*r* =0.56*; *P* =0.024) were observed in improved bean intercropped with maize (Table 12). Positive and significant correlations between bean grain yield with total biomass (*r* =0.67**; *P* =0.0043) and ground coverage at weeks 6 (*r* =0.77***; *P* =0.0004) and 7 (*r* =0.76***; *P* =0.0006) after sowing were obtained in local bean intercropped with maize (Table 13).

Table 10: Relationships between measured variables and the monoculture of improved bean variety *Lyamungu 90* for the measurements taken over four cropping seasons at 15 degree of freedom (d.f.)

		Correlations (r) and probabilities (*P*)								
	Measured variables	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
1	100-seed wt (g)	1								
2	Biomass (t ha^{-1})	0.14	1							
3	GC at Week 6	0.53 (0.0417)	0.50	1						
4	GC at Week 7	0.45	0.45	0.98 (0.0000)	1					
5	Ph at Week 6	-0.39	-0.07	-0.13	-0.04	1				
6	Ph at Week 7	-0.52 (0.0473)	-0.16	-0.07	0.04	0.74 (0.0016)	1			
7	Pods per plant	0.46	0.48	0.45	0.31	-0.66 (0.0078)	-0.64 (0.0105)	1		
8	Seeds per pod	0.01	0.42	0.28	0.34	0.22	0.34	-0.26	1	
9	Yield (t ha^{-1})	0.25	0.85 (0.0001)	0.70 (0.0035)	0.65 (0.0086)	-0.16	-0.14	0.59 (0.0195)	0.1 7	1

GC – ground coverage (%); Ph – plant height (cm). Two-sided test of correlations different from zero; probabilities (*P*) of significant correlation between contrasting variables are indicated in brackets

Table 11: Relationships of the measured variables for the improved bean variety *Lyamungu 90* intercropped with maize for the measurements taken over four cropping seasons at 15 degree of freedom (d.f.)

	Measured variables	1	2	3	4	5	6	7	8	9
		Correlations (r) and probabilities (*P*)								
1	100-seed wt (g)	1								
2	Biomass (t ha^{-1})	0.10	1							
3	GC at Week 6	0.41	0.29	1						
4	GC at Week 7	0.33	0.30	0.98 (0.0000)	1					
5	Ph at Week 6	-0.33	-0.52 (0.037)	-0.14	-0.09	1				
6	Ph at Week 7	-0.27	-0.53 (0.0349)	0.06	0.11	0.92 (0.0000)	1			
7	Pods per plant	0.18	0.80 (0.0002)	0.00	0.02	-0.52 (0.0411)	-0.51 (0.0435)	1		
8	Seeds per pod	-0.36	-0.11	-0.02	0.00	-0.07	-0.07	0.07	1	
9	Yield (t ha^{-1})	-0.17	0.81 (0.0001)	0.38	0.43	-0.34	-0.25	0.56 (0.024)	-0.06	1

GC – ground coverage (%); Ph – plant height (cm).Two-sided test of correlations different from zero; probabilities (*P*) of significant correlation between contrasting variables are indicated in brackets

Table 12: Relationships of the measured variables for the intercropped local bean variety *Mkanamna* for the measurements taken over four cropping seasons at 15 degree of freedom (d.f.)

		Correlations (r) and probabilities (*P*)								
	Measured variables	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
1	100-seed wt (g)	1								
2	Biomass (t ha^{-1})	-0.11	1							
3	GC at Week 6	-0.04	0.62 (0.0097)	1						
4	GC at Week 7	-0.07	0.59 (0.0163)	0.99	1					
5	Ph at Week 6	0.02	-0.28	-0.17	-0.14	1				
6	Ph at Week 7	0.20	-0.13	-0.04	0.00	0.70 (0.0025)	1			
7	Pods per plant	0.14	0.27	0.26	0.27	-0.31	-0.56 (0.0243)	1		
8	Seeds per pod	-0.47	0.16	0.27	0.27	-0.11	-0.29	0.19	1	
9	Yield (t ha^{-1})	0.00	0.67 (0.0043)	0.77 (0.0004)	0.76 (0.0006)	-0.48	-0.21	0.19	-0.09	1

GC – ground coverage (%); Ph – plant height (cm). Two-sided test of correlations different from zero; probabilities (*P*) of significant correlation between contrasting variables are indicated in brackets

(ii) Effects of cropping seasons and cropping systems on performance of maize

Cropping seasons were significant (*P* <0.001) on 100-seed weight and maize grain yield, and maize total biomass (*P* =0.002). The highest total biomass of maize (6.8 and 6.6 t ha^{-1}) was obtained during 2016 short and 2017 long rainy seasons, respectively. The lowest total biomass of maize (3.2 t ha^{-1}) was recorded during 2015 long rainy season. The largest weight of 100-seed was 39.0 g obtained in 2017 long rainy season. All long rainy seasons and 2015 short rainy season recorded significantly higher maize grain yields ranging from 2.3 to 2.6 t ha^{-1} as opposed to the lowest maize grain yield (0.8 t ha^{-1}) obtained in 2016 short rainy season. Cropping systems were not significant on total biomass of maize, 100-seed weight, and maize grain yield. Further, there was no significant effect of the interaction of cropping seasons and cropping systems on total biomass of maize, 100-seed weight, and maize grain yield (Table 14).

Table 13: Grain yield and yield components of maize as affected by the cropping seasons, cropping systems and their interactions

Factors	Treatments	Measured variables in maize		
		Total biomass (t ha^{-1})	100-seed wt (g)	Yield (t ha^{-1})
Cropping seasons (S)	2015 – Long rainy season	3.2^{a}	27.8^{a}	2.4^{b}
	2015 – Short rainy season	4.6^{a}	35.5^{bc}	2.6^{b}
	2016 – Long rainy season	4.8^{a}	32.3^{b}	2.3^{b}
	2016 – Short rainy season	6.8^{b}	33.8^{b}	0.8^{a}
	2017 – Long rainy season	6.6^{b}	39.0^{c}	2.5^{b}
Cropping systems (C)	Maize monoculture	5.13^{ab}	32.02^{a}	2.04^{a}
	M+Ly90	4.87^{a}	33.97^{a}	2.03^{a}
	M+Lb	5.58^{b}	35.00^{a}	2.25^{a}
2 -WAY ANOVA (F-stat.)				
S		8.58**	10.28***	13.84***
C		0.73ns	1.54ns	0.45ns
S×C		0.74ns	0.82ns	0.69ns

M+Ly90 and M+Lb are maize intercropped with improved *Lyamungu 90* and local *Mkanamna* bean varieties, respectively. The means in a column for each measured variables bearing different letter(s) for each assessed treatment in a specific category of factors differ significantly; ns, **, *** are not significant, <0.01, and <0.001, respectively

Positive and significant correlation (*r* =0.48*; *P*=0.0325) was obtained between maize grain yield and ground coverage by leaf canopy at week seven after sowing in monoculture maize (Table 15). Positive and significant correlation (*r* =0.63**; *P* =0.0036) was also observed between 100-seed weight and total biomass of maize in maize intercropped with the local bean variety *Mkanamna* (Table 16).

Table 14: Relationships of the measured variables for the monoculture maize for the measurements taken over five cropping seasons at 18 degree of freedom (d.f.)

		Correlations (r) and Probabilities (*P*)						
	Measured variables	**1**	**2**	**3**	**4**	**5**	**6**	**7**
1	Biomass (t ha^{-1})	1						
2	GC at Week 6	-0.22	1					
3	GC at Week 7	-0.29	0.95 (0.0000)	1				
4	Ph at Week 6	0.04	0.09	0.03	1			
5	Ph at Week 7	0.09	0.13	0.06	0.90 (0.0000)	1		
6	100-seed wt (g)	0.39	0.00	-0.01	-0.18	0.06	1	
7	Yield (t ha^{-1})	0.12	0.42	0.48 (0.0325)	0.42	0.41	0.04	1

GC – ground coverage (%); Ph – plant height (cm). Two-sided test of correlations different from zero; probabilities (*P*) of significant correlation between contrasting variables are indicated in brackets

Table 15: Relationships of measured variables for the maize intercropped with local bean variety *Mkanamna* for the measurements taken over five cropping seasons at 18 degree of freedom (d.f.)

		Correlations (r) and probabilities (*P*)						
	Measured variables	**1**	**2**	**3**	**4**	**5**	**6**	**7**
1	Biomass (t ha^{-1})	1						
2	GC at Week 6	-0.69 (0.001)	1					
3	GC at Week 7	-0.68 (0.0015)	0.95 (0.0000)	1				
4	Ph at Week 6	-0.22	0.28	0.26	1			
5	Ph at Week 7	-0.18	0.28	0.24	0.93 (0.0000)	1		
6	100-seed wt (g)	0.63 (0.0036)	-0.39	-0.37	-0.56 (0.0119)	-0.44	1	
7	Yield (t ha^{-1})	0.42	0.08	0.22	0.06	0.09	0.17	1

Two-sided test of correlations different from zero; probabilities (*P*) of significant correlation between contrasting variables are indicated in brackets. GC – ground coverage (%); Ph – plant height (cm)

The PLERs and overall LER were assessed to derive land benefits associated with intercrops of maize and the local bean variety *Mkanamna* and improved bean variety *Lyamungu 90*. The LER in intercrops ranged from 1.39 to 1.60 throughout the cropping seasons of maize and the two varieties of common bean. However, the LER of both long and short rainy seasons in 2015 were above 50%. Based on the cropping systems, intercropping maize with the local bean yielded LER of 1.55, which is in line with the LER recorded in 2015 cropping seasons. The LER obtained in intercrop of maize with improved bean was 1.48 (Table 17).

Table 16: Partial (P) and total land equivalent ratios (LERs) of improved bean variety *Lyamungu 90*, local bean variety *Mkanamna* intercrops with maize for the measurements presented from each cropping season of the year

Factors	Treatments	$PLER_{bean}$	$PLER_{maize}$	LER-Total
Cropping seasons (S)	2015-long rainy season	0.80^{a}	0.80^{ab}	1.60^{a}
	2015-short rainy season	0.69^{a}	0.88^{b}	1.58^{a}
	2016-long rainy season	0.80^{a}	0.60^{a}	1.39^{a}
	2017-long rainy season	0.83^{a}	0.66^{ab}	1.49^{a}
Bean varieties (V)	Improved *Lyamungu 90*	0.77^{a}	0.72^{a}	1.48^{a}
	Local bean *Mkanamna*	0.80^{a}	0.75^{a}	1.55^{a}
2 -WAY ANOVA (F-stat.)				
S		0.28ns	4.2*	1.25ns
V		0.2ns	0.38ns	1.06ns
S×C		0.3ns	0.69ns	0.82ns

Means in a column bearing different letter(s) for each assessed treatment in a specific category of factors differ significantly. $PLER_{bean}$ and $PLER_{maize}$ are partial land equivalent ratios (LERs) of common bean and maize in intercrops, respectively and LER-Total is the total LER of $PLER_{bean}$ and $PLER_{maize}$; ns and * are not significant and ≤0.05 respectively

(iii) Soil properties in the middle zone after intercropping experiments

The properties of soils involved in the intercropping experiments of maize and common bean in the middle zone are presented in Table 18. The pH, SOC, total N and available P were not significantly affected by the intercropping of maize and common bean in comparing with the initial results presented in Table 7. Although the soil pH increased depending on the cropping systems and the crop involved, the increase was more in plots where the local bean was cultivated in monoculture and in plots where the improved bean was intercropped with maize. In such plots the soil reaction changed from strongly acid (pH 5.6–6.0) to slightly acid (pH 6.0–6.5). The SOC was decreased but not significantly in all soils. The total N increased in soils from low (0.1% to 0.2%) to medium (0.21% to 0.50%) but the increase was higher in the cropping systems where the improved and local beans were included. There was a decrease in soil available P but the decrease was not significant hence maintaining the high status of greater than 25 mg P kg^{-1}.

Table 17: Chemical properties of the soils in the middle zone Kimashuku site after the intercropping experiments of maize and common bean

Cropping	Soil properties							
	pH		SOC		N		P	
	Value	Status	Value (%)	Status	Value (%)	Status	Value (mg kg^{-1})	Status
M	6.085[a]	Increased	2.47[a]	Decreased	0.34[a]	Increased	27.35[a]	Decreased
IB	6.038[a]	Increased	2.13[a]	Decreased	0.29[a]	Increased	24.89[a]	Decreased
LB	6.125[a]	Increased	2.25[a]	Decreased	0.40[a]	Increased	26.13[a]	Decreased
M+IB	6.105[a]	Increased	2.14[a]	Decreased	0.41[a]	Increased	28.33[a]	Decreased
M+LB	6.022[a]	Increased	2.42[a]	Decreased	0.36[a]	Increased	27.41[a]	Decreased
P prob.	0.48		0.207		0.974		0.14	
s.e.d.	0.064ns		0.170ns		0.202ns		1.285ns	

Means in the same column bearing similar letter(s) did not differ significantly. M = maize; IB = improved bean; LB = local bean; *P* prob. = probability; s.e.d. = standard errors of differences of means; ns means not significant ($P \geq 0.05$); SOC = soil organic carbon; N = nitrogen; P = phosphorus

4.1.3 Assessing Rotations of Maize and Common Bean over FIve Cropping Seasons

(i) Effects Cropping Seasons, Cropping Systems and Bean Varieties on Performance of Common Bean during Long Rainy Seasons

The main effect of years of cropping was significant on all measured yield and yield components of common bean except the number of seeds per pod. The effect of cropping systems was significant on yield and all yield attributes of common bean but not on seeds per pod and 100-seed weight. The main effect of bean varieties on yield and yield related variables was significant except on total biomass. The effects of years, cropping systems and bean varieties interaction were significant on grain yield and 100-seed weight. The highest bean grain yield (5.0 t ha^{-1}) was obtained in local bean intercropped with maize in 2017 cropping season while the largest 100-seed weight (56.28 g) was in improved bean intercropped with maize in 2016 cropping season. Significantly higher bean grain yield (4.4 t ha^{-1}) was obtained in 2015 cropping season for beans intercropped with maize as interaction effects of years and cropping systems. Similar significant interaction effects of years and cropping systems were in 100-seed weight (40.25 g) where the higher weight was obtained in 2016 on plots which common bean started and ended during the years of experiment involved rotation with maize.

The significantly higher bean grain yield (3.38 t ha^{-1}) was obtained in improved bean in 2015 as effects of interaction between years and bean varieties. Similar significant interaction effects were observed with higher total biomass (9.58 t ha^{-1}) obtained in bean intercropped with maize in 2015 and 100-seed weight (55.08 g) recorded in improved bean in 2016. Further, significantly higher grain yield (4.6 t ha^{-1}) was obtained in local bean intercropped with maize as interactions of cropping systems and bean varieties. The main effect of bean variety on total biomass test statistic W was 0.9409 (P =0.002) and Chi-square of 0.00 on 1^o of freedom (P =1.000). The main effect of years of cropping on the number of seeds per pod test statistic W was 0.9885 (P =0.759) and Chi-square of 4.76 on 2^o of freedom (P =0.093) (Table 19).

Table 18: Grain yield (t ha^{-1}) and yield components including total biomass (t ha^{-1}), number of pods per bean plant, number of seeds per pod, 100-seed weight and yield of common bean as affected by the long cropping seasons of years, bean varieties, cropping systems and their interactions

Factors	Assessments	Measured variables in common bean				
		Yield (t ha^{-1})	Total biomass (t ha^{-1})	Pods per plant	Seeds per pod	100-seed wt (g)
Years of cropping (S)	2015 –Long rainy season	3.3^{b}	8.8^{b}	10^{b}	2.7^{a}	34.6^{b}
	2016 –Long rainy season	1.8^{a}	3.6^{a}	7^{a}	3.2^{a}	39.8^{c}
	2017 –Long rainy season	1.4^{a}	2.1^{a}	7^{a}	2.9^{a}	31.6^{a}
Cropping systems (C)	F&E (Rotation with maize)	1.5^{a}	4.4^{a}	6^{a}	3.2^{b}	35.1^{ab}
	Intercrop with maize	1.6^{a}	5.9^{b}	10^{c}	2.9^{ab}	36.4^{b}
	Monoculture	3.4^{b}	4.2^{a}	8^{b}	2.7^{a}	34.5^{a}
Variety (V)	Improved bean *Lyamungu 90*	1.6^{a}	4.4^{a}	5^{a}	2.2^{a}	48.4^{b}
	Local bean *Mkanamna*	2.7^{b}	5.3^{a}	11^{b}	3.7^{b}	22.3^{a}
3-WAY-ANOVA (F-stat.)						
S		90.55 (*P* <0.001)	45.14 (*P* <0.001)	21.68 (*P* =0.002)	0.63 (*P* =0.562)	384.43 (*P* <0.001)
C		70.14 (*P* <0.001)	3.87 (*P* =0.04)	5.12 (*P* =0.017)	0.73 (*P* =0.496)	0.77 (*P* =0.480)
V		45.30 (*P* <0.001)	1.52 (*P* =0.228)	53.7 (*P* <0.001)	28.28 (*P* <0.001)	451.57 (*P* <0.001)
S×C		9.38 (*P* <0.001)	0.82 (*P* =0.531)	1.01 (*P* =0.429)	0.64 (*P* =0.643)	3.25 (*P* =0.036)
S×V		21.35 (*P* <0.001)	4.42 (*P* =0.022)	0.96 (*P* =0.394)	0.06 (*P* =0.938)	4.8 (*P* =0.016)
C×V		20.25 (*P* <0.001)	0.39 (*P* =0.681)	0.53 (*P* =0.596)	0.22 (*P* =0.802)	3.06 (*P* =0.064)
S×C×V		3.02 (*P* =0.035)	1.84 (*P* =0.151)	0.45 (*P* =0.77)	0.26 (*P* =0.901)	3.48 (*P* =0.020)

Means with different letter(s) in a column differed significantly from each other. F&E means common bean started (F =First) and ended (E =Ended) in the plot during the years of experiment involved rotation of common bean and maize

Multiple linear regressions analysis indicated that total biomass (*P* <0.001) and the number of seeds per pod (*P* =0.014) have a strong and significant influence on bean grain yield during the long rainy season. In addition, the number of pods per plant, ground coverage and plant height after seven weeks had a positive contribution to grain yield although the influence is not significant (Table 20).

Table 19: Estimates of parameters generated from multiple linear regression analysis based on three long cropping seasons as their relationships with bean grain yield

Parameter	estimate	s.e.	t(63)	t pr.
Constant (C)	-0.69	1.2	-0.57	0.568
100-seed weight (g)	-0.0092	0.0109	-0.85	0.401
Total biomass (t ha^{-1})	0.1681	0.0361	4.66	<0.001
Pods per plant	0.044	0.036	1.22	0.226
Seeds per pod	0.2386	0.0947	2.52	0.014
Ground coverage (%) at week 6	0.0131	0.0226	0.58	0.563
Ground coverage (%) at week 8	0.0238	0.0272	0.88	0.384
Plant height (cm) at week 6	-0.0931	0.023	-4.05	<0.001
Plant height (cm) at week 8	0.033	0.0223	1.48	0.145

The percentage variance accounted for is 65.3 and the standard error of observations is estimated to be 0.998; s.e. is the standard error; t(63) is the total number of observations/frequency, t pr. is the test probability

(ii) Effects of cropping systems and bean varieties on the performance of common bean in a short rainy season

Grain yield and yield attributes of common bean for the measurements taken in the 2015 short rainy season are presented in Table 21. The main effect of cropping systems was significant on grain yield while bean variety was significant on the number of pods per bean plant. Sowing of the bean as part of a rotation with maize in situations where maize started on the plot produced higher grain yield (1.8 t ha^{-1}) compared with grain yield (1.7 t ha^{-1}) obtained in bean sown as a monoculture. The main effect of bean varieties was significant on the number of pods per bean plant. The interaction effects of cropping systems and bean varieties on total biomass test statistic W was 0.9603 (*P* =0.667) and Chi-square of 4.90 on 3^0 of freedom (*P* =0.179) (Table 21).

Table 20: Grain yield (t ha^{-1}) and yield components including total biomass (t ha^{-1}), number of pods per bean plant, number of seeds per pod, 100-seed weight and yield of the common bean as affected by the long cropping seasons of years, bean varieties, cropping systems and their interactions

		Measured variables in common bean				
Factors	**Assessments**	**Yield (t ha^{-1})**	**Total biomass (t ha^{-1})**	**Pods per plant**	**Seeds per pod**	**100-seed wt (g)**
Cropping systems (C)	Bean after maize (rotation)	1.8[b]	4.0[a]	4.6[a]	2.4[a]	29.7[a]
	Continuous bean (monoculture)	1.7[a]	3.9[a]	4.8[a]	2.2[a]	29.3[a]
Variety (V)	Improved bean *Lyamungu 90*	1.8[a]	3.9[a]	2.8[a]	2.3[a]	32.3[a]
	Local bean *Mkanamna*	1.6[a]	4.1[a]	6.5[b]	2.3[a]	26.6[a]
2-WAY-ANOVA (F-stat.)						
C		22.63 (P =0.018)	0.01 (P =0.939)	0.03 (P =0.867)	0.2 (P =0.688)	0.04 (P =0.85)
V		3.54 (P =0.109)	0.09 (P =0.778)	15.76 (P =0.007)	0.001 (P =0.955)	1.81 (P =0.228)
C×V		0.43 (P =0.536)	0.001 (P =0.974)	0.41 (P =0.547)	0.02 (P =0.894)	5.59 (P =0.056)

Means with different letter(s) in a column differed significantly from each other

Multiple linear regressions analysis results between bean grain yield and measured variables are presented in Table 22. The results indicated that 100-seed weight, total biomass and bean plant height had a positive influence on the increase in grain yield of beans.

Table 21: Estimates of parameters generated from multiple linear regression analysis based on a single short cropping season (2015) as their relationships with bean grain yield

Parameter	estimate	s.e.	t(63)	t pr.
Constant (C)	1.718	0.633	2.71	0.03
100-seed weight (g)	0.0178	0.0118	1.51	0.174
Total biomass (t ha^{-1})	0.0397	0.0221	1.79	0.116
Pods per plant	-0.0089	0.0447	-0.2	0.847
Seeds per pod	-0.0377	0.0407	-0.93	0.385
Ground coverage at week 6	-0.124	0.169	-0.74	0.486
Ground coverage at week 8	0.124	0.164	0.76	0.474
Plant height at week 6	-0.0016	0.0172	-0.09	0.929
Plant height at week 8	-0.0054	0.0143	-0.38	0.717

The percentage variance accounted for is 40.0 and the standard error of observations is estimated to be 0.148; s.e. is the standard error; t(63) is the total number of observations/frequency, t pr. is the test probability

(iii) Effects of cropping seasons and cropping systems on performance of maize during long rainy seasons

The main effect of long seasons of cropping years was significant on total biomass (*P* =0.019) and 100-seed weight (*P* =0.014) with the higher yield of 5.9 t ha^{-1} and 40.13 g, respectively in 2017 long season. The main effect of the cropping system was significant on maize grain yield (*P* =0.039) and total biomass (*P* =0.026). The interactions of both long seasons of cropping years and cropping systems were not significant on all variables measured in maize. The significantly higher maize grain yield (2.9 t ha^{-1}) and total biomass (6.2 t ha^{-1}) were obtained in maize sown as part of the rotation with the local bean variety *Mkanamna* as the main effect of cropping systems. There was no significant effect of cropping seasons and cropping systems interactions on the measured variables in maize during long cropping seasons for three years (Table 23). The main effect of cropping seasons on maize grain yield test statistic W was 0.9548 (*P* =0.111) and Chi-square of 0.94 on 1^0 of freedom (*P* =0.333). The main effect of cropping seasons on total biomass test statistic W was 0.9594 (*P* =0.160) and Chi-square of 0.19 on 1^0 of freedom (*P* =0.666). In addition, the main effect of cropping systems on 100-seed weight test statistic W was 0.9815 (*P* =0.744) and Chi-square of 6.10 on 4^0 of freedom (*P* =0.192) (Table 23).

Table 22: Grain yield, total biomass and 100-seed weight of maize as affected by the long seasons of cropping years, cropping systems and their interactions for the measurements taken over three long cropping seasons (2015 to 2017)

Factors	Assessments	Measured variables in maize		
		Yield (t ha^{-1})	Total biomass (t ha^{-1})	100-seed wt (g)
Years of cropping (S)	2015 –Long rainy season	2.4^{a}	3.2^{a}	28.45^{a}
	2016 –Long rainy season	2.5^{a}	5.3^{ab}	29.35^{a}
	2017 –Long rainy season	2.2^{a}	5.9^{b}	40.13^{b}
Cropping systems (C)	M+L90AftM	2.0^{ab}	4.1^{ab}	32.24^{a}
	M+LbAftM	1.8^{a}	3.6^{a}	29.93^{a}
	M-Cont	2.3^{ab}	4.6^{ab}	31.69^{a}
	MAftL90	2.7^{ab}	5.8^{ab}	33.21^{a}
	MAftLb	2.9^{b}	6.2^{b}	34.66^{a}
2-WAY-ANOVA (F-stat.)				
S		0.52 (*P* =0.619)	8.3 (*P* =0.019)	9.42 (*P* =0.014)
C		2.83 (*P* =0.039)	3.15 (*P* =0.026)	1.14 (*P* =0.352)
S×C		1.15 (*P* =0.355)	1.26 (*P* =0.295)	2.0 (*P* =0.074)

Means with different letter(s) in a column differed significantly from each other. *Key:* M + L90AftM is maize intercropped with the improved bean variety *Lyamungu 90* sown after sole maize; M+LbAftM is maize intercropped with the local bean variety *Mkanamna* sown after sole maize; M-cont is maize sown continuously (monoculture); MAftL90 is maize sown in rotation with the improved bean variety *Lyamungu 90*, MAftLb is maize sown in rotation with the local bean variety *Mkanamna*; s.e.d. is the standard errors of differences of means

The multiple linear regressions analysis results between maize grain yield and measured variables from 2015 to 2017 long rainy seasons are presented in Table 24. The results indicated that total biomass had significant (*P*<0.001) influence on the increase in maize grain yield. Other important attributes of an increase in maize grain yield during long cropping rainy seasons included maize plant height and ground coverage over time although the impact is not significant (Table 24).

Table 23: Estimates of parameters generated from multiple linear regression analysis based on three long cropping seasons (2016 and 2017) as their relationships with maize grain yield

Parameter	estimate	s.e.	t(33)	t pr.
Constant (C)	-0.037	0.803	-0.05	0.964
Ground coverage (%) at week 6	-0.01634	0.00922	-1.77	0.082
Ground coverage (%) at week 8	0.0083	0.0123	0.68	0.502
Plant height (cm) at week 6	0.00576	0.00394	1.46	0.149
Plant height (cm) at week 8	0.0046	0.00375	1.23	0.225
Total biomass (t ha^{-1})	0.3452	0.0251	13.78	<.001
100-seed weight (g)	-0.00133	0.0092	-0.14	0.886

The percentage variance accounted for is 80.7 and the standard error of observations is estimated to be 0.438; s.e. is the standard error; t(63) is the total number of observations/frequency; t pr. is the test probability

(iv) Effects of short cropping seasons and cropping systems on performance of maize

The main effect of short seasons of cropping years was significant on maize grain yield (*P* =0.007) and total biomass of maize (*P* =0.03) but not on 100-seed weight. The 2015 short rainy season produced higher maize grain yield (2.6 t ha^{-1}) than maize grain yield (1.8 t ha^{-1}) produced in the 2016 short rainy season. However, the significantly higher total biomass (8.1 t ha^{-1}) was obtained in maize cultivated in the 2016 short rainy season. The main effect of cropping systems and interactions with the short seasons of cropping years on all measured variables of maize in 2015 and 2016 short showers of rain were not significant. The results also indicated that interactions between short seasons of cropping years and cropping systems of maize were not significant on all measured variables in maize (Table 25).

Table 24: Grain yield, total biomass and 100-seed weight of maize as affected by the short seasons of cropping years, cropping systems and their interactions for the measurements taken over short cropping seasons of two years (2015 and 2016)

Factors	Assessments	Measured variables in maize		
		Yield (t ha^{-1})	Total biomass (t ha^{-1})	100-seed wt (g)
Years of cropping (S)	2015 –Short rainy season	2.6^{b}	5.0^{a}	34.92^{a}
	2016 –Short rainy season	1.8^{a}	8.1^{b}	32.20^{a}
Cropping systems (C)	Monoculture	1.6^{a}	6^{a}	33.28^{a}
	M-AftM+Lb	1.8^{a}	5.6^{a}	33.59^{a}
	M-AftLb	1.9^{a}	6.1^{a}	34.61^{a}
	M-AftM+L90	2^{a}	7^{a}	34.21^{a}
	M-AftL90	2.1^{a}	8^{a}	32.12^{a}
2-WAY-ANOVA (F-stat.)				
S		43.7 (P =0.007)	15.04 (P =0.03)	2.13 (P =0.24)
C		0.34 (P =0.847)	2.35 (P =0.083)	0.33 (P =0.855)
S×C		0.38 (P =0.822)	0.78 (P =0.547)	0.42 (P =0.791)

Means with different letter(s) in a column differed significantly from each other. ***Key:*** M-AftM+Lb is maize sown after an intercrop of maize and the local bean variety *Mkanamna*; M-AftLb is maize sown after the local bean variety *Mkanamna*; M-AftM+L90 is maize sown after an intercrop of maize and the improved bean variety *Lyamungu 90*; M-AftL90 is maize sown after the improved bean variety *Lyamungu 90*

Multiple linear regressions analysis results between maize grain yield and other measured variables in 2015 and 2016 short rainy seasons are presented in Table 26. The results indicated that total biomass had positive and significant (*P* =0.003) influence on the increase in grain yield of maize during short rainy seasons of the two years.

Table 25: Estimates of parameters generated from multiple linear regressions analysis based on two short seasons of cropping years (2015 and 2016) as their relationships with maize grain yield

Parameter	estimate	s.e.	t(33)	t pr.
Constant (C)	-2.08	1.31	-1.58	0.123
Ground coverage (%) at week 6	-0.0097	0.0176	-0.55	0.586
Ground coverage (%) at week 8	0.0452	0.0147	3.08	0.004
Plant height (cm) at week 6	0.0044	0.0106	0.41	0.683
Plant height (cm) at week 8	-0.00122	0.0062	-0.2	0.846
Total biomass (t ha^{-1})	0.1815	0.0566	3.21	0.003
100-seed weight (g)	0.0009	0.025	0.04	0.971

The percentage variance accounted for is 55.2 and the standard error of observations is estimated to be 0.699; s.e. is the standard error; t(63) is the total number of observations/frequency; t pr. is the test probability

(v) Soil properties in the middle zone after rotational cropping experiments

Rotational cropping of maize and common bean resulted to the increase of soil pH, SOC, total N and available P (Table 27) relative to the results presented in Table 7. The pH of the soil did not change significantly but the reaction was around slightly acid (6.1–6.5). The SOC increased from 3.737% to 4.487% compared with the initial SOC of 3.07% before establishment of the experiment. Total N in soils increased from 0.266% to 0.427% but the increase was higher in the cropping systems where the improved and local beans were included. Rotational cropping of maize and the improved bean had higher total N in soils (0.364%) than the total N (0.266% to 0.287%) recorded in soils where maize was cultivated in rotation with the local bean. The highest total N (0.427%) was obtained in soils where the intercrop of maize and the local bean was cultivated in rotation with the pure maize. Relatively low total N in soils (0.322%) was obtained where the intercrops of maize and the improved bean were rotated with the pure maize. Soil available P decreased in all cropping systems but the decrease realized in soils where the improved bean was cultivated in monoculture was down to a medium category (13–25 mg P kg^{-1} soil).

Table 26: Some chemical properties of the soils in the middle zone Kimashuku site after rotational cropping experiments of maize and common bean

Cropping	**Soil properties**							
	pH		**SOC**		**N**		**P**	
	Value	Status	Value (%)	Status	Value (%)	Status	Value (mg kg^{-1})	Status
M monoculture	6.085[a]	Increased	4.332[a]	Increased	0.336[a]	Increased	27.35[a]	Decreased
IB monoculture	6.038[a]	Increased	3.737[a]	Increased	0.287[a]	Increased	24.89[a]	Decreased
LB monoculture	6.125[a]	Increased	3.948[a]	Increased	0.399[a]	Increased	26.13[a]	Decreased
M-F&E in IB	6.01[a]	Decreased	4.487[a]	Increased	0.364[a]	Increased	28.49[a]	Decreased
M-F&E in LB	6.043[a]	Increased	4.053[a]	Increased	0.266[a]	Increased	26.75[a]	Decreased
IB-F&E in M	6.09[a]	Increased	4.105[a]	Increased	0.364[a]	Increased	26.96[a]	Decreased
LB-F&E in M	6.075[a]	Increased	4.298[a]	Increased	0.287[a]	Increased	28.12[a]	Decreased
M+IB rotat. M	6.08[a]	Increased	4.020[a]	Increased	0.322[a]	Increased	27.62[a]	Decreased
M+LB rotat. M	6.108[a]	Increased	4.455[a]	Increased	0.427[a]	Increased	25.87[a]	Decreased
P prob.	0.95		0.387		0.966		0.288	
s.e.d.	0.090ns		0.3348ns		0.1449ns		1.417ns	

Means in the same column bearing similar letter(s) did not differ significantly. **Key:** M = maize; IB = improved bean; LB = local bean; M-F&E in IB = maize started (F) and ended (E) in seasons of rotational cropping with the improved bean; M-F&E in LB = maize started (F) and ended (E) in seasons of rotational cropping with the local bean; IB-F&E in M = improved bean started (F) and ended (E) in seasons of rotational cropping with maize; LB-F&E in M = local bean started (F) and ended (E) in seasons of rotational cropping with maize; M+IB rotat. M = intercrop of maize with improved bean rotated with maize; M+LB rotat. M = intercrop of maize with local bean rotated with maize; *P* prob. = probability; s.e.d. = standard errors of differences of means; ns means not significant ($P \geq 0.05$); SOC = soil organic carbon; N = nitrogen; P = phosphorus

4.2 Discussion

4.2.1 Productivity of Bean Intercrops with Maize Across Agro-ecological Zones

The present study provides a better insight that seasons of the year, altitudes, and cropping systems are the important elements in improving productivity of common bean in intercrops with maize on smallholder farms. This is supported by the main effects of the cropping seasons and agro-ecological zones on the production of many pods per bean plant as this has implication on the seeds formed and the resultant grain yield. The pods per plant in 2016 dropped from 12 to 4 in 2015 while grain yield and biomass were almost the same in both years. This could be attributed to a delay in the onset of rainy season and the rains were little with short distribution in 2016 growing period compared with 2015 growing period. Through field observation, many pods were formed per bean plant during the 2015 growing period but these pods senesced before harvest and therefore were not captured during data collection.

The main effects of cropping systems were realized on all measured variables related to yield and grain yield. The significantly higher bean grain yields (2.9–3.0 t ha^{-1}) obtained in monoculture beans relative to grain yields (1.9–2.1 t ha^{-1}) obtained in beans intercropped with maize signify the importance of cropping systems on the overall productivity of common bean (Nassary *et al*., 2020). Interactions of the cropping seasons with the agro-ecological zones and cropping systems were significant on bean grain yield. Exceptions of the interaction effects on bean grain yields were observed between agro-ecological zones and cropping systems probably due to the lack of the effect of cropping seasons. The increase in bean grain yields in intercrops with maize over two cropping seasons (2015 and 2016) suggests yield advantage derived from these intercrops, which could be attributed to the complementarities of growth resources between the bean and maize plants. It is also likely that there are additional nutrients or their levels and improvement of soil quality between the two cropping seasons during off seasons (Nassary *et al*., 2020). This finding shows the implication of cropping systems on the productivity of common bean when intercropped with maize (Nassary *et al*., 2020). Intercropping common bean with maize can also be a useful tool in breeding for environmental adaptability due to associated competitions on one side and niche complementarity on the other (O'Leary & Smith, 2004).

The low bean grain yields obtained in intercrops in the lower and upper zones could be attributed, probably, to the competition encountered by bean plants from maize plants. In addition, rainfall in the lower zone was lower and poorly distributed due to the short cycle hence induced higher inter-specific competitions between crops in intercrops. The upper zone is relatively cool due to higher altitude with closer proximity to the forest belt, which probably retarded bean plants in intercrops with maize. These arguments are similar to the findings of a study conducted by Matusso *et al*. (2014) that crops with C4 photosynthetic characteristics, like maize, are competitively dominant in the system when intercropped with C3 species, like the common bean. Low performance of common bean in intercrop with maize could also be associated with the short root system of beans and their shallow distributions, which probably reduced competitive advantage for the growth factors such as light, nutrients, water, and space (Mucheru-Muna *et al*., 2011; Karuma *et al*., 2016). According to Mekbib (2003), common bean production is determined by the interactions of environments and the cropping systems employed. The number of pods produced by individual bean plant has implications on the grains formed and yield and the cropping systems should be a critical factor to consider in each agro-ecological zone. It is also likely that common bean in an intercrop with maize created good niche complementarity between each other for water, light, and nutrients such as N-fixed, phytoavailability of P from phosphates, and solubility of micronutrients including iron (Fe), zinc (Zn), manganese (Mn), and copper (Cu) (Zhang *et al*., 2010; Dotaniya *et al*., 2013).

The performance of common bean was not significantly influenced by the cropping seasons × agro-ecologies × cropping systems interactions, deviating from Keba (2018), which may be explained by the differences in these factors (Baijukya *et al*., 2016). According to Atuahene-Amankwa *et al*. (1998), evidence of bean varieties and cropping system interactions indicates the advantages of interactions by selecting compatible intercrops. Consistent with the findings of the present study, Mebrahtu *et al*. (2001) found that bean genotypes and management interactions were significant on grain yields of legumes. The inherent soil properties, agronomic practices, decisions of farmers to allocate resources or combinations of these have been among the drivers of the variability of crop performance (Baijukya *et al*., 2016).

There is variability in relationships of the critical variables considered in identifying the productivity of bean and maize intercrops in each agro-ecological zone. Comparing three agro-ecological zones, an intercrop of common bean with maize is best suited in the lower and middle zones and this could be explained by the growth and branching habit as well as the nature of canopy architecture of the studied bush beans (Nassary *et al*., 2020). Studies conducted by Woolley and Rodriguez (1987) and Atuahene-Amankwa *et al*. (1998) indicated that positive relationships between common bean grain yields sown in intercrop with cereals could predict the performance of the bean crop and the overall system productivity.

The variation in agro-ecological zones and differences in common bean varieties used as component crops to maize were significant on the PLER of bean with the higher PLER-bean recorded in the middle and upper agro-ecological zones but not in the lower zone. This finding could be attributed to the increase in organic matter and nutrients pool in the middle and upper zones compared with the lower zone where livestock grazing is by nomadic pastoralist (Hai District Profile, 2011; Funakawa *et al*., 2012). Further, the higher total LER (1.58) was obtained in the middle zone indicating better land utilization advantage over other zones. The significant PLER of beans as the main effect of the variation in bean varieties could be attributed to the differences in grain yields between these varieties. The two bean varieties used in the present study also substantiate the significance of this finding as their individual total LERs ranged from 1.48 to 1.57.

The land utilization advantage derived from intercrops of these bean varieties with maize could be attributed to their competitive advantages over the effects associated with a component maize crop for light, nutrients, and water (Baijukya *et al*., 2016; Vendelbo *et al*., 2017; Nassary *et al*., 2020). These beans also add more residues and nutrients in the soil after decomposition as they shed most of their leaves on the ground at senescence. The LER obtained in the present study involving intercrops with common bean and maize are greater than 1.36 obtained by Alemayehu *et al*. (2018) in simultaneously sown intercrops of maize and common bean. Saban *et al*. (2007) also reported LER greater than 1.0 with intercrops of bean and maize. Alemayehu *et al*. (2018) found that the interaction of cropping and different varieties of common bean had no significant effect on LER similar to the findings of the present study. The LERs greater than 1.0 in all intercrops show advantages derived from land utilization efficiency of intercropping common bean with maize over sole cropping of each crop. These findings suggest that more lands will be required in the monoculture of either of the component crops to produce the same yield obtained from their intercropping (Willey, 1979).

In summary, the cropping seasons and variations of agro-ecological zones and the cropping systems deployed indicate some promising options for sustainable intensification of common bean in an intercrop with maize on smallholder farms where land resource is scarce. The productivity of a common bean is determined by the main effects of cropping seasons, agro-ecological zones, and well designed bean-maize intercrops relative to bean monoculture. However, bushy varieties of common bean crop cultivated as part of intercrops with maize are best suited in the lower Tindigani and middle Kimashuku agro-ecological zones with altitude ranging from less than 900 to 1350 m above sea level. The apparent and variable interaction effects of cropping seasons, agro-ecological zones, and cropping systems on the performance of beans is related to the influence of complementarities and/or facilitation between the two crops.

4.2.2 Productivity of Maize and Common Bean Intercrops over Five Cropping Seasons

In assessing the performance of common bean, the significant interaction effects of cropping seasons and bean varieties on bean grain yield and 100-seed weight indicates that the effect of cropping systems was not expressed over the cropping seasons. This, further, showed that seasonal variation in combination with the sown variety of a bean is important in achieving optimum grain yield. It further suggests that variety selection for the two afore-mentioned variables is highly affected by the cropping seasons, which could be either short or long rainy seasons.

Of the measured variables in common bean, only the number of pods per individual bean plant differed significantly as affected by the interaction between cropping systems and bean varieties. This finding is consistent with Gebeyehu *et al*. (2006), who found that the genotypes and cropping systems interaction were significant for the number of seeds per pod, 100-seed weight, harvest index and seed yield in common bean. The 100-seed weight was significantly affected by the cropping seasons only in improved bean relative to the local bean, which was not statically different throughout all cropping seasons. An explanation to this difference observed in 100-seed weights as an effect of interaction of cropping seasons and bean varieties could be due to small size and vigour of the seed of the local bean. This could have reduced vulnerability of the local bean variety to seasonal variations and the likely inherent discrepancies in acquisition and utilization of growth resources. In contrast, the seed of improved bean variety *Lyamungu 90* is large with improved vigour. This finding indicates that the local bean variety is more stable (100-seed weight, yield), but realizing lower yield in some years compared with the improved bean variety. This depicts also a general observation for varieties improved under high-yielding conditions (Hillocks *et al*., 2006; Baijukya *et al*., 2016). Significant effect of common bean varieties and cropping systems interactions on number of nodules per plant, number of pods per bean plant, seed length and seed coat in common bean intercropped with maize has also been reported by Santalla *et al*. (2001).

The highest bean grain yields found in improved bean range from 2.2 to 3.5 t ha^{-1} but 0.18 to 2.5 t ha^{-1} in local bean for the measurements taken in all cropping seasons. These findings reflect the impact of seasonal variability, particularly rainfall, and the variety of common bean on the performance of common bean during the growth period (Baijukya *et al*., 2016). The improved bean outperformed the local bean based on cropping season and bean variety interaction. However, this may not be true for all years as also the farmer may be interested above all with a stable yield, instead of some years with very high yields. Bean grain yields were higher for intercrop than monoculture in 2017 contrary to similar seasons in 2015 and

2016. These are similar seasons but appearing in different years, which also varied in the amounts of rainfall, temperature, and the abundance and severity of diseases and pests which affected the performance of plants. The experiments were also conducted completely in the open fields hence the crops encountered many effects from the environments and the biotic factors.

The interactions of cropping seasons and cropping systems significantly affected the bean total biomass and bean grain yields indicating their inseparable importance on the two bean varieties. This suggests that either sowing of any one of these bean varieties in sole or intercrop with maize will have impact on total biomass and the bean grain yield. Furthermore, cropping seasons for the two bean varieties significantly affected total biomass, bean grain yield, 100-seed weight, and the number of pods per bean plant. This finding suggests that the onset, availability and distribution of rain in the cropping season are important in the overall performance of the studied bean varieties (Munishi *et al.*, 2015). However, beans were sown simultaneously with the maize early in the season, which might have affected performance of the bean plants and the resulted grain yield. It has been shown that early sowing in the season of a grain legume in intercrops with maize could result in flowering, pod setting and maturation coinciding with the peak of rainfall leading to high diseases and pests' pressure thereby reducing grain yield (Kermah *et al*., 2018). In contrast, late sowing of the same grain legumes as part of an intercrop with the maize crop may coincide with insufficient rainfall resulting into the failure or low grain yield in the legume (Kermah *et al*., 2018).

The local common bean variety performed better than the improved bean in total biomass, number of pods per bean plant, and number of seeds per pod. The effect of cropping systems was only significant on common bean total biomass suggesting that monoculture and intercropping of any of these bean varieties with maize resulted in varying total biomass. With regard to the difference of intra- and inter-specific competition, e.g. for the maize crop (taller crop, high N-acquisition), the inter-specific competition is lower than the intra-specific competition with common bean (Brooker *et al*., 2015). Therefore, the maize crop has advantages when grown in an intercrop with the studied varieties of common bean.

The performance of maize was evaluated based on growth variables, yield and yield components with respect to cropping seasons and systems of including any of the two bean varieties. Only the cropping seasons significantly affected 100-seed weights, grain yield and total biomass. Except for the 2016 short rainy season, which had poor performance of maize crops due to shortage of rains and/or water for supplemental irrigation other rainy seasons produced maize grain yields ranging from 2.3 to 2.6 t ha^{-1}. This finding suggests that maize crop productivity is dependent on the water either from rain or irrigation at all active developmental stages of the crop. There was no significant effect of cropping systems on maize measured variables. However, studies have shown that maize and common bean intercrops with application of synthetic fertilizers increased the total grain yield compared with the sole maize due to efficient utilization of growth resources (Kermah *et al*., 2017). The increase in productivity of contrasting crop species when are growing in intercrops is also associated with facilitation, sharing, and complementarity in resource acquisition and their efficient utilization (Dakora & Phillips, 2002; Brooker *et al*., 2015).

Land equivalent ratio (LER) was used to evaluate land utilization benefits of intercrops over sole crops/monocultures of maize and contrasting varieties of common bean. There is a slight discrepancy between LERs of intercrops between maize and common bean combinations compared with monoculture of each crop where land is increased by over 40%. The LER 1.55 suggests that there is 55% greater land area requirement for the monoculture system or 55% greater relative yield for intercropping of maize with local bean variety *Mkanamna* and/or 55% greater biological efficiency for intercropping these two crops. Similar description holds for the LER 1.48 obtained in an intercrop of maize with the improved bean variety *Lyamungu 90*. Studies (Pelzer *et al*., 2014; Yu *et al*., 2016) indicate that environmental factors including weather conditions, soil fertility or soil quality related to the productivity of intercrops result in unexplained variation in LER. High variability in rainfall and soil properties of the study area is also reflected by the results of the present study (Funakawa *et al*., 2012; Munishi *et al*., 2015). These findings suggest that land utilization advantages derived from maize and common bean intercrops will depend on the situations where some given yield ratios of both crops are needed by the farmer (Willey, 1985). For instance, both maize and common bean are highly needed as staple food and cash crops along with improvement of soil fertility through N_2-fixation by the bean. On the criterion of land requirement for maize and common bean intercrops, the local bean variety *Mkanamna* outperforms improved bean variety *Lyamungu 90*. Herein, not maize and common bean are compared but the benefits derived from intercrops of maize with any of the studied contrasting bean varieties at the magnitude of their overall systems productivity.

The higher LER obtained in intercrop of maize with the local bean variety *Mkanamna* could be attributed to competitive advantage of this bean in an intercrop for efficiently utilize growth resources including light, nutrients, water and ability of N_2-fixation (Latati *et al*., 2016). Abera *et al*. (2017) found that the LERs of intercropping with maize and the local and improved varieties of common bean ranged from 1.01 to 1.34. However, greater LERs are not necessarily indicators of higher yielding crops under monoculture as there are interactions associated with varieties and cropping systems (Abera *et al*., 2017). In the present study, maize and common bean were sown simultaneously in every cropping season and the overall LERs were 1.48 and 1.55 using maize intercropped with improved and local bean varieties, respectively. Simultaneously sown improved variety of maize with common bean has been indicated to yield maximum LER of 1.53 (Gebru, 2015; Abebe *et al*., 2017). The higher but non-significance LER obtained in local bean variety *Mkanamna* could be attributed to the growth habit of this bean of escaping shading effect from tall maize crop in intercrops and captures more light as well as its efficient utilization for production of nutrient enriched residues and N_2-fixation (Baijukya *et al*., 2016; Vendelbo *et al*., 2017). The local bean variety *Mkanamna* has additional advantages over improved bean variety *Lyamungu 90* as it sheds most of its leaves on ground at senescence, which provides more N-inputs to the soil after decomposition. The added N in soils is used by the component maize crop in a continuous practice of intercropping with the bean crop (Kamanga, 2002; Franke *et al*., 2016). However, the non-significance of the LERs could mean that the advantage of intercropping, in this study, was independent of the common bean variety, which perhaps could also be seen as an encouraging result. Storkey *et al*. (2015) indicated that growing species in intercrops will improve multi-functionality compared with monocultures in sustainable delivery of multiple benefits on the same piece of land.

The soil reaction (pH) in the middle zone did not change significantly as an influence of the cropping systems. There was no variation in soils where maize and the local and improved bean varieties were sown in monocultures or as intercrops. The total N increased by 0.7% in soils where maize was intercropped with the improved bean and by 0.2% in soils where maize was intercropped with the local bean compared with the soils where maize was cultivated in monoculture. The SOC increased by 7.6% and 1% in soils where maize was intercropped with local and improved beans, respectively compared with the SOC recorded in the soils where the two bean varieties were sown in monoculture. Further, the higher SOC recorded in soils where maize was intercropped with the local bean could be attributed to the formation of many leaves by this bean variety, which dropped on the land at senesce and decomposed (Nassary *et al*., 2020). Studies have indicated that continuous cultivation of multiple crops depletes SOC and reduces soil quality compared to native vegetation, regardless of the cropping system practiced (Oldfield *et al*., 2019; Tesfahunegn & Gebru, 2020).

Intercropping of maize and common bean resulted in higher available P in soils compared with the P measured in soils where these crops were cultivated in monoculture. The increased available P in soils as an impact of intercropping maize with common bean could be attributed to the facilitation and complementarity between the two species (Brooker *et al*., 2015; Latati *et al*., 2016; Nassary *et al*., 2020). According to Latati *et al*. (2016), common beans are capable of producing phosphatase activity, which increases the mineralization of organic P and facilitates its availability in soils and uptake by the component maize crop. However, the soil available P measured at the end of the intercropping experiment was lower than the initial amount of P measured before the establishment of this experiment. This finding suggests that part of P was taken-up by the plants and probably some of it was coupled with high adsorption and fixation, thus contributing to its deficiency (Mndzebele *et al*., 2020). The amount of total N recorded in the soil of the present study for the measurements taken at the end of intercropping experiments signified the importance of a common bean crop in fixing atmospheric N to the system. Rodriguez *et al.* (2020) found a higher total soil N acquisition in a legume + cereal system than in a sole legume system. According to Rodriguez *et al.* (2020), intercropping of cereals and grain legumes stimulated complementary use of the fixed N between the component crops by increasing the amount of N-fixation by the grain legume and increasing the acquisition of soil N by the cereal crop.

Potassium (K) is another primary macronutrient (after N and P) (Marschner, 1990), which was deficient in the soils of the study areas. However, there was no any application of K made to crops in this study in form of NPK or as potassium chloride (KCl) due to shortage of funds. Further, it was not easy to order KCl due to procedures associated with laboratory complications and its application as NPK could have compromised the contribution of common bean to soil N nutrition through BNF (Reinprecht *et al*., 2020; Wu *et al*., 2020). In contrast to N or P deficiencies, checked by application of urea and TSP, the effect of K deficiency is pronounced more on crops with storage roots than on the fruits and seeds storage crops. In common bean and maize, it is fruits (pods) and seeds (grains) are the food storage parts hence K deficiency is not likely to cause much yield loss. The main function of K is to alleviate the consequences of drought stresses by regulating the physiological and biochemical processes in these plants (Liu *et al*., 2013; Ul-Allah *et al*., 2020).

In summary, the interaction effects of cropping seasons and bean varieties were significant on bean grain yield and 100-seed weight. The improved bean variety Lyamungu 90 outweighed the local bean variety Mkanamna with grain yields ranging from 2.2 to 3.5 t ha-1 and 0.18 to 2.5 t ha-1, respectively. Cropping seasons were also significant on all measured variables in beans but cropping systems were only significant in total biomass. Cropping seasons significantly affected all measured variables in maize 100-seed weights, grain yield and total biomass with grain yields ranging from 2.3 to 2.6 t ha-1. The LERs of intercrops between maize and common bean showed that the saved lands were 48 and 55%, which would have been required as additional land for monoculture of each crop (maize or common bean) if not intercropped. In this study, both varieties of common bean were sown simultaneously with the maize, which might have resulted in differential performance of these bean varieties. There is a need to include studies on time of introducing a legume crop in the cropping system such as early sowing, sowing mid in the season after a maize crop is well established, and sowing late in the season when the leaves in maize plant have started to senesce.

4.2.3 Productivity of Maize and Common BEAN Rotations over Five Cropping Seasons

The main effects of long seasons of cropping years, cropping systems, bean varieties and their interactions significantly increased bean grain yields suggesting that these factors are important factors to consider in the production of the common bean through rotation/intercropping with maize. The main effect of long seasons of cropping years contributed to the higher bean grain yield (3.3 t ha^{-1}) in 2015 compared with other years. However, delay of rains in 2016 and 2017 long seasons could be one of the causes of low grain yields obtained in the bean. Further, the sowing of the common bean as part of a continuous intercrop with maize produced higher bean grain yield (3.4 t ha^{-1}) compared with bean sown as a monoculture and/or in rotations with maize where common bean started and ended in the cultivated land. The main effect of cropping systems was also realized on 100-seed weight (56.28 g) obtained in improved bean intercropped with maize in 2016. These main effects (on grain yield and 100-seed weight) were observed after one year with two seasons of cropping (long and short in 2015) in which the same cropping systems (intercrops with maize) were always maintained on the same plots. The findings of the present study show that bean intercropped with maize was always higher in grain yield compared with bean sown in monoculture and/or in rotation with maize in all long seasons. The higher performance of common bean in intercrops with maize could be attributed to complementarities between maize and common bean for growth resources including light, water and nutrients (Nassary *et al*., 2020).

In assessing the main effect of bean varieties, the local bean variety produced significantly higher grain yield (2.7 t ha^{-1}) than the improved bean variety (1.6 t ha^{-1}), which could be due to adaptability and escaping mechanisms of the local bean to harsh climatic conditions. The local bean is also characterized by delayed growth during adverse conditions before sets for flower setting and/or rather delayed development, production of pods, smaller seed size and a more vigorous vine growth (Rurangwa *et al*., 2018; Nassary *et al*., 2020). The local bean variety also produces more leaves, which resulted in more ground coverage before leaf senescence and consequent improvement of soil health. Most of these leaves fall on the ground before bean plants are harvested and add organic residues and nutrients to the soil when they decompose and benefit crops in the subsequent cropping season. Besides, there was a lower incidence and severity of insect pests and diseases throughout the growing period for the local bean variety *Mkanamna* cropping systems compared with those systems where improved bean variety *Lyamungu 90* was included (Vendelbo *et al*., 2017; Nassary *et al*., 2020). There are also other additional but not clearly distinguished 'rotation effects', which are associated with rotations involving common bean as grain legumes on improving systems productivity (Giller, 2001; Kamanga, 2002; Franke *et al*., 2016). These 'other rotation' effects, include improvement of soil physical and chemical properties, hastening of soil microbial activity, elimination of phytotoxic substances, application of growth-promoting (GP) substances and reduced disease incidence (Peoples & Crasswell, 1992; Giller, 2002). These 'other rotation' effects warrant further investigation as they are not assessed in the present study. The higher performance of local bean than the improved bean substantiates the adaptability of the local bean to harsh climatic conditions and the realization of stable yield (Baijukya *et al*., 2016). Further, the significant contribution of total biomass and the number of seeds per pod on bean grain yield over long cropping seasons of years is also justified by the multiple linear regression analysis between grain yield and the measured variables in the present study.

The interactions between long cropping seasons of years and cropping systems were significant on grain yield (4.4 t ha^{-1}) in 2015 in bean intercropped with maize compared with bean sown as a monoculture (2.8 t ha^{-1}) or as part of a rotation (2.7 t ha^{-1}). This rotation is such that bean starts and ends in the long cropping season but maize is included in the short season, which is between the two long cropping seasons. Further, the importance of intercrops is observed in 2017 (i.e. 3rd long season) in bean intercropped with maize where the higher grain yield (3.5 t ha^{-1}) was recorded compared with grain yields obtained in bean monoculture (0.33 t ha^{-1}) and bean rotated with maize (0.28 t ha^{-1}) in the same year. These findings signify the importance of cropping seasons and the system by which bean is included in the maize-based cropping systems in a given long cropping season. In addition, the findings depict that apart from considering long cropping seasons, it is also important to consider intercropping and/or rotational advantages of bean in maize-based systems over a monoculture bean.

The interactions between years and bean varieties were significant on grain yield (3.4 t ha^{-1}) in improved bean in 2015 compared with local bean variety and other long cropping seasons (2016 and 2017). However, in 2016 and 2017 long rainy seasons the grain yields were 2.9 and 1.9 t ha^{-1} respectively in the local bean, which was superior to those obtained in improved bean (0.7 and 0.9 t ha^{-1}) in the same years. These findings provide an insight that better performance of improved bean is well observed at the beginning of experimentation but its continuous cultivation over time is negatively affected, probably, by variations in climatic factors including rains. On the other hand, the local bean seems to be stable in the production of better grain yield over time, which could be due to its adaptability and coupling mechanisms to harsh environments.

The effects of cropping systems and bean varieties interactions were significant on grain yield (4.6 t ha^{-1}) in a local bean intercropped with maize compared with the improved bean (2.2 t ha^{-1}) using the same cropping system. Rotational cropping where bean starts and ends in seasons (such that maize is cropped between bean seasons) also resulted in a higher grain yield (1.8 t ha^{-1}) in the local bean than the grain yield (1.2 t ha^{-1}) in the improved bean. These findings suggest that the local bean variety *Mkanamna* had more competitive advantage than the improved bean variety *Lyamungu 90* in maize intercrops and/or rotations. This is probably due to trailing growth habit of escaping shading effect from tall maize and the ability to add more residues and nutrients to the soil as also indicted by Nassary *et al*. (2020). These findings provide an insight that growth characteristics of bean need to be well known before the bean crop is included in maize-based cropping systems.

The effect of long cropping seasons of years, cropping systems, and bean varieties interactions were significant on grain yield (4.4 t ha^{-1}) in intercrops of common bean with maize in 2015. The significantly higher 100-seed weight (40.25 g) was obtained in 2016 in a cropping system where the common bean was cultivated during long rainy seasons and rotated with maize cultivated during short rainy seasons. Between 2015 and 2016 long seasons is the 2015 short season during which sole maize was in the same plots. This finding suggests that the practice of including maize between two long seasons of cropping common bean is an important option to increase the weight of seeds and hence resultant grain yield in the bean. The performance of common bean crop assessed during the short rainy season (2015), which is preceded by a single cropped long season (2015), provides varying insights about bean grain yield and other yield attributes. Even so not significance, the higher grain yield obtained in the bean due to the effect of cropping systems was based on situations where bean crop was sown as part of a rotation with maize such that maize started on the same plots during the previous long rainy season (in 2015). This finding suggests that maize created a favourable environment where the subsequent bean crop was well suited for growth and production of better grain yield than yields in plots where the bean was continuously cultivated over successive cropping seasons.

Besides the fact that this is a short rainy season, crops in the experimental fields were supplemented with irrigation and no disease and insect pests observed during the entire period of crop growth. The main effects of bean varieties was significantly higher in the number of pods per bean plant (7) in the local bean compared with the pods (3) produced in the improved bean. This finding reflects some characteristics of the local bean variety *Mkanamna* of producing many leaves, pods and seeds compared with the improved bean variety *Lyamungu 90*. The improved bean variety *Lyamungu 90* is highly affected by environmental conditions such as drought, excessive rains and the outbreak of disease and insect pests although it is bred for high yielding (Baijukya *et al*., 2016). Drought caused grain yield of the improved bean variety *Lyamungu 90* to drop by 86% while that of the local variety remained almost the same. However, this shortcoming should not deny the improved bean variety *Lyamungu 90* from been advised for cultivation by the smallholder farmers. The seeds of the improved bean variety *Lyamungu 90* used in the present study had additional advantage on weight (almost twice) over the local bean variety *Mkanamna* hence can still be recommended for smallholder farmers especially where weight is the acceptable market measure.

Further analysis of the results through multiple linear regressions provides an insight that increases in grain yield of the bean during the short rainy season are largely determined by the height of a bean plant, 100-seed weight and the total biomass of beans although the increase is not significant. This finding provides an important indication of the factors to be put into consideration to increase grain yield in common bean when are cultivated during short cropping seasons (Nassary *et al*., 2020). In addition, it is important to consider the outcomes related to the sowing of bean in rotation with maize (and which crop starts in a field), and/or sowing in a monoculture along with these factors.

The performance of maize under rotation with common bean produced interesting results. The main effect of long cropping seasons of years was significantly higher on maize total biomass (5.9 t ha^{-1}) and 100-seed weight (40.13 g) in 2017 compared with total biomass yield produced in 2015 and 2016 long rainy seasons. This finding suggests that long seasons are important in the increase in total biomass and weight of seeds in maize, which are also related to grain yield. Further, significantly higher grain yield (2.9 t ha^{-1}) and total biomass (6.2 t ha^{-1}) were produced in maize sown as part of a rotation with the local bean variety *Mkanamna* as the main effect of cropping systems. This grain yield was higher than maize grain yield (2.7 t ha^{-1}) obtained in the rotation of maize with improved bean variety *Lyamungu 90*, monoculture maize (2.3 t ha^{-1}), and/or with other cropping systems (1.8 and 2.0 t ha^{-1}) used in the present study. This finding reflects, probably, soil fertility improvement in situations where the bean is included in rotation with maize but much advantage is derived from the local bean, which may be through larger quantities of decomposed residues (Rurangwa *et al*., 2018). Further analysis through multiple linear regression indicated that a significant increase in maize grain yield in long rainy seasons (2015 to 2017) is dependent largely on the quantities of total biomass. This finding suggests that an increase in total biomass will result in grain yield advantages of maize over long rainy seasons. There are other important reasons for an increase in maize grain yield including increased maize plant height and the extent at which the crop covers ground over time of growth although the impact is not significant. Ojiem *et al*. (2014) indicated that legumes increased maize grain yield when included as part of rotation compared with maize sown in a monoculture. These arguments are also supported by the importance of N_2-fixing grain legumes in rotation with a non-fixing maize crop (Giller, 2002; Papastylianou, 2004; Rurangwa *et al*., 2018).

The increase in maize grain yields in rotations with the two contrasting bean varieties also depicts a rotational effect, which was not necessarily due to benefits gained from residual N_2-fixed but improvement in overall soil health/quality (Franke *et al*., 2016). Previous studies have also indicated that other rotational benefits are derived from the improvement of soil properties and increase in mycorrhizal infection as well as shielding against disease and pests to the subsequent maize crop (Argaw *et al*., 2015; Gan *et al*., 2015; Munishi *et al*., 2015). The findings of the present study are also consistent with studies conducted elsewhere (Wahbi *et al*., 2016; Niyuhire *et al*., 2017). Kamanga (2002) pointed that the subsequent cereal crop utilizes at least 50% of the N returned to the soil through the incorporation of dead and decomposed legume residues over the growing season.

Apart from the importance of common bean on N_2-fixation for the subsequent maize crop, rainfall content is an important factor to consider. Thilakarathna *et al*. (2019) indicated that rainfall variation is critical to the performance of common bean interventions on smallholder farmers. The inclusion of N_2-fixing legumes as part of a rotation with maize is also indicated to be an important economic approach that provides farmers with an alternative of those most appropriate for their farms (Goplen *et al*., 2018). In addition, the use of legumes in rotation with maize on smallholder farms reduces costs associated with the purchasing of N-containing fertilizers for the maize crop in the subsequent season (Yost *et al*., 2014). In the present study, the main effect of cropping seasons produced significantly higher maize grain yield (2.6 t ha^{-1}) in the 2015 short rainy season compared with maize grain yield (1.8 t ha^{-1}) produced in 2016 short rainy season. The similar main effect of short cropping season produced significantly more total biomass (8.1 t ha^{-1}) was obtained in maize cultivated in 2016. The significantly higher maize grain yield obtained in the 2015 short season could be attributed to some rains experienced during that season compared with the 2016 short season, which relied completely on supplemental irrigation of crops in the field. The shortage of rains during these cropping seasons could be the reason for lack of significant impact of cropping systems on the measured variables in maize including grain yield. Further analysis of the results through multiple linear regressions indicates that increases in grain yield of maize during short rainy seasons are proportional to the increase of maize total biomass.

There was variation in the amounts of total N and available P as well as SOC and soil pH for the measurements taken at the end of a rotational cropping experiment. Rotational cropping of maize and common bean resulted in the increase of soil pH, SOC, total N and available P following a period of five cropping seasons. The reaction of the soils was adjusted from strongly acid (pH 5.6–6.0) before the establishment of the experiment to slightly acid (pH 6.1–6.5) at the end of the experiment. The use of the improved and local bean varieties had an important influence on the increase of SOC in cropping systems signifying the contribution of grain legumes to the improvement of soil organic matter (Giller, 2001). Crop rotation increases soil organic carbon if measurements are taken during the fallowing phase but this benefit is lost quickly during the cropping phase (Nyamadzawo *et al*., 2008).

Rotational cropping of pure maize and/or its intercrops with the improved and local beans contributed to the increase in soil total N. Comparing the intercrops of maize with the two varieties of common bean, resources facilitation and complementarities between maize and the local bean produced higher total N (0.427%) than with the improved bean (0.322%). This finding suggests that the local bean is more profitable than the improved bean in fixing and distribution of atmospheric N when sown in intercrop or rotation with the non-N_2-fixing crop like maize (Nassary *et al*., 2020). The soil available P decreased in all cropping systems but the decrease realized in soils where the improved bean was cultivated in monoculture was down to a medium (13–25 mg P kg^{-1} soil). Apart from the fact that nutrient P was applied at sowing, the decrease realized at the end of the experiment was low indicating that the two crop species (maize and common bean) had a good complementarity in enhancement/facilitation and the utilization of this nutrient (Brooker *et al*., 2015). The roots of grain legumes are capable of scavenging the deep residual soil N and increase its availability to the subsequent non-legume crops (Riedell *et al*., 2009). The cropping systems where grain legumes are included in rotation with maize increase the uptakes of nutrients like Ca, N, P and K (Riedell *et al*., 2009). Rotation of crops differing in the root architecture facilitates the availability of the nutrients P and K through their distribution within the soil profile (Marschner, 1990).

In summary, the present study provides an insight that cropping seasons (of the years), and interactions of these seasons with cropping systems (intercrops and/or rotations) and the types of bean varieties (local and/or improved) are the important drivers of intensification of maize and common bean rotations on smallholder farms. Inclusion of intercrops (of both maize and common bean) as part of a rotation with one of these crops is an important element to intensify rotational cropping as they also overcome risks associated with food insecurity that could be caused by a complete failure of one crop in the season.

CHAPTER FIVE

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

The findings of this study have revealed important options for the sustainable intensification of common bean cultivation to improve food security and income to the smallholder farmers in the northern highlands of Tanzania. One of the options was continuous cultivation of the improved and/or local varieties of common bean in intercrops with the maize throughout both long and short rainy seasons of the year. Another option was cultivation of the improved and/or local varieties of common bean intercropped with maize in long rainy season and rotating of these intercrops with the maize cultivated in short rainy seasons. The primary benefits derived from intercrops across altitudes were related to the greater resource capture through uptake of nutrients and utilization of light and water.

The main effects of the cropping seasons, altitudes, cropping systems, and their interactions were significant on bean grain yields during long rainy seasons. Although the rains were very low, being long seasons was an advantage that there was residual moisture for crop use. Intercropping of maize and common bean across the three altitudes provided an insight that these intercrops can potentially be intensified.

The productivity of intercrops of maize and common bean in the middle altitude Kimashuku site using bimodal rainy seasons was independent of the bean varieties. The higher land saved in intercrops of common bean and maize in the middle altitude and/or across altitudes exceeded 30%. The assessed soil pH, SOC, total N and available P showed different trends with the cropping of maize and common bean and/or their intercropping. The soil reaction (pH) increased from strongly acid (5.6–6.0) to slightly acid (6.1–6.5) in the cultivated soils relative to the uncultivated soils. Total N increased signifying the importance of bean in fixing atmospheric N to the system and the complementarity in its utilization by the component crops. The SOC and available P decreased suggesting that organic matter was mineralized slowly or part of C was not captured by the method of extraction used and part of P was taken-up by the plants and probably some of it was coupled with high adsorption and fixation, thus contributing to its decrease.

Rotational cropping where intercrops of maize and common bean were cultivated in rotation with any of these crops was more productive than a commonly practiced rotational system of one crop subsequent to another. In comparing the weight of 100 dry seeds, the local bean variety *Mkanamna* had almost half the weight of improved bean variety *Lyamungu 90* with the same number of seeds. This study indicated that the improved bean is worth noting for marketing apart from volume, where weight is the accepted standard marketing measure of beans.

Rotational cropping of maize and common bean had effects on the soil pH, SOC, total N, and available P. The soil reaction pH increased from strongly acid (5.6–6.0) to slightly acid (6.1–6.5) in the cultivated soils relative to the uncultivated soils except in soils where maize started the rotational cycle with the improved bean and the same maize ended in the firth cropping season. Total N and SOC increased suggesting that common bean provided additional N to the soil through symbiosis with rhizobia in fixation of atmospheric N and decomposition and mineralization of both maize and bean residues after harvest. The increase in SOC is also related to the higher levels of organic matter added to the soil by the plant residues. Soil available P decreased relative to the initial P but not to below 25 mg P kg^{-1} suggesting that there was high nutrients facilitation, complementarities, and sharing between the two crop species during rotational cropping.

The new information/facts found in this study, which were not there in the literature, depended on the cropping systems of maize and common bean in the northern highlands of Tanzania. Firstly, there were no intercropping experiments where two varieties of common bean (improved and local varieties) were cultivated in intercrops with maize over long periods thereby taping both long and short rainy seasons on smallholder farms especially in the tropical highlands. Secondly, no experiments where the intercrops of maize and common bean (improved and/or local varieties) have been cultivated during long rainy season and rotated with the maize cultivated in the short rainy season. Thirdly, there has not been any study before that compared the market benefits (value) in weight basis reflected in the seeds of the improved bean variety (e.g. the *Lyamungu 90*) relative to the local bean variety (e.g. the *Mkanamna*) under normal cultivation settings of the smallholder farmers in Tanzania or elsewhere in tropics.

5.2 Recommendations

The findings of this study summarized the performance of common bean intercropped with maize across three altitudes using only two cropping long rainy seasons as well as continuously intercropped in middle altitude using short and long rainy season. The benefits derived from continuous intercrops of these crops in the middle altitude such as land use budget and improvement of soil fertility were measured. The study also summarized the performance of the same crops cultivated in rotations and the effect of rotations on the improvement of soil fertility. However, in order to be able to recommend a continuous intercrop or rotational system for all altitudes, some more trials and more years of experience would be very valuable.

The study evaluated plant growth, grain yield and yield attributes of common bean and maize in rotations. However, the benefits to be derived from mycorrhizae symbiotic relationship over longer-term rotations of maize and common bean (and/or with maize + common bean) to the soil fertility remain to be addressed.

This study used the improved and local varieties of common bean. The dry weight of 100 seeds of improved bean was twice higher than that of the local bean of the same number of seeds, which is also an indication of the differences in market values where weight is the acceptable standard of measure. Therefore, further studies on the market preferences of these bean varieties are the important areas for investigation.

The lack of soil analysis data during the two long rainy seasons at the end of field experiments of intercropping of maize and common bean across three altitudes remained to be a limitation of this study. In addition, only the soil pH, total N, available P and SOC were tested in the middle altitude where the long-term experiments of rotations and intercrops of maize and common bean were conducted. This was due to a shortage of time and lack of funds for total soil analysis after every cropping season and/or at the end field experiments. It is important that other researchers to establish the extent at which intercropping conduct soil characterization (physical and chemical properties and microbial population) in the studied fields and rotations of maize and common bean contributed to the improvement of the soil fertility and its overall health.

Based on the findings of this study, three recommendations are provided to the farmers in the northern highlands of Tanzania: (a) Intercrops of maize and common bean (improved *Lyamungu 90* and/or local *Mkanamna*) can be cultivated throughout long rainy seasons across altitudes ranging from 743 to 1743 m above sea level. (b) Intercrops of maize and common bean (improved *Lyamungu 90* and/or local *Mkanamna*) can be cultivated throughout long and short rainy seasons in the middle altitude (1051 m above sea level) depending on the availability of water for irrigation during short rainy season. (c) Intercrops of maize and common bean (improved *Lyamungu 90* and/or local *Mkanamna*) can be cultivated during long rainy seasons and rotated with sole maize cultivated during short rainy seasons in the middle altitude (1051 m above sea level).

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APPENDICES

Appendix 1: Major pests of grain legumes in the field, the plant parts that they damage, their global distribution and their control by crop rotation and/or intercropping

Insect pests	Crops attacked[a]	Plant parts damaged[b]	Distribution[c]	Control measure[w]	References
Acyrthosiphon pisum (Harris)[f]	CP, FB, Le, FP	V, Re	A,B,C	I & R	Clement *et al*. (2000)
Aphis craccivora (Koch)[f]	All Legumes	V, Re	A,B,C,D	R	Clement *et al*. (2000); Dar *et al*. (2012)
Aphis fabae Scopoli[f]	FB	V	B,C	I & R	Clement *et al*. (2000)
Bean bugs [*Riptortus pedestris* (F.), *R. clavatus* (Thunberg)][q]	Sb, Cb	V, Re	G, H	I	Wada *et al*. (2006)
Bean flies [Ophiomyia phaseoli Tryon, O. centrosematis, de Meijere, O. spencerella Greathead, Melanagromyza sojae Zehntner, M. obtusa Malloch][e]	All Legumes	V	B, D, Oceania	I	Srinivasan (2014)
Bean foliage beetles [*Ootheca sp.*][n]	CW, Cb	V, Re	I, J	I & R	Srinivasan (2014)
Beet army worm [*Spodoptera exigua* Hubner][m]	Sb	V, Re	Widely	I & R	Srinivasan (2014)
Blue butterfly [*Lampides boeticus* (L.), *Euchrysops cnejus* (F.)][u]	All Legumes	V, Re	A, B, D, Pacific	I & R	Srinivasan (2014)
Bruchus pisorum L.[i]	FP	Re	A,B,C,D	I & R	Clement *et al*. (2000)
Common armyworm [*Spodoptera litura* Fabricius][m]	All Legumes	V	E, G, H	I & R	Srinivasan (2014)
Halotydeus destructor Tucker[j]	FP, Lu, FP	V	D	I & R	Clement *et al*. (2000)
Helicoverpa armigera Hiibner[d]	C, Mb, Lu, PP, Sb	V, Re	B,C,D	R	Clement *et al*. (2000); Srinivasan (2014)
Helicoverpa punctigera (Wallengren)[d]	All Legumes	V, Re	D	I & R	Clement *et al*. (2000)
Helicoverpa/Maruca	CP, CW, PP	V, Re	B, D, Oceania	I & R	Dar *et al*. (2012)
Leafhoppers [*Empoasca kerri* Puthi, *E. facialis* Jacobi, *E. fabae* Harri][l]	All Legumes	V	A, B	I	Ranga Rao *et al*. (2013); Srinivasan (2014)
Legume pod borer [*Maruca vitrata* (F.)][s]	CW, PP, Cb	V, Re	A,B,D,H	I & R	Srinivasan (2014)
Lima bean pod borer (*Etiella zinckenella* Treitschke)[t]	Le, FP,	V, Re	A, B, D,	I	Wada *et al*. (2006)

Insect pests	Crops attacked [a]	Plant parts damaged[b]	Distribution[c]	Control measure [w]	References
	Sb		Caribbean		
Liriomyza cicerina (Rondani)[e]	CP	V	B	I & R	Clement *et al*. (2000)
Lygus hesperus Knigh[g]	Le	Re	A	I & R	Clement *et al*. (2000)
Myzus persicae (Sulzer)[f]	Lu	V	D	I & R	Clement *et al*. (2000)
Pod bugs [*Clavigralla gibbosa* Spinola, *C. scutellaris* (Westwood), *C. tomentosicollis* (Stal.)][p]	All Legumes	V, Re	B^{A}, K	I	Srinivasan (2014)
Sitona crinitus Herbst[h]	Le	R, V	B	I & R	Clement *et al*. (2000)
Sitona lineatus (L.)[h]	FB, FP	R, V	A,B	I & R	Clement *et al*. (2000)
Southern green stink bug [*Nezara viridula* (L.)][r]	All Legumes	V, Re	G, H	I & R	Muniappan *et al*. (2012)
Spider mite [*Tetranychus sp.*][v]	All Legumes	V, Re	B, C, Mediterranean	I & R	Srinivasan (2014)
Thrips [*Megalurothrips distalis* Kany, *M. usitatus* (Bagnall), *M. sjostedti* (Tribom)][o]	All Legumes	V, Re	G, H, B^{A}, Oceania	I & R	Srinivasan (2014)
Whitefly (*Bemisia tabaci* Gennadius)[k]	All Legumes	V	E, F	I	Srinivasan (2014)

Here: [a]Legume crops: Cb=Common bean; Sb= Soyabean; CP=Chickpea; CW= Cowpea; Mb=mungbean; PP= Pigeon pea; FB=Faba bean; Le=Lentil; Lu=Lupins; FP=Field pea. [b]Plant parts: R=Root; V=Vegetative organs (stems, leaves); Re=Reproductive organs (flower, pod and/or seed damaged). [c]Insect species on legumes in: A=America; B=Europe, Africa, W. Asia; BA=Africa; C=Southeast Asia including Indian subcontinent; D=Australia; E=Tropics; F=Sub-tropics; G=South Asia; H=Asia; I=Eastern Africa; J=Southern Africa; K=Asia. [d]Lepidoptera: Noctuidae; [e]Diptera: Agromyzidae; [f]Homoptera: Aphididae; [g]Heteroptera: Miridae; [h]Coleoptera: Curculionidae; [i]Coleoptera: Bruchidae; [j]Acarina: Penthaleidae; [k]Hemiptera: Aleyrodidae; [l]Homoptera: Cicadellidae; [m]Lepidoptera: Noctuidae; [n]Coleoptera: Chrysomelidae; [o]Thysanoptera: Thripidae; [p]Hemiptera: Coreidae; [q]Hemiptera: Alydidae; [r]Hemiptera: Pentatomidae; [s]Lepidoptera: Crambidae; [t]Lepidoptera: Pyralidae; [u]Lepidoptera: Lycaenidae; [v]Acari: Tetranychidae. [w]Locally available option of controlling insects: I=Intercropping; R=Rotation.

Appendix 2: Important foliar diseases of legumes in the field, causal agents, their distribution, likely economic losses and some cultural control measures

Legume	Disease	Causal agent	Distribution	Losses	Control measure	References
Chickpea (*Cicer arietinum* L.)	Stunt	Bean leaf roll luteovirus (BLRV)	North Africa, Middle East, India, Spain, Turkey, USA	N/I	Rotation	Makkouk *et al*. (2003); Pande *et al*. (2006; 2009); Darai *et al*. (2017)
	Ascochyta blight	*Ascochyta rabiei*	West Asia, northern Africa, Mediterranean region	> 50%		
	Botrytis gray mold	*Botrytis cinerea*	India, Nepal, Bangladesh, Pakistan, North Africa, Australia, America	50-100%		
Lentil (*Lens culinaris* Medik.)	*Stemphylium blight*	*Stemphylium botryosum*	Bangladesh, Egypt, Syria, USA	Up to 70%	Rotation	Makkouk *et al*. (2003); Pande *et al*. (2009)
	Rust	*Uromyces viciae-fabae*	Bangladesh, Chile, Ecuador, Ethiopia, India, Morocco, Nepal, Pakistan	50-100%		
	Ascochyta blight	*Ascochyta lentis*	Argentina, Australia, Brazil, Canada, Chile, Cyprus, Ethiopia, Greece, Iran, Jordan, New Zealand, Pakistan, Russia, Spain, Syria, USA	Up to 70%		
Faba bean (*Viciae faba* L.)	Rust	Faba bean necrotic yellows virus	Mediterranean countries	Up to 50%	Rotation	Makkouk *et al*. (2003); Pande *et al*. (2009)
	Ascochyta blight	*Ascochyta fabae*	Mediterranean countries	5-50%		
	Necrotic yellows	N/I	West Asia, North Africa	Up to 80%		
	Chocolate leaf spot	*Uromyces viciae-fabae*	Mediterranean countries	Up to 50%		
Field pea (Pisum sativum L.)	Downy mildew	*Peronospora viciae*	N/I	30%	Intercropping & Rotation	Pande *et al*. (2009); Darai *et al*. (2017)
	Powdery mildew	*Erysiphe polygoni*	India, Nepal	10%		
Pigeon pea (Cajanus cajan [L.] Millsp.)	Sterility mosaic	Pigeonpea sterility mosaic virus	Bangladesh, India, Myanmar, Nepal, Sri Lanka, Thailand	N/I	Rotation	Pande *et al*. (2009)
Mungbean (Vigna radiata [L.] Wilczek and black gram (Vigna	Powdery mildew	*Erysiphe polygoni*	India, southeast Asian countries	9-50%	Intercropping & Rotation	Pande *et al*. (2009)
	Cercospora leaf spot	*Cercospora cruenta*, *C. canescens*	Bangladesh, India, Indonesia, Taiwan, Thailand, Philippines, Malaysia	Up to 50%		

mungo [L.] Hepper)	Yellow vein mosaic	Mungbean yellow mosaic virus	Bangladesh, India	10-100%		
	Cowpea aphid-borne mosaic	Cowpea aphid-borne mosaic virus	Europe, Africa, Mediterranean basin, Turkey, Iran, India, Indonesia, China, Japan, Australia, Brazil, USA	13-87%	Intercropping & Rotation	Pande *et al*. (2009)
Cowpea (*Vigna ungiculata* [L.] Walp.)	Cowpea golden mosaic	Cowpea golden mosaic virus	Kenya, Nigeria, Tanzania, Cuba, Surinam, USA	60-100%		
	Cercospora leaf spot	*Cercospora canescens* and *Pseudocercospora cruenta*	Fiji, Brazil, Kenya, Nigeria, Zimbabwe, India, Bangladesh, Egypt, Iran, Japan, Malaysia, Thailand	18-42%		
Common bean (*Phaseolus vulgaris* L.) (Fungal diseases)	Anthracnose	*Colletotrichum lindemuthianum*	Widely	N/I	Use of disease-free seed, crop rotation, intercropping	Kelly *et al*. (2003); Miklas *et al*. (2006); Singh and Schwartz (2010); Schwartz and Singh (2013); Porch *et al*. (2013); OECD (2016)
	Fusarium wilt	*Fusarium oxysporum*		N/I		
	Fusarium root rot	*Fusarium solani*		N/I		
	Angular leaf spot	*Phaeoisariopsis griseola*		N/I		
	Ascochyta blight	*Phoma exigua* var. *diversispora*, *P. exigua* var. *exigua*		N/I		
	Rhizoctonia root rot	*Rhizoctonia solani*		N/I		
	White mold	*Sclerotinia sclerotiorum*		N/I		
	Web blight	*Thanatephorus cucumeris*		N/I		
	Bean rust	*Uromyces phaseoli*, *U. appendiculatus*		N/I		
Common bean (*P. vulgaris* L.) (Bacterial diseases)	Halo blight	*Pseudomonas syringae* pv. *phaseolicola* or *Pseudomonas savastonoi* pv. *Phaseolicola*	Widely	N/I	Use of disease-free seed, crop rotation, intercropping	Kelly *et al*. (2003); Liebenberg (2009); Singh and Schwartz (2010); Porch *et al*.
	Bacterial brown spot	*Pseudomonas syringae* pv. *Syringae*		N/I		

	Common bean blight	*Xanthomonas campestris* pv. *phaseoli* or *Xanthomonas axonopodis* pv. *Phaseoli*		N/I		(2013); OECD (2016)
Common bean (*P. vulgaris* L.) (Viral diseases)	Bean common mosaic necrosis virus	Potyvirus	Widely	N/I	Use of disease-free seed, intercropping	Miklas *et al*. (2006); Bonfim *et al*. (2007); Singh *et al*. (2009); Singh and Schwartz (2010); Faria *et al*. (2014); OECD (2016)
	Bean common mosaic virus	Potyvirus		N/I		
	Bean golden mosaic virus	Geminivirus		N/I		
	Bean yellow mosaic virus	Potyvirus		N/I		
	Beet curly top virus	Curtovirus		N/I		

Here N/I = Not identified

Appendix 3: Maize grain yields (in t ha^{-1}) recorded over two cropping seasons (2015 & 2016) as affected by the agro-ecological zones, cropping seasons (in years), cropping systems with beans, and the interactions of these factors

A:	Lower	Middle	Upper	S.E.D.	F. Stat.	*P - value*
	1.4^{c}	1.8^{b}	2.5^{a}	0.11	54.63***	<.001

S:

	2015	**2016**	S.E.D.	F. Stat.	*P - value*
	2.1^{a}	1.8^{a}	0.13	3.77ns	0.084

C:

	m+L90	m+Lb	Sole	S.E.D.	F. Stat.	*P - value*
	1.7^{a}	1.9^{a}	2.2^{a}	0.21	2.57ns	0.09

A×S:

	Lower	Middle	Upper	S.E.D.	F. Stat.	*P - value*
2015	1.4^{b}	2.4^{a}	2.3^{a}	0.19	13.06**	0.002
2016	1.4^{b}	1.2^{b}	2.7^{a}			

A×C:

	Lower	Middle	Upper	S.E.D.	F. Stat.	*P - value*
Sole	1.6^{bc}	2.1^{a-c}	2.9^{a}	0.32	0.42ns	0.793
m+Lb	1.6^{bc}	1.7^{bc}	2.3^{ab}			

m+L90	1.1^{c}	1.7^{bc}	2.4^{ab}

S×C:

	Sole	m+Lb	m+L90	S.E.D.	F. Stat.	*P - value*
2015	2.1^{ab}	2.0^{ab}	2.1^{ab}	0.2747	2.51ns	0.095
2016	2.3^{a}	1.7^{ab}	1.4^{b}			

A×S×C:

Zone	**2015**			**2016**			S.E.D.	F. Stat.	*P - value*
	m+L90	m+Lb	Sole	m+L90	m+Lb	Sole	0.46	1.83ns	0.145
Lower	1.1^{c}	1.6^{bc}	1.6^{bc}	1.1^{c}	1.6^{bc}	1.6^{bc}			
Middle	2.4^{a-c}	2.3^{a-c}	2.6^{a-c}	1.0^{c}	1.2^{bc}	1.5^{bc}			
Upper	2.8^{ab}	2.1^{a-c}	2.1^{a-c}	2.0^{bc}	2.5^{a-c}	3.7^{a}			

Maize grain yields were significantly affected by the variation in agro-ecological zones and the interactions of agro-ecological zones and the cropping seasons. **Key:** m+L90 = maize intercropped with the improved bean variety *Lyamungu 90*; m+Lb = maize intercropped with the local bean variety *Mkanamna*; S.E.D. = standard errors of the differences of means; A = agro-ecological zones; S = seasons of cropping (2015 & 2016); C = cropping systems (monoculture or intercropping); ns = not significant.

RESEARCH OUTPUTS

Journal papers

Nassary, E. K., Baijukya, F., & Ndakidemi, P. A. (2020). Sustainable intensification of grain legumes optimizes food security on smallholder farms in sub-Saharan Africa – A review. *International Journal of Agriculture & Biology*, 23, 25–41. doi: 10.17957/IJAB/15.1254.

Nassary, E. K., Baijukya, F., & Ndakidemi, P. A. (2020). Assessing the productivity of common bean in intercrop with maize across agro-ecological zones of smallholder farms in the northern highlands of Tanzania. *Agriculture,* 10, 117. doi:10.3390/agriculture10040117.

Nassary, E. K., Baijukya, F., & Ndakidemi, P. A. (2020). Productivity of intercropping with maize and common bean over five cropping seasons on smallholder farms of Tanzania. *European Journal of Agronomy,* 113, 125964. https://doi.org/10.1016/j.eja.2019.125964.

Nassary, E. K., Baijukya, F., & Ndakidemi, P. A. (2020). Intensification of common bean and maize production through rotations to improve food security for smallholder farmers. *Journal of Agriculture and Food Research,* 2, 100040. https://doi.org/10.1016/j. jafr.2020. 100040.

Podcasters

Nassary, E. K. (2015). Studying the benefits of intensifying common bean cultivation on smallholder farms in the Northern Highlands of Tanzania. Page 5. N2Africa Podcaster no. 32 July and August 2015: Putting nitrogen fixation to work for smallholder farmers in Africa. 15 pp. Available at: https://ndo.or.tz/wp-content/uploads/2015/05/N2Africa-Podcaster-July-and-August-2015.pdf.

Nassary, E. K. (2016). Comparing yields and some yield components of common bean from intercropping and rotations with maize in the northern highlands of Tanzania. Page 6–7. N2Africa Podcaster no. 39 PhD Student Special, September 2016: Putting nitrogen fixation to work for smallholder farmers in Africa. 16 pp. Available at: https://www.n2africa.org/sites/default/files/N2Africa%20Podcaster%2039.pdf.