CONTRIBUTION OF PIGEONPEA (*Cajanus cajan* L. Millsp.) TO SOIL FERTILITY AND PRODUCTIVITY OF MAIZE (*Zea mays* L.) CROPPING SYSTEMS IN SEMI-ARID KENYA

KIZITO MUSUNDI KWENA

B.Sc.Forestry (Moi Univ.), M.Phil.Soil Science (Moi Univ.)

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DECLARATION

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

....
Kizito Musundi Kwena Date

This thesis has been submitted for examination with our approval as university supervisors.

....
Dr. Fredrick O. Ayuke Date
Department of Land Resource Management & Agricultural Technology
University of Nairobi

....
Dr. George N. Karuku Date
Department of Land Resource Management & Agricultural Technology
University of Nairobi

....
Dr. Anthony O. Esilaba Date
Kenya Agricultural & Livestock
Research Organization (KALRO)

DEDICATION

To my father, the late Maurice Kwena, who always encouraged and provided me the means with which to pursue an education, but unfortunately did not live to witness the completion of this work.

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LIST OF ACRONYMS

AAS	- Atomic Absorption Spectroscopy
ANOVA	- Analysis of variance
APSIM	- Agricultural Production Systems Simulator
ASALS	- Arid and Semi-arid lands
BNF	- Biological Nitrogen Fixation
C	- Carbon
Ca	- Calcium
CNRM	- National Meteorological Research Centre
CRD	- Completely Randomized Design
CSIRO	- Commonwealth Scientific and Industrial Research Organization
DMRT	- Duncan Multiple Range Test
DR	- Dispersion Ratio
Eo	- Potential evaporation
ETo	- Evapotranspiration
GCM	- Global Climate Change Model
HI	- Harvest Index
IAEA	- International Atomic Energy Agency
ICRISAT	- International Crop Research Institute for the Semi-Arid Tropics
IPCC	- Intergovermental Panel on Climate Change
K	- Potassium
KALRO	- Kenya Agricultural and Livestock Research Organization
KEFRI	- Kenya Forestry Research Institute
LR	- Long Rains
LSD	- Least Significant Difference

LER - Land Equivalent Ratio

MIRCEN - Microbial Resource Centre

Mg - Magnesium

N - Nitrogen

P - Phosphorus

RCBD - Randomized Complete Block Design

SDSM - Statistical Downscaling Model

SOC - Soil Organic Carbon

SOM - Soil Organic Matter

SR - Short Rains

TSP - Triple Super Phosphate

WUE - Water Use Efficiency

ABSTRACT

Pigeonpea breeding programs in Kenya have focused mainly on developing high yielding varieties that are resistant to *Fusarium* wilt and adaptable to a broad range of ecological conditions. However, few studies have evaluated these pigeonpea varieties for soil fertility improvement and contribution to the productivity and sustainability of maize-based cropping systems under a changing climate. A study comprising field and greenhouse experiments was conducted between 2009 and 2013 to: (i) quantify the amount of nitrogen fixed by improved pigeonpea varieties under maize-pigeonpea intercropping systems, (ii) determine the amount of nitrogen (N), phosphorus (P), potassium (K), magnesium (Mg) and calcium (Ca) accumulated by the different components of maize-pigeonpea intercropping systems and its effect on total soil N, available P and exchangeable K, Mg and Ca content, (iii) determine the effect of pigeonpea and maize residues on soil aggregation and soil water content, and (iv) predict the impact of climate change on maize and pigeonpea yields. Field experiments were conducted in Katumani Research Centre using a split-split plot design with three pigeonpea varieties, two cropping systems and three crop residue regimes as the main plot, sub-plot, and sub-sub-plot, respectively. Greenhouse experiments were conducted at Muguga Research Centre where five pigeonpea varieties were screened for biological nitrogen fixation (BNF) and response to Rhizobia inoculation in plastic pots filled with 10 kg of soil and replicated four times in a completely randomized design. Agricultural Production Systems Simulator (APSIM) model version 7.3 was used to predict the impact of climate change on maize and pigeonpea yields. Data collected on total soil N and organic carbon (C), available P, exchangeable K, Mg and Ca, N-uptake, BNF, soil water content, aggregate stability, bulk density and maize and pigeonpea yields were subjected to analysis of variance using GENSTAT statistical software version 14.2. Results showed that all the three pigeonpea varieties fixed 60–70 kgN ha^{-1}, meaning they were all

good nitrogen-fixers. However, Mbaazi II fixed significantly ($p \leq 0.05$) higher N (70 kg N ha^{-1}) compared to KAT 60/8 (66 kg N ha^{-1}) and Mbaazi I (62 kg N ha^{-1}) when intercropped with maize. Pigeonpea had significantly ($p \leq 0.05$) higher N uptake compared to maize; Mbaazi II (84-114 kg N ha^{-1}) absorbed more N followed by Kat 60/8 (29-44 kg N ha^{-1}) and Mbaazi I (20-37 kg N ha^{-1}). Intercropping maize with pigeonpea reduced ($p \leq 0.05$) soil organic carbon and total soil N from 1.4 and 0.2% in 2009 to less than 1 and 0.1%, respectively, in 2013. Intercropping maize with long duration pigeonpea (Mbaazi II) and ploughing back 4 t ha^{-1} of crop residues had no significant effect on available P. However, it increased ($p \leq 0.05$) available P from 26 ppm at the start of the study to 50 ppm and 47 ppm in eight seasons under maize-Mbaazi I and maize-Kat 60/8 intercrops, respectively. Exchangeable K, Mg and Ca also declined significantly ($p \leq 0.05$). All the maize-pigeonpea cropping systems tested in this study did not improve soil physical properties due to very low soil organic carbon accumulation (< 1%). Instead, they increased soil bulk density beyond the prescribed range for non-restricted plant growth and reduced soil aggregation thereby exposing soils to degradation. However, they did not alter texture of the soils at the study site. Intercropping maize with the three pigeonpea varieties, especially the long duration variety (Mbaazi II), requires more water compared to maize and pigeonpea sole crops. This can be addressed by conserving more water in the profile by ploughing back crop residues. Mbaazi II-maize intercrop offers the best option for farmers in marginal areas like Katumani since it gave the highest maize (1.9 t ha^{-1}) and pigeonpea (1.4 t ha^{-1}) grain yields and produced sufficient maize stover (2.1t ha^{-1}) and pigeonpea stalks (2.9 t ha^{-1}) to plough back and feed the livestock. Simulations showed that maize yields from sole maize crop would increase by 141-150% and 10-23% in 2050 and 2100, respectively. Intercropping maize with pigeonpea will give mixed results on maize yields. Pigeonpea yields will decline by 10-20 and 4-9% by 2100 under CSIRO and CNRM models, respectively, due to the projected 2°C and 11%

increase in temperature and precipitation, respectively. Therefore, efforts should be made to develop heat and waterlogging-tolerant pigeonpea varieties to help farmers adapt to climate change and to protect the huge pigeonpea export market currently enjoyed by Kenya.

CHAPTER ONE

1.0. INTRODUCTION

1.1. General Introduction

Per capita food production in Kenya has declined over the past two decades, contrary to the global trend. For instance, maize yields have fallen from over 2 t ha^{-1} to less than 1 t ha^{-1} over the past 10 years resulting in widespread household food insecurity, malnutrition, a recurrent need for emergency food supply and an increasing dependence on food imports (Ngome *et al*., 2011; Karaya *et al*., 2012; Mucheru-Muna *et al*., 2013). Estimates available indicate that about 46% of the Kenyan population lacks access to adequate food and lives in abject poverty, and this figure is bound to increase given the current population growth rate of 3% (GoK, 2013). Consequently, Kenya has had to import on average 350, 000 tons of maize per year over the last ten years to fill the deficit in its domestic demand (FAO, 2014a).

Shortfalls in food production have been attributed partly to climate variability, but mainly to declining soil fertility, caused by continuous cropping without commensurate nutrient replenishment, particularly among the smallholders who produce over 75% of the food consumed in the country (Mugwe *et al*., 2008, 2009; GoK, 2013a; Mucheru-Muna *et al*., 2013). Most of the soils in Kenya are heavily depleted of nitrogen (N) and phosphorus (P), and are extremely low in organic matter content (NAAIAP, 2014). In the densely populated and heavily cropped County of Kisii in South-Western Kenya, for instance, aggregate nutrient losses are estimated at 112 kg N, 3 kg P and K 70 kg ha^{-1} yr^{-1}, with serious P deficiencies (NAAIAP, 2014). In central Kenya highlands, annual net nutrient depletion rate exceeds 30 kg N ha^{-1} (Smaling *et al*., 1993).

Numerous soil fertility management options have been suggested to reverse this situation, but the level of adoption has been very low (Jaetzold *et al*., 2006). Some of these methods have been found to be obsolete or not viable altogether. For instance, chemical fertilizers and manure have found very minimal use in the Country. The low use of chemical fertilizers has been attributed to high levels of risk associated with low and highly variable rainfall patterns, inefficient input distribution systems that make the input unavailable when it is needed, unavailability of the input in rural retail shops, and difficulty farmers have in assessing the relative returns to fertilizer (Jaetzold *et al*., 2006; Ariga *et al*., 2008; Mugwe *et al*., 2009; Itabari *et al*., 2011; Mucheru-Muna *et al*., 2013). On the other hand, the low use of farmyard manure has been ascribed to low animal population hence inadequate animal refuse, and lack of transport facilities to ferry the manure to the farm (Bationo and Waswa, 2011; Okalebo *et al*., 2011; Itabari *et al*., 2011). The net effect has been unabated decline in soil fertility and crop yields (NAAIAP, 2014). There is urgent need to identify socially and economically viable soil fertility management practices that will effectively improve soil fertility and increase crop yields, especially in arid and semi-arid areas, which account for over 80% of Kenya's land mass.

1.2. Problem statement

Substantial areas of arid and semi-arid lands (ASALs) are located in Machakos, Kitui, Makueni and Kajiado Counties and are characterized by fragile ecosystems, persistent climatic variability and poor soils (GoK, 2013b). Despite their marginal agricultural potential, population in these regions has increased tremendously due to high birth rates and immigration from medium and high potential areas. Available estimates indicate that ASALs support about a third of Kenya's population and this figure is bound to increase given the current population growth rate of 2.7% (Jaetzold *et al*., 2006; GoK, 2013a).

The ASAL communities are faced with chronic poverty and food shortages and hence rely on government relief supplies. About 65% of the inhabitants live below the poverty line (GoK, 2013). Several researchers have described the situation currently evident in these regions as a "poverty trap", in which the highly subsistence population living on degraded soils receives low income, afford low or no farm inputs, and consequently get low crop yields (Shiferaw, 2008; Itabari *et al*., 2011; Recha *et al*., 2012). Soils are low in organic matter, Nitrogen, Phosphorus and other essential nutrients and cereal and legume yields from farmers' fields rarely exceed 1t ha^{-1} and 0.5 t ha^{-1}, respectively, per season compared to over 2 t ha^{-1} obtained from research stations and commercial farms in the region (Jaetzold *et al*., 2006; Recha *et al*., 2012; NEMA, 2013).

This situation can be reversed through the use of mineral fertilizers and cattle manure. However, the few farmers who apply mineral fertilizers, hardly use the recommended rates, and often it is utilized with poor efficiency due to environmental or soil-related factors (e.g. P-fixation by sesquioxides, leaching and volatilization of N) as well as management factors, such as poor timing or placement of fertilizer (Chichongue *et al*., 2013; Itabari *et al*., 2011; Vanlauwe *et al*., 2010; Mugwe *et al*., 2009, 2008; Ariga *et al*., 2008). The use of locally available manure is limited by its low quality and quantity (Bationo and Waswa, 2011; Itabari *et al*., 2011). Other studies indicate that including legumes such as pigeonpea in maize cropping systems improves soil fertility and increases maize yield by availing N to the maize and mobilizing large amounts of sparingly soluble P into organic forms, especially in N and P deficient soils predominant in semi-arid Eastern Kenya and the rest of Africa (Adu-Gyamfi *et al*., 2007; Audi *et al*., 2008; Gwata and Shimelis, 2013; HØgh-Jensen *et al*., 2007; Nagarajan *et al*., 2008; Shiferaw *et al*., 2008; USAID, 2010). In Kenya, however, little research has been conducted to ascertain and explore this opportunity (Silim *et al*., 1998). There is need to elucidate and exploit these benefits to increase agricultural production in the ASALs to support the rapidly increasing population and to alleviate poverty by increasing farm income and creating employment opportunities.

1.3. Justification of the study

Kenya is the world's fourth largest producer of pigeonpea after India, Myanmar and Malawi, of which 99% is produced in semi-arid eastern Kenya, especially Machakos, Kitui, Mwingi, Makueni, Meru, Lower Embu, Nyambene, and Tharaka-Nithi Counties (Audi *et al*., 2008). It is also grown in the drier parts of Kirinyaga, Murang'a, and Kiambu Counties in Central Kenya; and some parts of Lamu, Kilifi, Kwale, Tana River, and Taita-Taveta Counties at the Coast; mainly by small-scale resource-poor farmers (Audi *et al*., 2008; Gwata and Shimelis, 2013; HØgh-Jensen *et al*., 2007; Nagarajan *et al*., 2008; Shiferaw *et al*., 2008; USAID, 2010). Most farmers intercrop pigeonpea with maize or sorghum on the same land, either in alternate or in multiple rows, as a form of security against total crop failure (Recha *et al*., 2012).

Pigeonpea provides multiple benefits to the rural poor. Firstly, its protein-rich grain that can be consumed both fresh and dry and provides a cheap source of protein for the poor farmers in the drylands. Secondly, its leaves and hulls are used as livestock feeds and the stem as fuelwood. Thirdly, it has the ability to enrich the soil through dinitrogen fixation (Kumar *et al*., 2011), litter fall and being a deep-rooted crop, to mobilize nutrients, particularly phosphorus, from the deep soil horizons (Adu-Gyamfi *et al*., 2007; Myaka *et al*., 2006; Snapp and Silim, 2002). Fourthly, intercropping pigeonpea with cereals enhances soil coverage, reduces soil erosion and boosts cereal yields (Adu-Gyamfi *et al*., 2007; Myaka *et al*., 2006). Finally, the crop provides an assured source of income for farm families and foreign exchange for Kenya. About 7000t of dhal (dehulled pigeonpea) and 15,000t of whole grain are exported annually to Europe, North America, the Middle East, and India, but this figure represents just 30% of Kenya's export potential (Audi *et al*., 2008; Nagarajan *et al*., 2008; Shiferaw *et al*., 2008; Simtowe *et al*., 2008; USAID, 2010). Thus, pigeonpea has immense untapped potential which if fully exploited could transform the lives of poverty-stricken semi-arid communities tremendously.

Despite the importance of pigeonpea in Kenya and elsewhere in the region, pigeonpea production has continued to decline. Yields on farmers' fields are low, averaging 0.3- 0.5 t ha^{-1} against a yield potential of 2.5 t ha^{-1}, mainly due to non-use of improved varieties and poor farming practices, low soil fertility and climate variability (Odeny, 2007; Shiferaw *et al*., 2008; USAID, 2010; Gwata and Shimelis, 2013). Most small-scale farmers in Kenya grow low-yielding, tall, long-duration landraces and use inadequate amounts of organic manure and virtually no inorganic fertilizers because they not only believe that legumes do not respond to inorganic fertilizers under poor rainfall and soil moisture conditions in the growing areas, but also lack capital to purchase these inputs (Odeny, 2007; Shiferaw *et al*., 2008; USAID, 2010).

Over the years, the Kenya Agricultural and Livestock Research Organization (KALRO), jointly with the International Crop Research Institute for Semi-Arid Tropics (ICRISAT) and the University of Nairobi have developed and released numerous pigeonpea varieties suitable for Kenya's semi-arid lands. Examples of these varieties include short, medium and long duration varieties called ICPL 87091 (under the release name KARI Mbaazi I), KAT 60/8 and ICEAP 00040 (under the release name KARI Mbaazi II), respectively. However, these efforts focused mainly on developing high yielding varieties that are resistant to *Fusarium* wilt and adaptable to a broad range of ecological conditions (USAID, 2010; Shiferaw *et al.*, 2008; Kimani, 2001). There have been few studies on how their inclusion in the cereal-based cropping systems influences soil physical and chemical properties and long-term sustainability of these production systems under a changing climate. This information would aid in developing intervention measures that would increase the contribution of pigeonpea to the productivity and sustainability of low-input agriculture prevalent in semi-arid lands in Kenya and other Sub-Saharan African countries and help thousands of vulnerable households in these areas to adapt to climate change.

1.4. Objectives of the study

1.4.1. Overall objective

The main objective of this study was to evaluate the effects of pigeonpea on soil fertility and productivity of maize cropping systems in semi-arid Kenya in order to recommend interventions that would increase food security and help thousands of vulnerable households to adapt to climate change. This was achieved through the following specific objectives:

1.4.2. Specific objectives

(i) To quantify the amount of nitrogen fixed by improved pigeonpea varieties under different cropping systems.

(ii) To determine the amount of nitrogen (N), phosphorus (P), potassium (K), magnesium (Mg) and calcium (Ca) accumulated by the different components of maize-pigeonpea intercropping systems and its effect on total soil N, available P and exchangeable K, Mg and Ca content.

(iii) To determine the effect of pigeonpea and maize residues on soil aggregation and soil water content.

(iv) To assess the impact of climate change on maize and pigeonpea yields.

1.5. Research hypotheses

1. Long duration pigeonpea varieties fix more N and contribute more N to the soil than short and medium duration varieties.
2. Inclusion of pigeonpea in maize cropping systems improves soil N, P and C status.
3. Retention of crop residues improves soil structure and enhances water retention in maize-pigeonpea cropping systems.
4. Climate change will increase maize and pigeonpea yields.

CHAPTER TWO

2.0. LITERATURE REVIEW

2.1. Farming systems of semi-arid Kenya

Mixed farming systems involving food crops and livestock are characteristic of these regions (Jaetzold *et al.*, 2006). Interacting demand for labor, nutrients, cash resources and management decisions are found at various levels. Most farmers use ox-drawn ploughs for their major cultivations, but much of the weeding is done by hand using hoes. The use of other farm equipment is often minimal (Itabari *et al*., 2011).

The crops grown are distributed according to agro-ecological zones, and are predominantly the drought-escaping or early maturing varieties of pigeonpea, maize, beans, sorghum and millet (Jaetzold *et al.*, 2006). Because of the erratic nature of rainfall, most farmers in semi-arid Kenya prefer to intercrop maize with at least a legume (beans, cowpeas or pigeonpeas) on the same land. This is often done either in alternate or in multiple rows, and is seen by many farmers as a form of security against total crop failure. However, rather than devote their entire arable land to either pure-stand cropping or intercropping, most farmers often dedicate one piece to pure-stand cropping and the remaining area to intercropping in a bid to spread the risk (Recha *et al*., 2012).

Pigeonpea planting is done during the short rains in October-November, and the crop is harvested in August-September the following year. The final uprooting of the crop is usually delayed until the satisfactory on-set of the rainy season. In case the rains turn out to be poor, the crop is continued into the next season (Omanga *et al*., 1990). The crop combinations, planting patterns and plant populations of pigeonpea and other crops vary considerably depending on soil type, climate and farmer's preferences. However, the dominant pigeonpea cropping systems practiced in these regions include: pigeonpea intercropped with maize, sorghum, millets, cowpea and green gram; pigeonpea and cowpea intercrops; and maize/bean/pigeonpea intercrops (Audi *et al*., 2008; Nagarajan *et al*., 2008; Shiferaw *et al*., 2008; USAID, 2010).

Complementarity exists between crops and livestock in the mixed farming conditions of semi-arid Kenya. Livestock provide manure and draught power while crops provide residues that are customarily fed to livestock. However, there is significant conflict between livestock and soil fertility enhancing activities. Thus, the crop residues (mainly maize stover) which could be returned to the field to curb run-off and supply nutrients for future crops are commonly used as feed, particularly during the dry season when there is scarcity of such feed. Moreover, the use of animal refuse (boma manure) is impeded by a host of factors such as insufficient quantity, poor quality, lack of knowledge on sound manure management and utilization, and lack of transport to ferry manure to cropland (Sanginga and Woomer, 2009; Itabari *et al*., 2011; Bationo and Waswa, 2011). In addition, due to cash flow problems among most households, the application of chemical fertilizers to crops is low, or non-existent in most farms, resulting in unabated decline in soil fertility and crop yields (Mugwe *et al*., 2009; Itabari *et al*., 2011).

Financial and labor constraints, particularly during weeding, often restrict cropping to about 1 to 2 hectares even though the total farm area may be 5 to 10 hectares per farmer (Recha *et al*., 2012). Such low hectareage of cropped land, coupled with soil fertility constraints and high probability of inadequate rainfall combine to produce low crop yields, which result in persistent food shortages in these regions.

2.2. Pigeonpea and soil fertility improvement

A dominant feature of agricultural production systems in semi-arid Kenya is land degradation and low crop yields. The cause of land degradation in these regions, apart from the drain on P and soil cations by crop removal, is ultimately a negative balance in soil organic matter. The rates of depletion of organic carbon and nitrogen (N) through microbial mineralization and crop removal in the intensive low-input cereal-based cropping systems widely practiced in these regions often exceed their rates of replenishment from crop root residues, other organic inputs and biological N fixation (Simpson *et al*., 1996; Mugwe *et al*., 2009; Itabari *et al*., 2011). There is need to identify socially and economically viable agronomic systems that will effectively promote re-accumulation of soil organic matter on the degraded farms within these regions and improve their productivity.

Pigeonpea cropping is one of the few options with the potential to do exactly that, due to pigeonpea's complementarity with most cereals. Pigeonpea has the ability to fix high amounts of nitrogen (Kumar *et al*., 2011), mobilize nutrients, particularly phosphorus, from the deep soil horizons, and to increase soil organic matter through litterfall and root senescence (Adu-Gyamfi *et al*., 2007; Myaka *et al*., 2006; Silim *et al*., 2005; Mapfumo and Mtambanengwe, 2004; Snapp and Silim, 2002; Sakala *et al*., 2000). Locally, however, little attempt has been made to quantify these benefits (Silim *et al*., 1998). Nonetheless, an account of what has been done to quantify these benefits locally and elsewhere is presented below.

2.2.1. Pigeonpea and Biological Nitrogen Fixation (BNF)

Like most tropical grain legumes, pigeonpea has the ability to fix a substantial amount of N and due to its small harvest index, retain a relatively large proportion of the fixed N in the field to benefit subsequent crops (Giller *et al*., 1997). However, the amount of N fixed is site-specific. For instance, recent work in western Kenya showed that pigeonpea fixed approximately 62% of its N requirement (Gathumbi *et al*., 2002), compared to 65% reported for the same variety in Australia and India (Peoples and Caswell, 1992).

Similarly, working in semi-arid southern and eastern Africa, Adu-Gyamfi *et al*. (2007) found similar pigeonpea varieties to derive between 93.8 and 99.9% of their N requirements from air in Tanzania compared to 65.6 to 99.3% in Malawi. The amount of N fixed in this study ranged from 37.5 to 117.2 kg N ha^{-1} in Malawi, compared to 6.3 to 71.5 kg N ha^{-1} in Tanzania. Further, the same varieties reportedly fixed an average of 64.3 kg N ha^{-1} in Nyambi and 85.3 kg N ha^{-1} in Ntonda in Malawi, compared to 34.1kg N ha^{-1} in Gairo and 54.3kg N ha^{-1} in Bahati in Tanzania. The low and high N fixed at Gairo and Ntonda, respectively, was attributed to low rainfall recorded and high pigeonpea biomass produced in the respective areas during the experimental period.

In a related study in Zimbabwe, Mapfumo and Mtambanengwe (2004) reported a contribution of 6-18 kg N ha^{-1} from pigeonpea. These results agree with earlier findings by Mapfumo *et al*. (1999) and Chikowo *et al*. (2004), who reported N fixed on several farms on very sandy soils in Zimbabwe to be largely less than 20 and 10 kg N ha^{-1}, respectively. Further, they corroborate earlier findings by KumarRao *et al*. (1980) that pigeonpea could fix upto 69 kg N ha^{-1}, equivalent to only 52% of the total N uptake. The low N fixation in Zimbabwe was attributed to low biomass production due to poor growing conditions.

In other studies across the globe, however, much higher values have been quoted for N_2-fixation by pigeonpea. For instance, Katayama *et al*. (1995), Tobita *et al*. (1994), Adu-Gyamfi *et al*. (1996) and Red de Grupos de Agricultura de Cobertura (2002) reported values in the range of 50-76, 75-165, 123-170 and 41- 280kg N ha^{-1}, respectively. However, most of these studies were based on the traditional long-duration pigeonpea varieties, with very little regard to the recently developed high yielding short duration varieties.

Conflicting results have been reported on genotypic differences in N_2-fixation. It is postulated that like other long-duration grain legumes, the long duration pigeonpea varieties consume most of their fixed N and therefore contribute less N to the soil compared to the short duration varieties, especially when a large portion of their aboveground biomass is removed from the field (Peoples and Herridge, 1990; Rego and Rao, 2000). However, in the Zimbabwean study, Mapfumo and Mtambanengwe (2004) reported a potential N contribution of 46 kg N ha^{-1} for the short duration compared to 150 kg N ha^{-1} for the long-duration variety.

Similarly, working in India, KumarRao *et al*. (1980) found N fixation by pigeonpea to increase with crop duration. In this study, short duration varieties apparently fixed little nitrogen, and even for the best fixing varieties, N_2- fixation represented only 52% of the total N uptake. The harvest index for N was also small, ranging from 21 to 57%, and decreased with crop duration. The authors, however, noted that there were differences even within maturity groups. For instance, two long-duration varieties reportedly fixed 13 and 69 kg N ha^{-1}, respectively, in the same experiment (KumarRao *et al*., 1980). It is also not clear yet whether, like other grain legumes, N_2-fixation by pigeonpea is also significantly influenced by the cropping systems. It has been postulated, however, that due to its phenological complementarity with most cereal crops, intercropping pigeonpea with a cereal does not affect its dry matter accumulation and N_2 fixing ability (Dalal, 1974; Giller *et al*., 1997). This view is supported by a study in India by KumarRao and Dart (1987) who observed that intercropping a medium duration variety with sorghum did not affect N_2- fixation by pigeonpea. It is, however, not known whether the same is true for the short-duration and some of the long duration varieties grown in India and parts of Africa (Kumar Rao, 1990).

Most of the available information on N_2-fixation by pigeonpea is from studies conducted on pigeonpea-cereal intercrops and very little attempt has been made to compare them with results from sole pigeonpea cropping systems despite the fact that many farmers also grow it as a sole crop in many parts of Africa. There is thus need to quantify the nitrogen made available by pigeonpea of different maturity groups in various cropping systems (sole, inter, and mixed cropping) to complement the available information on the economically valuable attributes of these varieties in order to make them more attractive to farmers (KumarRao, 1990).

2.2.2. Effect of pigeonpea on N and P budgets of cereal-based cropping systems

Generally, inclusion of legumes in cereal-based cropping systems can lead to either positive or negative N and P budgets depending on the initial soil fertility, dry matter yield, N and P partitioning patterns of the crop, growth habit of the legume (indeterminate versus determinate), efficiency of BNF (effective versus ineffective) and management of crop residues (Snapp *et al*., 1998; Giller *et al*., 1997; Rao and Mathuva, 2000; Singh *et al*., 2005; Singh and Dwivedi, 2006).

Thus, whereas negative budgets have been reported for pigeonpea-cereal cropping systems, positive budgets have also been reported for the same cropping systems. In a study by Adu-Gyamfi *et al*. (2007), for instance, exporting all above-ground material reportedly gave a mean N budget of -26.1 kg N ha^{-1} for sole maize crop and -40.3 kg N ha^{-1} for maize-pigeonpea intercrop at two locations in Malawi, and -50.1 kg N ha^{-1} for sole maize crop and -51.1 kg N ha^{-1} for maize-pigeonpea intercrop at two sites in Tanzania.

Conversely, retaining and incorporating all the aboveground material of maize and pigeonpea, except the edible parts, into the soil reportedly gave a positive value of 30.5 kg N ha^{-1} for the maize-pigeonpea intercrop and a less negative one (-8.9 kg N ha^{-1}) for the sole maize crop in Malawi, and a more negative value (-35.4 kg N ha^{-1}) for sole maize compared to the intercrops (-5.9 kg N ha^{-1}) in Tanzania. The huge disparity in N budgets between the two countries was attributed to low and high maize grain yields realized in Malawi and Tanzania, respectively (Adu-Gyamfi *et al*., 2007).

Including roots in the calculations in this study did not change the difference between sole maize crop and maize-pigeonpea intercrop. Similarly, the cropping systems under consideration had no effect on N accumulation in the grain nor on total N accumulation. The N harvest index (HIN) of maize in sole stand or in mixture with pigeonpea did not differ either (Adu-Gyamfi *et al*., 2007). This contrasts sharply with the results from similar work in Malawi in which total N uptake was reportedly higher in the maize-pigeonpea intercrop than in sole maize crop (Chirwa *et al*., 2006). However, the authors reported a negative P budget irrespective of whether the aboveground biomass of maize and pigeonpea were incorporated or exported out of the fields, whether the root biomass was included or not, and the values were similar for maize-pigeonpea intercrop and sole maize crop.

Further, they established that pigeonpea varieties had no effect on the N and P budgets of maize-pigeonpea intercrop, and the most negative N and P budgets were specific to areas where the initial soil P and maize yields were high. These results corroborate findings by Yeboah *et al.* (2004) who reported a 26% decline in available P and no change in total soil N after one year of pigeonpea cultivation in Ghana. From this study, it was apparent that incorporating pigeonpea into maize-based cropping systems could improve N budgets without necessarily increasing the proportion of P mined from the soil (Adu-Gyamfi *et al.*, 2007).

In a related study in Malawi and Tanzania, incorporating pigeonpea into maize cropping systems reportedly had no effect on grain or total N and P of maize (Myaka *et al.*, 2006). In this study, the N and P harvest indices of maize under both mono and intercrops did not differ either. They, however, differed between locations. For instance, the N harvest index (HIN) of maize for Babati and Gairo in Tanzania was 73 and 65%, respectively, compared to 51% for Ntonda and 38% for Nyambi in Malawi. The HIN for pigeonpea was 34, 20, 22 and 24% for Babati, Gairo, Ntonda and Nyambi, respectively. However, only 27, 28, 37, and 39% of the N in the pigeonpea crops were located in the stems and 40, 46, 36 and 31% were located in the leaves for Babati, Gairo, Ntonda and Nyambi, respectively (Myaka *et al.*, 2006). These values differ substantially from those quoted for a similar study in Malawi in which pigeonpea reportedly accumulated about 48-60% of its N in foliage and a paltry 7-20% in the grain (Chirwa *et al.*, 2006).

The P harvest index (HIp) for maize was 82, 76, 46 and 38% for Babati, Gairo, Ntonda and Nyambi, respectively. The HIp for pigeonpea was 28, 22, 14 and 32% for Babati, Gairo, Ntonda and Nyambi, respectively. However, only 47, 24, 57, and 30% of P in the pigeonpea crops were located in the stems and 25, 49, 27 and 30% in the leaves for Babati, Gairo, Ntonda and Nyambi, respectively. The disparity in allocation of N and P from the vegetative plant parts to the grain was ascribed to differences in the growing conditions among the study sites (Myaka *et al.*, 2006). The study did not find any impact on both total soil N and inorganic N contents after two seasons of pigeonpea inclusion in maize crops. However, there tended to be more N in the upper soil layer of the intercropped plots in Tanzania and a decrease in the same at Nyambi in Malawi. These findings were based on samples taken from the upper 15cm soil layer, but since pigeonpea is deep-rooted, it is probable that parts of the beneficial effects may have occurred below the 15cm depth. Nonetheless, pigeonpea added upto 60 kg N ha^{-1} to the system and accumulated upto 6 kg P ha^{-1} and only 25% of this N and P were exported in the grain (Myaka *et al*., 2006). Thus, it was evident from this study that including pigeonpea in maize cropping systems increased the recirculation of dry matter, N and P, and could have a long-term effect on soil fertility.

Further, working in Machakos in semi-arid eastern Kenya, Rao and Mathuva (2000) reported a significant decline in extractable P after 6.5 years of maize-pigeonpea cropping; extractable P declined from the initial 16 to 11ppm by the end of 6.5 years. The authors also noted that pigeonpea-maize intercrop recycled a meagre 27 kg N and 1.6 kg P ha^{-1} yr^{-1} through litterfall. However, the study only considered the traditional long duration pigeonpea variety and did not measure the contribution of BNF and residue management to the N and P budgets of the maize-pigeonpea cropping system. Nonetheless, the results confirm earlier reports by Sheldrake and Narayanan (1979), Rao and Wiley (1979) and KumarRao *et al*. (1983) that N contribution by pigeonpea from litterfall and root senescence ranged from 0 to 40kg N ha^{-1}. They also tally with findings from similar studies in India in which the inclusion of pigeonpea in wheat systems reportedly led to massive depletion of both N and P, irrespective of the treatments imposed (Singh *et al*., 2005; Singh and Dwivedi, 2006). Available P, for instance, diminished by 16% in the first year, 22% in the second, and 29% in the third year (Singh *et al*., 2005). On the other hand, 121.2-135.2 kg N ha^{-1} was removed and a meagre 38.4-41.6 kg N ha^{-1} recycled from stubble, nodules and leaf litter by pigeonpea in these studies (Singh and Dwivedi, 2006).

In other studies across the world, Rego *et al.* (2003) reported positive N and P budgets for a two-year sorghum-pigeonpea-castor rotation system in farmers' fields in India, Abunyewa and Karbo (2005) reported a 48.5% increase in total soil N on pigeonpea fallow plots after a two-year fallow period in Ghana, KumarRao and Dart (1987) reported negative budgets for pigeonpea in India, Diekow *et al*. (2005) reported a 28% increase in soil N stock after 17 years of maize-pigeonpea cropping in Brazil, Tolanur and Badanur (2003) reported a significant increase in soil N and available P after one year of pigeonpea-pearl millet cropping in India, and Chirwa *et al*. (2006) reported no improvement in soil fertility when pigeonpea was included in agroforestry systems in Malawi. It is apparent from the foregoing studies that including pigeonpea in maize cropping systems can either deplete or maintain soil fertility.

2.2.3. Effect of pigeonpea on soil carbon stocks

Studies have shown that pigeonpea has the ability to increase soil organic matter (SOM) from leaf biomass and senescent material it produces at a rate of 1-4.5 t ha^{-1} (Sakala *et al*., 2000; Snapp and Silim, 2002; Mapfumo and Mtambanengwe, 2004; Silim, 2005; Myaka *et al*., 2006; KumarRao *et al*., 2011). However, like other legumes, its contribution to SOM is site-specific and therefore depends on the growing conditions, residue management, and the duration of the crop in the field (Mafongoya *et al*., 1998; Snapp *et al*., 1998; Yeboah *et al*., 2004; Abunyewa and Karbo, 2005). Generally, pigeonpea residues mineralize slowly (Mafongoya *et al*., 1998; Rao and Mathuva, 2000) and, like other grain legumes, the long duration varieties accumulate more organic matter than the early maturing varieties (Kumar Rao *et al*., 1980).

In a study in Ghana, for instance, Yeboah *et al*. (2004) reported a 2.5% decline in mean organic carbon content of soils after just one year of pigeonpea cultivation. Conversely, working in the same country (Ghana), Abunyewa and Karbo (2005) reported a 30.5% increase in soil organic carbon on pigeonpea fallow plots after a two-year fallow period. The disparity in pigeonpea contribution to SOM in these two cases may have been due to differences in the amount of pigeonpea biomass returned to the soil and the duration of the crop in the field. However, working in Malawi, Chirwa *et al*. (2006) found no change in soil fertility when pigeonpea was included in agroforestry systems. Similarly, Adu-Gyamfi *et al*. (2007) reported no significant change in total soil C after two seasons of maize-pigeonpea intercropping in Malawi and Tanzania. They noted, however, that in Tanzania the maize-pigeonpea intercrop tended to accumulate more C in the upper soil layer whilst at Nyambi in Malawi it was the reverse, total C content decreased in intercropped plots compared to sole maize plots.

In a related study in India, inclusion of pigeonpea in wheat cropping systems reportedly enhanced carbon accumulation in the soil profile by 13.9% after three years of continuous cropping, especially when N and P fertilizers were applied (Singh *et al*., 2005). The pigeonpea-wheat plots accumulated 2.6 Mg ha^{-1} more carbon than the rice-wheat plots. These results are consistent with the findings of Singh and Dwivedi (2006) who reported increases in soil organic carbon of 13% at 0-15 cm, 11% at 15-30 cm and 9% at 30-45cm soil depth after three years of pigeonpea-wheat cropping in the same region. Diekow *et al*. (2005) reported similar results from a long-term trial in Brazil. In this study, maize-pigeonpea cropping systems increased soil C stocks by 26% after 17 years of cropping.

Similarly, working in India, Tolanur and Badanur (2003) reported a significant increase in soil C after just one year of pigeonpea-pearl millet cropping. They attributed the increase in soil C to massive litter fall from pigeonpea. However, working in Machakos in semi-arid eastern Kenya, Rao and Mathuva (2000) reported a significant decline in soil organic C after 5 years of maize-pigeonpea cropping; soil organic C reduced by about 6%. The study did not, however, measure the contribution of residue management to soil carbon stocks of the cropping system. Similar efforts by Silim *et al.* (1998) to determine the long-term benefit of including pigeonpea, among other legumes, in cereal-based low input cropping systems in semi-arid eastern Kenya generated scanty information as the study was abandoned before any conclusive results were obtained. Nonetheless, it is apparent from these studies that incorporating pigeonpea into maize cropping systems may or may not enhance the soil organic matter content of the system.

2.2.4. Effect of pigeonpea on soil structure

Unlike other legumes, pigeonpea has a strong deep root system, which acts as a biological plough that breaks hard pans and loosens the soil, thereby improving its infiltration and aeration. Similarly, through its microbial activity, pigeonpea enhances formation and maintenance of soil aggregates. Reports also indicate that cultivation of pigeonpea increases soil organic matter (SOM) substantially through leaf biomass and senescent material it produces at a rate of 1-4.5 t ha^{-1} (Sakala *et al*., 2000; Snapp and Silim, 2002; Mapfumo and Mtambanengwe, 2004; Silim *et al*., 2005; Myaka *et al*., 2006; Kumar *et al*., 2011). And the importance of SOM in stabilizing soil has been well-documented (Tisdall and Oades, 1983; Oades, 1984; Chaney and Swift, 1984; 1996; Six *et al*., 2000; Bronick and Lal, 2005). Generally, the higher the SOM content the greater the stability of soil aggregates, especially in mineral soils (Onweremada *et al*., 2007; Barreto *et al*., 2009; Lawal *et al*., 2009; Samahadthai *et al*., 2010).

In a study in Ghana, for instance, Dowuona and Adjetey (2010) found a very strong correlation between aggregate stability and SOM from pigeonpea fallows among other cropping systems. In this study, pigeonpea plots had more stable aggregates than natural fallow and bare plots. The greater stability of soil aggregates under pigeonpea and other tree legumes was attributed to the protective cover of their canopy and binding action of their roots. However, in subsequent studies in the same region, Dowuona *et al.* (2011) reported a marked decline is aggregate stability of soils under pigeonpea and other legumes compared to the natural fallow, despite addition of pigeonpea biomass. Pigeonpea plots registered a 42% decrease in the dispersion ratio (DR) values compared to 46-50% in the natural fallow plots. Addition of pigeonpea biomass did not increase aggregate stability, attesting to the fact that it takes time for organic matter levels to build up in the soil and influence soil physical properties.

In a related study in Zambia, Chirwa *et al.* (2004) reported the highest percentage of water stable aggregates in pigeonpea land use systems at 76.9% followed by natural fallow at 65.8%. The least was recorded in maize without fertilizer at 44%. The disparity was attributed to high organic matter content under pigeonpea cropping systems compared to maize with or without fertilizer. Improved soil aggregation in pigeonpea increased water infiltration and water holding capacity, which reduced surface water run-off and decreased erosion compared to the maize monocrop. Mapa and Gunasena (1995) and Yamoah *et al.* (1986) reported similar results, albeit from hedgerow intercropping studies.

It is apparent that pigeonpea has the potential to improve soil structure by breaking the hardpan and enhancing the formation and maintenance of soil aggregates. Improved soil aggregation improves infiltration, aeration and root penetration, and increased crop yields. However, since soil physical properties such as aggregate stability and infiltration are difficult to assess, time consuming and expensive to measure, their importance has received insufficient research attention (Chirwa *et al*, 2004).

2.2.5. Effect of pigeonpea on soil water dynamics

Farmers in Kenya intercrop pigeonpea with cereals such as maize, sorghum and millets. This is often done either in alternate or in multiple rows, and is seen by many farmers as a form of security against total crop failure. The maize is generally harvested earlier leaving pigeonpea to continue in the field. This enables pigeonpea to utilize residual moisture or any rain that comes after the maize is harvested which may be why it is labeled as a dryland crop.

Rooting habits differ widely in cereal- legumes cropping systems. Cereals have extensive but shallow root systems while legumes, particularly pigeonpea, have deep roots which provide access to water stored deep in the soil profile when that in the surface layers is depleted (Rachie and Roberts, 1974; Sheldrake and Narayanan, 1979). However, tall, upright pigeonpea varieties have much deeper root system than spreading, bushy ones (Kay, 1979). Thus, root penetration and water extraction are deeper in late-maturing varieties compared to early maturing ones. The depth of root penetration and vertical distribution of roots appears to depend on the replenishment of soil water. They penetrate deeper when the upper soil layers remain dry. However, regardless of soil moisture distribution, around 70% of root biomass and 50% of root length are commonly found in the top 30 cm of soil. Available reports indicate that either roots or extraction of soil water have been detected to the full depth sampled. For instance, they have been detected at 120 cm (De Vries, 1986), 150 cm (Sheldrake and Narayanan, 1979), 180cm (Sardar and Russell, 1981), and down to 220 cm (Nene and Sheila, 1990). Some reports indicate that root development of pigeonpea is less, or at least slower, than that of other crops, presumably reflecting its initial slower crop growth rates. Natarajan and Willey (1981), for instance, noted that pigeonpea roots penetrated deeper than those of sorghum on the same site, although root length density was greater in sorghum in all soil layers except the deepest sampled.

Intercropping causes changes in root development and uptake of water and nutrients (Snaydon and Harris, 1981), although in a pigeonpea-sorghum mixture these effects seem to be small (Natarajan and Willey, 1981). On average, pigeonpea uses about 20-25cm of water to produce about 1t ha^{-1} of grain under traditional production systems (Saxena and Yadar, 1975; Sardar and Russell, 1981). However, intensively managed pigeonpea systems that involve short duration varieties have a higher water requirement because they are grown at higher densities (Mehrotra *et al*., 1977; Singh *et al*., 1986). Mehrotra *et al*. (1977), estimated water use by one such variety to be in the range of 55-60 cm. In a two-year maize –pigeonpea intercropping study in India, Sardar and Russell (1981) found that pigeonpea obtained about half of its water from the upper 52-cm layer even though it had the capacity to extract water from as deep as 180 cm. Rates of water extraction by roots ranged from 0.003 to 0.055 mm/cm/day and varied with time, depth in the profile, and available water content. However, maize had higher water use efficiency (WUE) than pigeonpea. The low WUE by pigeonpea was attributed to low grain yields due to poor season.

In Zambia, improvement in soil physical properties (improved soil aggregation and decreased resistance to penetration) due to pigeonpea cultivation led to high cumulative water intake compared to maize sole crop (Chirwa *et al.,* 2004). Similar results were reported by Lal (1989) and Hulugalle and Ndi (1993) from hedgerow intercropping studies. Generally, pigeonpea cropping increases soil moisture storage (Yeboah *et al*., 2004; Chirwa *et al*., 2004). However, given the low and highly unpredictable rainfall regime in most of the pigeonpea growing areas in the country, proper accounting of profile moisture changes is important for predicting the behavior of the newly developed pigeonpea varieties, especially when intercropped with cereals.

2.3. Effect of pigeonpea cropping systems on pigeonpea and maize yields

Like in the rest of sub-Saharan Africa, maize is the major staple food in Kenya where 95% of the maize produced is consumed by humans (McCann, 2005). However, per capita maize production in the country has declined over the past two decades, contrary to the global trend. Maize yields have fallen from 2 to 0.5 t ha^{-1} over the past 10 years resulting in widespread malnutrition, a recurrent need for emergency food supply and an increasing dependence on food imports (Dudal, 2002; Rutunga *et al*., 2003; Ayaga *et al*., 2004; Jaetzold *et al*., 2006; Mugwe *et al*., 2008; Ngome *et al*., 2011; Karaya *et al*., 2012; Mucheru-Muna *et al*., 2013).
This scarcity has been attributed partly to drought, but mainly to declining soil fertility, particularly among the smallholders who produce over 75% of the maize and other foods consumed in the country (GoK, 2004; FAO, 2004; Wasonga *et al*., 2008; Mucheru-Muna *et al*., 2013). Most of the soils across the country are heavily depleted of nitrogen (N) and phosphorus (P), and are extremely low in organic matter content (NAAIAP, 2014; Itabari *et al*., 2011; FAO, 2004; Smaling *et al*., 1993).

Several studies (Dalal, 1974; Giller *et al*., 1997; Rao and Mathuva, 2000; Adjei-Nsiah *et al*, 2007; Degrande, 2001; Akanvou *et al*, 2002; Abunyewa and Karbo, 2005; Chamango, 2001) have shown that intercropping pigeonpea with cereals boosts cereal yields tremendously without affecting its dry matter accumulation and could, therefore, help reverse this trend. However, the superiority of pigeonpea-cereal intercrop over their sole crops depends on pigeonpea variety and the growing conditions. Generally, the longer the duration of the cereal, the lower the pigeonpea yield. Therefore, intercropping cereals with early-maturing pigeonpea often leads to drastic reduction in pigeonpea yield (Tarhalkar and Rao, 1981; Ali, 1990). In two separate studies in Kenya, for instance, maize-pigeonpea intercropping systems reportedly out-yielded continuous sole cropping by 24-75% (Rao and Mathuva, 2000; Kimani *et al*., 1993). According to Kimani *et al*. (1993), alternating two rows of maize with two rows of pigeonpea gave the highest total yield whilst one row of maize (two plants per hill) between two rows of pigeonpea gave the highest land equivalent ratio. These reports contradict earlier findings by Nadar (1984) who, working in Machakos too, found the maize-pigeonpea intercrop to be about 2% less advantageous than sole maize crop. These studies, however, were based on the traditional long-duration pigeonpea varieties and did not consider the newly developed high yielding short and medium duration varieties that are currently gaining popularity among farmers.

Similarly, working in Tanzania and Malawi, Myaka *et al*. (2006) reported a significant increase in total system yield (in terms of biomass) in maize-pigeonpea cropping systems compared to sole maize. However, the inclusion of pigeonpea in these studies had no effect on the total dry matter accumulation of maize. Further, the harvest index, (HI_{dm}), calculated based on dry matter of maize in sole stand or in the maize-pigeonpea intercrop, did not differ. Similar results were reported by Egbo and Ngumalen (2010) from a two-year study in Nigeria. The authors noted that intercropping decreased the number of pods per plant, dry pod weight and grain yield of the pigeonpea component as well as the panicle length, panicle weight and dry grain yield of the cereal component. However, based on the land equivalent ratio (LER) pigeonpea-cereal intercrop outperformed their sole crops.

These results agree with those of Silim *et al*. (1997) who found no clear difference from the preliminary yield results of a study conducted in semi-arid Eastern Kenya, between the intercropped maize and its sole crop after three cropping seasons. They noted, however, that the yield of intercropped maize was substantially lower than its sole crop in seasons when moisture supply was limiting. Unfortunately, the study was abandoned before any conclusive results were generated. In other studies across the world, Natarajan and Wiley (1981) reported that in a sorghum-pigeonpea intercrop, the pigeonpea component suffered considerable competition from the sorghum, but after the sorghum harvest it compensated for the initial slow growth and produced seed yields equivalent to 70% of the sole crop. Similarly, Tarhalkar and Rao (1981) found that intercropping sorghum with long-duration pigeonpea caused less reduction in sorghum yield than if it was intercropped with a short–duration variety.

2.4. Effect of climate change on pigeonpea yields

Temperatures and rainfall in Kenya and the rest of East Africa are expected to increase by about 2°C and 11%, respectively, by 2050 due to climate change (Thornton *et al*., 2009; Christensen *et al*., 2007; Cooper *et al*., 2008; Doherty *et al*., 2009). However, the rise in temperature may cause a substantial increase in evaporation rates, which are likely to balance and exceed any benefit from the predicted increase in precipitation (Osbahr and Viner, 2006). Thus, if not checked, climate change will undermine agricultural productivity and expose millions of people to hunger and poverty, especially in semi-arid areas where temperatures are already high and rainfall low and unreliable, agriculture is predominantly rain-fed and adoption of modern technologies is low (Herrero *et al*., 2010; Ochieng *et al*., 2016).

A lot of work has been done to quantify some of the agricultural impacts associated with projected changes in future climate using a variety of simulation models, but most of it has been carried out at global, regional and country levels hence not applicable to community-based adaptation planning (Parry *et al*., 2004; Cline, 2007; Lobell *et al*., 2008; Herrero *et al*., 2010). Similarly, despite the importance of pigeonpea in Kenya and elsewhere in the region, few studies have assessed the impact of climate change on its performance. Most studies have focused on staple and commercial crops such as maize, tea, wheat, rice, beans and groundnuts (Jones and Thornton, 2003; Kabubo-Mariara and Karanja, 2007; Herrero *et al*., 2010; FAO, 2014b; Ochieng *et al*., 2016) and tomatoes (Karuku *et al*., 2014). There is a need for more detailed information on the impacts of climate change on pigeonpea-maize intercropping systems to guide in formulating appropriate adaptation measures that will increase their productivity, ensure food security in future and safeguard pigeonpea's niche markets.

2.5. Pigeonpea research in Kenya: An overview

Research on pigeonpea in Kenya started in 1977 at the University of Nairobi and in 1980 at KALRO's Research Centre in Katumani. The research objectives were to: (1) Develop short-duration, high-yielding varieties with acceptable seed characters and resistance to drought, major diseases (especially *Fusarium* wilt), and pests; (2) Develop improved production practices; (3) Identify the socio-economic constraints to production, and devise approaches to overcome them; (4) Develop and implement sustainable seed systems; and (5)Transfer technologies to farmers (USAID, 2010; Audi *et al*., 2008; Nagarajan *et al*., 2008; Shiferaw *et al*., 2008; Kimani, 2001).

To date, the two institutions in collaboration with ICRISAT have developed numerous short, medium and long-duration pigeonpea varieties with considerably high yield potential, good seed qualities and high resistance to major pests and diseases. The three maturity groups (short, medium and long-duration varieties) take on average 100, 150 and 180 days, respectively, to mature (Gwata and Shimelis, 2008; Kimani, 2001). The short-duration cultivars are widely adapted, but perform best at medium altitude (600-1500 m) locations with warmer temperatures (mean 26^{o}C). With good management, grain yields of 1.2 to 2.5 t

ha^{-1} can be obtained. They can be grown in October/November, harvested before the onset of the long rains in March/April and ratooned with a second harvest obtained in July/August. The crop can also be grown in April and harvested before September (Kimani *et al*., 1993). They are a completely new plant type designed for cultivation under mono-cropping systems (Johansen, 1990; KumarRao, 1990). However, farmers in Kenya routinely intercrop them with maize, sorghum and millets (Audi *et al*., 2008; Nagarajan *et al*., 2008; Shiferaw *et al*., 2008; USAID, 2010).

The medium-duration varieties are intended for areas with bimodal rainfall where the long rains are less reliable. They are grown in October/November at the onset of the short rains, and harvested after the long rains. The medium duration lines are more adapted to medium/high elevations (900-1800m) with 600-1500mm annual rainfall, and can be grown in mixed or intercropped systems. They have a yield potential of up to 3.5t ha^{-1} (Kimani *et al*., 1993; Fungoh *et al*., 1995; Rao and Mathuva, 2000).

However, whilst a lot of work has been done on the breeding, agronomy, pathology, and economics of pigeonpea in Kenya, very little research has been conducted on its nutrition and its role in the sustainability of dryland cropping system. The few reports available are from nutritional studies conducted on the traditional, long-duration varieties (Johansen, 1990). Information on the nutrition of the recently developed short duration varieties is scanty. Further, most of the available data is from studies conducted in India where unlike in Kenya, pigeonpea is grown under high and dependable rainfall conditions (Reddy and Virmani, 1980).

CHAPTER THREE

3.0. THE EFFECT OF INTERCROPPING AND INOCULATION ON NITROGEN FIXATION AND ACCUMULATION BY PIGEONPEA

Abstract

Few studies have evaluated improved pigeonpea varieities developed and released in Kenya for soil fertility improvement and contribution to the productivity of cereal-based cropping systems prevalent in marginal areas. A study comprising field and greenhouse experiments was conducted between 2009 and 2013 to evaluate improved pigeonpea varieties for nitrogen (N) uptake, biological nitrogen fixation (BNF), response to *Rhizobia* inoculation and their effect on maize yields. Field experiments were conducted in Katumani Research Centre using a split-split plot design with three pigeonpea varieties, two cropping systems and three crop residue regimes as the main plot, sub-plot, and sub-sub-plot, respectively. Greenhouse experiments were also conducted at Muguga Research Centre where five pigeonpea varieties were screened for BNF and response to Rhizobia inoculation in plastic pots filled with 10 kg of soil and replicated four times in a completely randomized design. Data collected on N-uptake, BNF and maize and pigeonpea yields were subjected to analysis of variance using GENSTAT statistical software. Pigeonpea had significantly ($p \leq 0.05$) higher N uptake compared to maize; Mbaazi II (84-114 kg N ha^{-1}) absorbed more N followed by Kat 60/8 (29-44 kg N ha^{-1}) and Mbaazi I (20-37 kg N ha^{-1}). All the three pigeonpea varieties fixed 60 – 70 kg N ha^{-1}, meaning they were all good nitrogen-fixers. Mbaazi II fixed significantly ($p \leq 0.05$) higher N (70 kg N ha^{-1}) compared to KAT 60/8 (66 kg N ha^{-1}) and Mbaazi I (62 kg N ha^{-1}) when intercropped with maize. Inoculation with *Rhizobia* gave mixed results. Mbaazi II-maize intercrop gave the highest maize (1.9 t ha^{-1}) and pigeonpea (1.4 t ha^{-1}) grain yields and produced sufficient maize stover (2.1t ha^{-1}) and pigeonpea stalks (2.9 t ha^{-1}).

Key words: nitrogen uptake, nitrogen fixation, inoculation, maize yields, pigeonpea varieties

3.1. Introduction

Per capita food production in Kenya has declined over the last two decades, contrary to the global trend. For instance, maize yields have fallen from over 2 t ha^{-1} to less than 1t ha^{-1} over the past 10 years resulting in widespread food insecurity, malnutrition, a recurrent need for emergency food supply and dependence on imports (Ngome *et al*., 2011; Karaya *et al*., 2012; Mucheru-Muna *et al*., 2013). Estimates available indicate that about 46% of the Kenyan population lacks adequate food and live in abject poverty, and this figure is bound to increase given the current population growth rate of 2.7% (GoK, 2013a). Consequently, Kenya imports on average 350, 000 tons of maize per year to fill the deficit in its domestic demand (FAO, 2014a).

Shortfalls in food production have been attributed partly to climate variability, but mainly to declining soil fertility, caused by continuous cropping without commensurate nutrient replenishment, particularly among the smallholders who produce over 75% of the food consumed in the country (GoK, 2013a; Mucheru-Muna *et al*., 2013). Most of the soils in Kenya are heavily depleted of nitrogen (N) which is essential for plant growth (Okalebo *et al*., 2011; Itabari *et al*., 2011). In the densely populated and heavily cropped County of Kisii in South-Western Kenya, for instance, aggregate N loss is estimated at 112 kg N ha^{-1} yr^{-1} (Smaling *et al*., 1993). In central Kenya highlands, annual net N depletion rate exceeds 30 kg N ha^{-1} yr^{-1}(Smaling *et al*., 1993).

The situation is worse in the arid and semi-arid lands (ASALs) which account for over 80% of Kenya's landmass. ASALs are fragile ecosystems with persistent climatic variability and poor soils (GoK, 2013b). Cereal and legume yields from farmers' fields rarely exceed 1t ha^{-1} and 0.5t ha^{-1}, respectively, per season compared to over 2t ha^{-1} obtained from research stations and commercial farms in the region (NEMA, 2013; Recha *et al*., 2012; Jaetzold *et al*., 2006). This situation is likely to be reversed through the use of mineral N fertilizers and cattle manure. However, few farmers in these areas can afford mineral N fertilizers and those using N fertilizer hardly use the recommended rates (Ariga *et al*., 2008; Mugwe *et al*., 2009; Itabari *et al*., 2011). Moreover, the little N fertilizer available when added to the soil is often utilized with low efficiency due to environmental or soil-related factors (e.g. leaching and volatilization) as well as management factors such as poor timing or placement of N fertilizer (Vanlauwe *et al*., 2010). The use of locally available manure is limited by its low quality and quantity (Bationo and Waswa, 2011; Okalebo *et al*., 2011; Itabari *et al*., 2011). Studies indicate that including legumes such as pigeonpea in maize cropping systems improves soil fertility and increases maize yield by availing N to the maize through biological nitrogen fixation and litterfall decomposition (Adu-Gyamfi *et al*., 2007; Audi *et al*., 2008; Gwata and Shimelis, 2013; HØgh-Jensen *et al*., 2007; Nagarajan *et al*., 2008; Shiferaw *et al*., 2008; USAID, 2010). Reports indicate that legumes can fix as much as 200kg N ha^{-1} yr^{-1} under optimal field conditions (Giller, 2001).

Over the years, the Kenya Agricultural and Livestock Research Organization (KALRO), jointly with the International Crop Research Institute for Semi-Arid Tropics (ICRISAT) and the University of Nairobi have developed and released numerous pigeonpea varieties suitable for Kenya’s semi-arid lands. However, these efforts focused mainly on early maturity and tolerance to biotic and abiotic stresses (Shiferaw *et al*., 2008; USAID, 2010). Few studies have evaluated these pigeonpea varieties for soil fertility improvement and contribution to the productivity of maize-based cropping systems prevalent in the ASALs. The objective of this study therefore, was to determine the amount of N fixed by these varieties and their effect on maize and pigeonpea yields.

3.2. Materials and methods

3.2.1. Study site

The study had two components: field trials and a pot (greenhouse) experiment. The field trials were conducted at the Kenya Agricultural and Livestock Research Organization (KALRO) Katumani Research Centre in Machakos County, 80 km south-east of Nairobi (37˚14´E and 1˚35´S) from 2009 to 2013. Katumani has bimodal rainfall pattern with a mean annual ranfall of 711 mm.The long rains (LR) occur from March to May and the short rains (SR) from October to December with peaks in April and November, respectively (Recha *et al*., 2012; Jaetzold *et al.*, 2006). Inter-seasonal rainfall variation is large with a coefficient of variation ranging between 45 and 58% (Keating *et al*., 1992). However, the second season (short rains) rains are more reliable for crop production (Recha *et al*., 2012). Temperatures range between 17 and 24^{o}C with February and September being the hottest months. The mean annual temperature is 20^{o}C. Evaporation rates are high and exceed the amount of rainfall, most of the year, except in the month of November. The mean potential evaporation (Eo) is in the range of 1820 to 1840mm per year whilst evapotranspiration (ETo) is estimated at 1239 mm (Gicheru, 1996) giving an r/ETo ratio of 0.57. Katumani is 1600 m asl and the terrain ranges from flat to hilly with slopes varying from 2-20% (Gicheru and Ita, 1987). It falls under agro-climatic zone IV which has a low potential for rainfed agriculture (Jaetzold *et al.*, 2006). The dominant soils are ferralo- chromic Luvisols (FAO/UNESCO, 1997; WRB, 2006), low in organic C, highly deficient in N and P and to some extent Zinc and generally have poor structure (NAAIAP, 2014). The site was a grazing field for many years prior to the study. It was cleared of weeds and sparse bushes and cropped uniformly with maize in the 2009 long rain season to even it out before setting up the experiement. All the crop residues were removed from the field after harvesting to eliminate any confounding effect.The pot experiment was conducted in 2010 in a greenhouse at KALRO-Muguga South Research

Centre in Kiambu County, about 27 km west of Nairobi City and 5 km off the Nairobi-Naivasha-Nakuru highway. Muguga is about 2080 m asl.

3.2.2. Treatments and experimental design

3.2.2.1. Field experiment

The field experiment was established during the 2009 short rain season to evaluate pigeonpea varieties for N-uptake, N_2- fixation and their effect on maize yield. The experiment was laid out in a randomized complete block design (RCBD) with a split-split plot arrangement.Three pigeonpea varieties namely Mbaazi I, Kat 60/8 and Mbaazi II representing the short, medium and long duration maturity groups, respectively, constituted the main plots whilst the split-plots consisted of two cropping systems (sole pigeonpea crop and pigeonpea-maize intercrop).The split-split plots were composed of three crop residue regimes (0, 2 and 4 t ha^{-1}) with sole maize and sole cotton crops as the controls. The treatments were laid out in 4.8 m x 4.6 m plots with an inter-plot spacing of 1.5 m and replicated four times. The land was prepared using a hand hoe at the beginning of each cropping season and crops sown at the on-set of the rains. Pigeonpea stalks and maize stovers were weighed, chopped into 5-10 cm pieces and placed into the soil to a depth of 15 cm at the rate of 0, 2 and 4 t ha^{-1}, respectively, every season after land preparation to allow crop residues to decompose. These crop residue application rates and cropping systems represent as closely as possible those practiced by farmers and take into account the competing uses for crop residues in the ASALs. Each zero-residue plot and maize and cotton sole crop plots were divided into two halves where one half was divided further into a micro-and yield- plot, each measuring 2.4 m wide and 2.3 m long to allow for measurement of N_2-fixation using the ^{15}N isotope dilution method (IAEA, 2001). Nitrogen fixation was determined using maize as the reference crop for the short and medium duration pigeonpea, and cotton for the long duration pigeonpea variety. A total of 18 treatments were investigated using sole cotton and sole maize crops as controls and are described in Table 1.

Table1. Summary of treatments investigated for Biological Nitrogen Fixation under field conditions.

Treatment	Description
$T0_a$	Cotton (HART*/control 1)
$T0_b$	Sole maize + 0 t ha^{-1} maize stover incorporated (Control 2)
T1	Short duration pigeonpea sole crop + 0 t ha^{-1} pigeonpea residues incorporated
T2	Short duration pigeonpea sole crop + 2 t ha^{-1} pigeonpea residues incorporated
T3	Short duration pigeonpea sole crop + 4 t ha^{-1} pigeonpea residues incorporated
T4	Maize/short duration pigeonpea intercrop + 0 t ha^{-1} maize stover + 0 t ha^{-1} pigeonpea residues incorporated
T5	Maize/short duration pigeonpea intercrop + 2 t ha^{-1} maize stover +2 t ha^{-1} pigeonpea residues incorporated
T6	Maize/short duration pigeonpea intercrop + 4 t ha^{-1} maize stover + 4 t ha^{-1} pigeonpea residuesincorporated
T7	Medium duration pigeonpea sole crop + 0 t ha^{-1} pigeonpea residues incorporated
T8	Medium duration pigeonpea sole crop + 2 t ha^{-1} pigeonpea residues incorporated
T9	Medium duration pigeonpea sole crop + 4 t ha^{-1} pigeonpea residues incorporated
T10	Maize/medium duration pigeonpea intercrop+ 0 t ha^{-1} maize stover + 0 t ha^{-1} pigeonpea residues incorporated
T11	Maize/medium duration pigeonpea intercrop+ 2 t ha^{-1} maize stover + 2 t ha^{-1} pigeonpea residues incorporated
T12	Maize/medium duration pigeonpea intercrop+ 4 t ha^{-1} maize stover + 4 t ha^{-1} pigeonpea residues incorporated
T13	Long duration pigeonpea sole crop + 0 t ha^{-1} pigeonpea residues incorporated
T14	Long duration pigeonpea sole crop + 2 t ha^{-1} pigeonpea residues incorporated
T15	Long duration pigeonpea sole crop + 4 t ha^{-1} pigeonpea residues incorporated
T16	Maize/long duration pigeonpea intercrop + 0 t ha^{-1} maize stover + 0 t ha^{-1} pigeonpea residues incorporated
T17	Maize/long duration pigeonpea intercrop + 2 t ha^{-1} maize stover + 2 t ha^{-1} pigeonpea residues incorporated
T18	Maize/long duration pigeonpea intercrop + 4 t ha^{-1} maize stover + 4 t ha^{-1} pigeonpea residues incorporated

* A cotton variety

Pigeonpea was planted without fertilizer additions at spacing of 90 cm x 60 cm, 75 cm x 30 cm and 50 cm x 25 cm for the long, medium and short duration varieties, respectively, at 2 seeds per hill and thinned to one two weeks after emergence. Mbaazi 1 and KAT 60/8 represented the short and medium duration pigeonpea varieties, respectively, due to their early maturity and high yields. They take on average 100 and 150 days, respectively. Mbaazi II served as the long duration variety owing to its longer duration in the field and its resistance to common pests and diseases and high yield. It takes 180-220 days to mature. Generally, the three pigeonpea varieties are popular among local farmers and their seeds are readily available. Maize was planted with application of Triple Super Phosphate (TSP) fertilizer at the recommended rate of 40 kg P_2O_5 ha^{-1} at spacing of 90 cm x 30 cm. However, in the intercrops, one row of pigeonpea was planted after every row of maize to replicate the farmers' practice. Maize variety KDV1 was selected for the study owing to its good adaptability, early maturity (120 -150 days to mature) and yields highly under semi-arid conditions.

Cotton was also planted with application of TSP fertilizer at the recommended rate of 40 kg P_2O_5 ha^{-1} at spacing of 100 cm x 30 cm. HART cotton variety was used owing to its inability to fix nitrogen, phenological complementarity with pigeonpea and good adaptability to semi-arid conditions. The micro- and yield- plots were top-dressed with ^{15}N labelled ammonium sulphate and unlabelled ammonium sulphate fertilizer, respectively, at the recommended rate of 20 kg N ha^{-1} two weeks after emergence. About 101.8g of ammonium sulphate with an enrichment of 10% atom excess (a.e) were weighed for each micro-plot, dissolved in 10 litres of distilled water and sprinkled evenly over the entire micro-plot using a watering can. Unlabelled ammonium sulphate fertilizer was applied around the base of each plant in the yield plot and allowed to be dissolved by rainwater. Both pigeonpea and cotton were protected from pests on a 'minimum-protection' basis, twice per season with Dimethoate^{TM} (dimethoate) at 0.5 Lha^{-1} to control pod borer (*Helicoverpa armigera*), pod fly (*Melanagromyza chalcosoma*) and cotton boll weevil. Bulldock^{TM} pesticide (beta-cyfluthrin) was applied on maize once every season to control stalk borers. The plots were kept weed-free by weeding regularly depending on weed emergence/intensity and characteristics. Nitrogen fixation was determined in one season (2010 short rainy season), whilst pigeonpea's N-uptake and its effect on maize yield was evaluated for four long rain and four short rain seasons (8 seasons) from October 2009 to July 2013.

3.2.2.2. Pot experiment

The pot experiment was conducted in a greenhouse during the 2010 short rainy season to screen pigeonpea varieties for BNF and response to *Rhizobia* inoculation. The treatments comprised five pigeonpea varieties drawn from three maturity groups (short, medium and long duration), 5 *Rhizobia* strains (USDA3456, KFR3, KFR269, KFR531 and a mixture of the four strains) and three cotton varieties (Siokra, Vered and Hart cotton varieties as reference crops for the short, medium and long duration pigeonpea varieties, respectively). USDA3456 was obtained from the MIRCEN (Microbial Resource Centre) Project of the University of Nairobi whilst KFR3, KFR269 and KFR531 were sourced from the Department of Biotechnology of the Kenya Forestry Research Institute (KEFRI). The experiment was conducted in plastic pots filled with 10kg of a mixture of air-dried sieved soil and sand sourced from Katumani in the ratio of 1:1. The treatments were replicated four times in a completely randomized design (CRD). The soil in each pot was labelled with ^{15}N at the recommended rate of 20 kg N ha^{-1} by dissolving 62.86g of ^{15}N-labelled ammonium sulphate fertilizer with an enrichment of 10% atom excess in 6.6 litres of distilled water and taking an aliquot of 50ml and sprinkling it on the soil while mixing it thoroughly before planting. Pigeonpea seeds were pre-inoculated with *Rhizobia* spp using the two-step seed inoculation procedure as described by Woomer (2010). Pigeonpea and cotton seeds were sown in the pots at a rate of three seeds per pot and thinned to one plant per pot two weeks after germination. Watering was done every day at the plant base using a water jug to avoid cross contamination by soil splashing and was maintained at below field capacity to avoid drainage. The pots were kept weed-free by weeding regularly by picking depending on weed emergence/intensity and characteristics. Both pigeonpea and cotton were sprayed twice with Dimethoate^{TM} (dimethoate) at 20ml/20L of water per spray to control pod borer (*Helicoverpa armigera*), pod fly (*Melanagromyza chalcosoma*) and cotton boll weevil. A total of 30 treatments were tested in this study using three cotton varieties as controls (Table 2).

Table 2. Treatments applied in the Biological Nitrogen Fixation pot experiment

Treatment	Description
$T0_a$	Siokra (non- inoculated) / control 1
$T0_b$	Vered (non- inoculated)/ control 2
$T0_c$	HART 89M (non- inoculated)/ control 3
T1	Non-inoculated Mbaazi 1
T2	Mbaazi 1 inoculated with USDA 3456
T3	Mbaazi 1 inoculated with Composite
T4	Mbaazi 1 inoculated with KFR 531
T5	Mbaazi 1 inoculated with KFR 269
T6	Mbaazi 1 inoculated with KFR 3
T7	Non-inoculated ICEAP 00536
T8	ICEAP 00536 inoculated with USDA 3456
T9	ICEAP 00536 inoculated with Composite
T10	ICEAP 00536 inoculated with KFR 531
T11	ICEAP 00536 inoculated with KFR 269
T12	ICEA P00536 inoculated with KFR 3
T13	Non-inoculated KAT 60/8
T14	KAT 60/8 inoculated with USDA 3456
T15	KAT 60/8 inoculated with Composite
T16	KAT 60/8 inoculated with KFR 531
T17	KAT 60/8 inoculated with KFR 269
T18	KAT 60/8 inoculated with KFR 3
T19	Non-inoculated KAT 677
T20	KAT 677 inoculated with USDA 3456
T21	KAT 677 inoculated with Composite
T22	KAT 677 inoculated with KFR 531
T23	KAT 677 inoculated with KFR 269

T24	KAT 677 inoculated with KFR 3
T25	Non-inoculated Mbaazi 2
T26	Mbaazi 2 inoculated with USDA 3456
T27	Mbaazi 2 inoculated with Composite
T28	Mbaazi 2 inoculated with KFR 531
T29	Mbaazi 2 inoculated with KFR 269
T30	Mbaazi 2 inoculated with KFR 3

3.2.3. Data collection

3.2.3.1. Plant sampling and analysis

Maize, pigeonpea and cotton in the field trials were harvested at physiological maturity when the maize stalks were beginning to dry and pigeonpea pods and cotton bolls were ripening. Plants lying within one metre of each side of the plot were omitted from the sample harvest to eliminate any plot border effects. All plants in the inner rows were counted, harvested and weighed using a precision weighing balance ±0.001g. Sub-samples of maize, pigeonpea and cotton plants were taken from the total number of plants harvested and divided into cobs and stover, pods and stalks, and bolls and stalks for maize, pigeonpea and cotton data collection, respectively. All samples were oven-dried at 60°C to constant weight and then ground to a fine powder using a Wiley Mill. Maize and pigeonpea grains were dried to 12.5% moisture content and the ratio of dry weight to fresh weight and plot fresh weight extrapolated to estimate maize and pigeonpea grain and biomass yields in tonnes per hectare. Plants in the pot experiment and a few from the inner central rows of the micro-plots were also harvested and disaggregated into roots, leaves, stover, grains, bolls and stalks.They were chopped into small pieces using a clean panga and quartered to obtain representative samples of each yield component which was then oven-dried at 60◦C for 24 hours, passed through 1 mm sieve in a Wiley Mill and analysed for total N and ^{15}N using the Kjeldahl digestion procedure (Bremner and Mulvaney, 1982) and emission spectrometry (IAEA, 2001), respectively. The proportion of N fixed was calculated using the equations described by IAEA (2001). The fractional contribution of fixed N derived from air (% Ndfa) in pigeonpea was calculated using Equation 1.0 and was done for all the plant parts:

$$\% \text{ Ndfa} = \left[1 - \frac{\text{Atom \% }^{15}\text{N excess}_{pigeonpea}}{\text{Atom \% }^{15}\text{N excess}_{maize}} \right] \text{X } 100 \text{ ....} 1.0$$

Where Atom % ^{15}N excess$_{pigeonpea}$ and Atom % ^{15}N excess$_{maize}$ were the ^{15}N enrichment values of pigeonpea and maize, respectively. The amount of N symbiotically fixed by pigeonpea (BNF, kg ha^{-1} yr^{-1}) was then calculated by multiplying the total N in pigeonpea plant parts by their respective % Ndfa.

3.2.3.2. Data analysis

All data on maize and pigeonpea yields, N-uptake and N_2-fixation were subjected to a two - way analysis of variance (ANOVA) using GENSTAT statitistical software version 14.2 (GENSTAT, 2016). Because of the large number of treatments involved, mean comparisons for the individual treatments was done using both Fischer's protected Least Significant Difference of means (LSD, $p \leq 0.05$) and the Duncan Multiple Range Test (DMRT).

3.3. Results and discussion

3.3.1. Nitrogen uptake by maize and pigeonpea during the growing periods

Amount of N taken up by maize and pigeonpea from the soil during eight seasons of continuous cropping are provided in Tables 3a and 3b. Maize sole crop (control) accumulated about 19 kg N ha^{-1} in grain and 11 kg N ha^{-1} in stovers annually when grown without ploughing back crop residues. A similar trend was observed in pigeonpea where most of the

N absorbed by pigeonpea sole crop was stored in the grains (37-114 kg N ha^{-1}) compared to the stalks (20-84 kg N ha^{-1}). The difference in N uptake could be attributed to the high maize and pigeonpea grain yields compared to maize stover and pigeonpea stalk yields (Tables 6a and 6b), given that N uptake is a function of biomass production and its N content (Holderbaum *et al*., 1990). These results differ with those reported by Chirwa *et al*. (2006) in a similar study in Malawi in which pigeonpea accumulated 48-60% of its N in foliage and a paltry 7-20% in the grain. The disparity could be attributed to differences in the growing conditions between the two sites. Mbaazi II sole crop had a higher N uptake of 84-114 kg N ha^{-1} followed by Kat 60/8 with 29-44 kg N ha^{-1} and then Mbaazi I with 20-37 kg N ha^{-1} per year, respectively. This could be due to the fact that total N of legumes is related to maturity period other than the location or season (Taylor *et al*., 1982), thus, the early duration of Kat 60/8 and Mbaazi I may have been responsible for the low N uptake. Similar results were reported by Wanderi *et al* (2011) in a study in which the long duration pigeonpea (1266 kg N ha^{-1}) absorbed more N than the medium duration pigeonpea (345 kg N ha^{-1}) after two cropping seasons.

Table 3a. Nitrogen accumulated by maize for eight cropping seasons from 2010-2013

	Maize grain and stover N yield (kg ha^{-1})[a]									
	2010		2011		2012		2013		Av. N yield per year	
Cropping systems	Gr.	St.	Gr.	St.	Gr.	St.	Gr.	St.	Gr.	St.
Maize sole crop + 0 tons (Control)	16	9	17	14	24	10	19	10	19	11
Mbaazi I/maize intercrop +0 tons*	18	9	16	12	15	12	14	11	16	11
Mbaazi I/maize intercrop + 2 tons†	16	9	16	11	15	9	13	10	15	10
Mbaazi I/maize intercrop + 4 tons‡	22	14	23	15	28	16	28	16	25	15
Kat 60/8/maize intercrop+ 0 tons	17	15	15	17	16	16	15	15	16	16
Kat 60/8/maize intercrop + 2 tons	23	20	21	23	22	18	20	19	22	20
Kat 60/8/maize intercrop + 4 tons	33	22	27	24	31	18	28	20	30	21
Mbaazi II/maize intercrop+0 tons	15	10	15	16	15	15	15	13	15	14
Mbaazi II/maize intercrop + 2 tons	19	11	19	18	19	17	19	14	19	15
Mbaazi II/maize intercrop + 4 tons	43	21	46	19	43	19	48	24	45	21
SED[b]	7	3	7	2	7	1	9	3	6	2
Rainfall (mm)	665.7		506.8		617.0		590.8		-	

[a]Data are treatment means averaged over 2 seasons; Gr: maize grain; St: maize stover; [b] Standard error of treatment means; *No crop residues were incorporated; † 2 t ha^{-1} of crop residues were incorporated; ‡ 4 t ha^{-1} of crop residues were incorporated.

Intercropping maize with the three pigeonpea varieties reduced marginally the mean maize grain N yield from 19 to < 16 kg N ha^{-1}, but increased stover N yield marginally from 11 to > 14 kg N ha^{-1} under maize-Kat 60/8 and maize-Mbaazi II intercrops. There was no significant difference in stover N yield between maize sole crop and maize-Mbaazi I intercrop. Nitrogen uptake by Mbaazi I declined significantly ($p \leq 0.05$) with N stored in the grains and stalks decreasing by 92 % (37-3 kg N ha^{-1} yr^{-1}) and 80% (20-4 kg N ha^{-1} yr^{-1}), respectively. A similar pattern was observed under maize-Kat 60/8 intercrop where mean pigeonpea grain and stalk N yields per year declined ($p \leq 0.05$) by 93% (44-3 kg N ha^{-1}) and 86% (29-4 kg N ha^{-1}), respectively. The decline in N uptake by both maize and pigeonpea could be attributed to low biomass production (Tables 6a and 6b) due to low soil fertility hence low N demand

and maize's longer duration in the field, respectively, since the longer the duration of the cereal, the lower the pigeonpea yield (Tarhalkar and Rao, 1981; Ali, 1990). These results are in contrast with reports from similar work in Malawi in which N uptake by maize was higher under maize-pigeonpea intercrop than maize sole crop (Chirwa *et al*., 2006). They are also different from results by Myaka *et al*. (2006) from a study in Malawi and Tanzania in which intercropping had no effect on N uptake by maize. The disparity could be attributed to differences in maize yields due to differences in growing conditions between the three countries. However, the amount of N accumulated by pigeonpea grain and stalks under maize-Mbaazi II intercrop increased marginally from 114-120 and 84-97 kg N ha^{-1} yr^{-1}, respectively. The high N uptake could be due to Mbaazi II's phenological complementarity with maize and its ability to mobilize extra N from deeper soil horizons due to its deep root system and massive litterfall (McCown *et al.*, 1992; Myaka *et al.*, 2006). Generally, pigeonpea had a higher N uptake than maize and this could be due to pigeonpea's ability to mobilize N from deeper soil horizons due to its deep roots as well as self- fertilization from the litterfall and biological nitrogen fixation (Snapp and Silim, 2002; Silim *et al*., 2005; Myaka *et al*., 2006; Adu-Gyamfi *et al*., 2007; Kumar *et al*., 2011). These results agree with Wanderi *et al* (2011) who noted from a two-season study in Thika near Nairobi that pigeonpea absorbed more N than maize, although the study was based on the medium and long duration pigeonpea varieties only.

Table 3b. Nitrogen accumulated by pigeonpea for eight seasons from 2010-2013

Cropping systems	Pigeonpea grain and stalk N yield (kg ha^{-1})[a]									
	2010		2011		2012		2013		Av. N yield per year	
	Gr.	Stks	Gr.	Stks	Gr.	Stks	Gr.	Stks	Gr.	Stks
Mbaazi I sole crop + 0 t ha^{-1} of residues	37	24	36	24	36	26	40	26	37	20
Mbaazi I sole crop +2 t ha^{-1} of residues	40	36	42	31	42	35	43	39	42	28
Mbaazi I sole crop + 4 t ha^{-1} of residues	40	33	43	29	42	37	52	42	44	28
Mbaazi I/maize intercrop +0 t ha^{-1} of residues	4	6	3	4	2	4	2	5	3	4
Mbaazi I/maize intercrop + 2 t ha^{-1} of residues	5	9	6	6	4	5	3	7	4	5
Mbaazi I/maize intercrop + 4 t ha^{-1} of residues	6	14	6	6	4	8	5	8	5	7
Kat 60/8 sole crop + 0 t ha^{-1} of residues	44	44	44	31	45	38	43	33	44	29
Kat 60/8 sole crop + 2 t ha^{-1} of residues	45	54	47	36	48	50	50	46	48	37
Kat 60/8 sole crop + 4 t ha^{-1} of residues	61	60	66	49	65	56	71	51	66	43
Kat 60/8/maize intercrop + 0 t ha^{-1} of residues	4	6	1	3	2	7	2	5	3	4
Kat 60/8/maize intercrop + 2 t ha^{-1} of residues	5	7	5	8	4	8	3	5	4	6
Kat 60/8/maize intercrop + 4 t ha^{-1} of residues	6	8	8	11	6	13	3	6	6	8
Mbaazi II sole crop + 0 t ha^{-1} of residues	100	64	91	54	111	97	131	119	114	84
Mbaazi II sole crop + 2 t ha^{-1} of residues	129	117	113	117	124	123	137	129	126	117
Mbaazi II sole crop + 4 t ha^{-1} of residues	145	119	114	119	142	134	141	130	136	126
Mbaazi II/maize intercrop + 0 t ha^{-1} of residues	125	63	120	97	109	111	125	118	120	97
Mbaazi II/maize intercrop + 2 t ha^{-1} of residues	145	120	132	126	115	127	136	130	132	126
Mbaazi II/maize intercrop + 4 t ha^{-1} of residues	153	125	143	129	135	130	140	133	143	129
SED[b]	36	23	30	27	31	30	37	33	34	36
Rainfall(mm)	665.7		506.8		617.0		590.8		-	

[a]Data are treatment means averaged over 2 seasons; Gr: pigeonpea grain; Stks: pigeonpea stalks; [b] Standard error of treatment means.

Ploughing back 2 t ha^{-1} of pigeonpea and maize crop residues gave mixed results. However, ploughing back 4 t ha^{-1} of crop residues increased N uptake by maize across all the cropping systems, albeit marginally in some cases. Relative to maize sole crop, the average amount of N absorbed from the soil and accumulated in maize grains annually increased marginally from 19-25 kg N ha^{-1}, 19-30 kg N ha^{-1} and 19-45 kg N ha^{-1} under maize-Mbaazi I, maize-Kat 60/8 and maize-Mbaazi II intercrops, respectively. Nitrogen accumulated by maize stover also increased marginally from 11-15 kg N ha^{-1} yr^{-1} under maize-Mbaazi I intercrop and 11-21kg N ha^{-1} yr^{-1} under maize-Kat 60/8 and maize-Mbaazi II intercrops. A similar trend was observed in pigeonpea as mean N accumulated in pigeonpea grains increased marginally from 37-44, 44-66, and 114-136 kg N ha^{-1} yr^{-1} under Mbaazi I, Kat 60/8 and Mbaazi II sole crops, respectively. Nitrogen accumulated by pigeonpea stalks also increased marginally from 20-28 and 29-43 kg N ha^{-1} yr^{-1} under Mbaazi I and Kat 60/8 sole crops, respectively, but increased significantly from 84-126 kg N ha^{-1} yr^{-1} under Mbaazi II sole crops. The increase in N uptake by both maize and pigeonpea could be attributed to improvement in soil fertility due to rapid decomposition and mineralization of the crop residues (Akanvou *et al*., 2002; Kwesiga *et al*., 2003; Degranade, 2001) thus releasing nutrients for uptake. However, N accumulated by pigeonpea grains declined significantly ($p \leq 0.05$) from 37-5 kg N ha^{-1} under maize-Mbaazi I and 44-6 kg N ha^{-1} under maize-Kat 60/8 intercrops per year. Nitrogen accumulated by pigeonpea stalks declined too albeit marginally from 20-7 and 29-8 kg N ha^{-1} per year under maize-Mbaazi I and maize-Kat 60/8 intercrops, respectively. The decline in N uptake could be due to low biomass production (Tables 6a and 6b) hence low N demand. Conversely, N accumulated by pigeonpea grain and stalks increased significantly ($p \leq 0.05$) from 114-143 and 84-129 kg N $ha^{-1}yr^{-1}$, respectively, under maize-Mbaazi II intercrop. The high N uptake by Mbaazi II could be attributed to its longer duration in the field which allowed it to recover from the initial slow growth after the maize was harvested, besides its ability to mobilize extra N from deeper soil horizons due to its deep root system (Snapp and Silim, 2002; Mapfumo and Mtambanengwe, 2004; Silim *et al*., 2005; Kumar *et al*., 2011). It is apparent from this study that pigeonpea had higher N uptake compared to maize and the long duration pigeonpea (Mbaazi II) absorbed more N from the soil followed by the medium duration (Kat 60/8) and short duration (Mbaazi I) pigeonpea. Ploughing back crop residues marginally increased N uptake by both maize and pigeonea sole crops. Intercropping reduced N uptake by maize and the short (Mbaazi I) and medium (Kat 60/8) duration pigeonpea, but increased N uptake by the long duration pigeonpea variety (Mbaazi II). This implies that allowing pigeonpea biomass to decompose in the field rather than using them as fuel and fodder would play a critical role in farm N economy.

3.3.2. Nitrogen fixation by pigeonpea varieties during the study period

The amount of N fixed by the short (Mbaazi I), medium (Kat 60/8) and long (Mbaazi II) duration pigeonpea varieties under sole and intercropping systems are presented in Table 4. All the three pigeonpea varieties fixed about 60-70 kg N ha^{-1} under non- restricting conditions. There was no significant difference in N_2-fixation between the long duration pigeonpea/Mbaazi II (65 kg N ha^{-1}) and medium duration variety/Kat 60/8 (64 kg N ha^{-1}) sole crops. However, the two varieties fixed more N than Mbaazi I/short duration pigeonpea (60 kg N ha^{-1}). A similar trend was observed when they were intercropped with maize as Mbaazi II fixed the most N at 69.6 kg N ha^{-1}, followed by KAT 60/8 with 66.4 kg N ha^{-1} and Mbaazi I at 62.4 kg N ha^{-1}. The higher N_2-fixation by Mbaazi II pigeon pea variety could be attributed to its high biomass productivity and late maturity (Taylor *et al*., 1982; Kumar Rao, 1990). These results corroborate those by KumarRao *et al*. (1980) who observed that N_2-fixation by pigeonpea increased with crop duration. Similar results were also reported by Wanderi *et al* (2011) from a study in Thika near Nairobi in which the long duration pigeonpea variety fixed more N than medium duration variety. However, working in

Katumani Nadar and Faught (1984) noted that long duration pigeonpea fixed as low as 15 kg N ha^{-1} and attributed the low fixation to low rainfall received during the study. Similarly, working on several farms on very sandy soils in Zimbabwe Mapfumo and Mtambanengwe (2004), Mapfumo *et al*. (1999) and Chikowo *et al*. (2004) reported fixed N amounts of as low as 6-18 , < 20 kg ha^{-1} and <10 kg N ha^{-1}, respectively, and attributed them to low biomass production due to poor growing conditions.

The short duration variety (Mbaazi I) used in this study fixed 75 to 78% of its N, contrary to reports by KumarRao *et al*. (1980) that most short duration pigeonpea varieties were very poor N fixers and could only fix upto 52% of their total N uptake. The high N fixation could be attributed to high biomass production due to high rainfall recorded during experimentation (Tables 6a and 6b). These results confirm reports by Gathumbi *et al*. (2002); Chikowo *et al.* (2004) and Adu-Gyamfi *et al*., (2007) who noted that N_2-fixation is site-specific and does not depend on pigeonpea variety alone. In other studies across the globe, however, much higher values have been quoted for N_2-fixation by pigeonpea varieties. For instance, Katayama *et al.* (1995), Tobita *et al*. (1994), Adu-Gyamfi *et al*. (1996) and Red de Grupos de Agricultura de Cobertura (2002) reported values in the range of 50-76, 75-165, 123-170 and 41- 280 kg N ha^{-1}, respectively. However, most of these studies were based on the traditional long-duration pigeonpea varieties, with very little regard to the recently developed high yielding short duration varieties.

Table 4. Effect of intercropping on Nitrogen-fixation by dominant pigeonpea varieties

Pigeonpea variety	Amount of N fixed (kg N ha^{-1}) [a]	
	Sole crop	Intercropped with maize
Mbaazi I (short duration)	60	62
Kat 60/8 (medium duration)	64	66
Mbaazi II(Long duration)	65	70
LSD ($p \leq 0.05$)	3	4

[a] Averaged over 4 replicates

3.3.3. Effect of Rhizobia on nitrogen-fixation in the study

The amounts of N fixed by dominant pigeonpea varieties inoculated with different *Rhizobia* strains are presented in Tables 5a and 5b. All the five pigeonpea varieties were good N_2-fixers as they all fixed over 80% of their N requirements. However, inoculating with KFR 3 increased N_2-fixation by 88% for Mbaazi I, 87% for Kat 60/8 and 89% for Mbaazi II, albeit marginally. A similar trend was observed when the same varieties were inoculated with a mixture of the four strains as Mbaazi I, Kat 60/8 and Mbaazi II fixed 86, 86 and 90%, respectively, compared to 84, 86 and 87% fixed by uninoculated Mbaazi I, Kat 60/8 and Mbaazi II, respectively. This implies that KFR3 and a mixture of the 4 rhizobia strains (KFR 531, KFR 269, KFR 3 and USDA 3456) were compatible with the three pigeonpea varieties (Mbaazi I, Kat 60/8 and Mbaazi II) and were more competitive than native *Rhizobia* in the potting soil.

However, inoculating ICEAP 00536 and KAT 677 with KFR 3 reduced N_2-fixation by 6% (83-77%) and 3% (92-89%), respectively. Similarly, N_2-fixation by ICEAP 00536 and KAT 677 declined by 12% (83-71%) and 5% (92-87%), respectively, when inoculated with a mixture of the four strains, suggesting that native *Rhizobium* populations in the potted soil were adequate and more competitive than KFR3 and the mixture of 4 strains. These results agree with reports by Faris (1983) who observed that pigeonpea can nodulate with *Rhizobium* naturally present in most soils without further innoculation. Inoculating with KFR 269 increased N_2-fixation by all pigeonpea varieties by 2-5% except Mbaazi I and ICEAP 00536 whose fixed N declined by 3-13%. Conversely, inoculating with KFR 531 increased N_2-fixation by Mbaazi I by 7% but reduced fixation by the other four pigeonpea varieties (Kat 60/8, Mbaazi II, ICEAP 00536 and Kat 677) by 2-12%. Similarly, inoculating with USDA 3456 increased N_2-fixtion by Kat 60/8 and Kat 677 by 1-2% but reduced N fixed by the other three pigeonpea varieties (Mbaazi I, Mbaazi II and ICEAP 00536) by 1-9%. Inoculating with a mixture of the four strains increased N_2-fixation by Mbaazi I and Mbaazi II by 2-3% but reduced N_2-fixation by the other varieties by 5-12%. However, it had no effect on N_2-fixation by Kat 60/8. The decline in N_2-fixation despite inoculation could be attributed to incompatibility of the inoculant strains with respective pigeonpea varieties. These results corroborate reports by KumarRao (1990), Abaido *et al* (2007), Fening and Danso (2002), Catroux *et al.* (2001) and Brockwell *et al*. (1995) that seed inoculation with *Rhizobia* does not always elicit positive response, it depends on the environment in which the legume is grown and the legume variety planted. Most of the N_2-fixed was stored in the seed, pods and stalks (Table 5b) and was therefore bound to be removed from the farm during harvesting. From the foregoing, it is apparent that it may not be necessary to inoculate pigeonpea in Katumani with the aim of increasing N_2-fixation since soils in Katumani seem to be endowed with high populations of highly competitive native *Rhizobia*.

Table 5a. Effect of *Rhizobial* inoculation on Nitrogen-fixation by dominant pigeonpea varieties

	Ndfa (%)					
Pigeonpea variety	Non-inoculated (control)	USDA 3456	Composite	KFR 531	KFR 269	KFR 3
Mbaazi I	84	78	86	91	81	88
Kat 60/8	86	88	86	85	91	87
Mbaazi II	87	86	90	85	92	89
ICEAP 00536	83	74	71	71	70	77
KAT 677	92	93	87	90	94	89

Ndfa: Nitrogen derived from air; KFR: Kenya Forestry Research Institute; USDA: United States Department of Agriculture.

Table 5b. Effect of *Rhizobial* inoculation on percentage Nitrogen-fixation by different components of dominant pigeonpea varieties.

Rhizobial strains/ Inocula	Ndfa (%) Mbaazi I				ICEAP 00536				KAT 60/8			
	Sd	Pd	Stk	Rt	Sd	Pd	Stk	Rt	Sd	Pd	Stk	Rt
Control (Non-inoculated)	90	83	87	74	88	86	85	71	89	90	89	82
USDA 3456	85	83	77	67	79	81	73	62	90	90	91	79
Composite	89	88	87	77	80	81	70	49	89	89	88	76
KFR 531	93	92	93	87	80	78	69	56	88	88	86	77
KFR 269	86	85	82	72	76	74	70	56	92	92	91	86
KFR 3	91	91	88	78	86	86	77	60	91	88	86	79

Ndfa: Nitrogen derived from air; Sd: pigeonpea seed; Pd: pigeonpea pods; Stk: pigeonpea stalks; Rt: pigeonpea roots.

3.3.4. Maize and pigeonpea yields under different cropping and crop residue management systems

3.3.4.1. Maize yield

Maize yields obtained from different maize-pigeonpea cropping systems and crop residue management options are reported in Tables 6a and 6b. Growing sole maize crop without ploughing back the stovers yielded 0.9 t ha^{-1} of grain and 1.2 t ha^{-1} of stover per season compared to < 0.5 t ha^{-1} per season obtained by most farmers in the region. The high yields could be attributed to good agronomic practices such as timely planting and weeding, correct spacing, use of certified seeds and protection against pests and diseases applied in this study. This implies that farmers, especially those in newly opened farms in the region, can double their maize and pigeonpea yields by simply adhering to sound agronomic practices such as timely planting and weeding, correct spacing, use of certified maize seed and protecting against pests and diseases.

Table 6a. Maize grain yield obtained per season from different maize-pigeonpea cropping systems, and crop residue manangement options from 2010 to 2013.

	Maize grain yield (t ha^{-1})[1]								
	2010		2011		2012		2013		Mean grain yield / season
Cropping system	LR[a]	SR[b]	LR	SR	LR	SR	LR	SR	
Maize sole crop + 0 tons (control)	0.997	0.580	1.153	0.541	1.751	0.645	0.896	1.020	0.948
Mbaazi I-maize intercrop + 0 tons*	0.986	0.879	0.842	0.813	0.842	0.759	0.635	0.808	0.821
Mbaazi I-maize intercrop + 2 tons†	1.009	0.906	0.986	0.915	0.968	0.836	0.713	0.850	0.898
Mbaazi I-maize intercrop + 4 tons‡	1.216	1.008	1.103	1.214	1.567	1.321	1.460	1.420	1.289
Kat 60/8-maize intercrop + 0 tons	0.998	0.765	0.793	0.763	0.968	0.712	0.753	0.747	0.812
Kat 60/8-maize intercrop + 2 tons	1.060	0.878	0.967	0.816	1.013	0.815	0.890	0.813	0.907
Kat 60/8-maize intercrop + 4 tons	1.984	1.598	1.490	1.479	1.793	1.583	1.498	1.499	1.616
Mbaazi II[c]-maize intercrop + 0 tons	-	0.748	-	0.768	-	0.746	-	0.776	0.760
Mbaazi II-maize intercrop + 2 tons	-	0.976	-	0.991	-	0.987	-	0.964	0.980
Mbaazi II-maize intercrop + 4 tons	-	1.789	-	1.894	-	1.796	-	1.978	1.864
SED[d]	0.185	0.195	0.120	0.210	0.215	0.210	0.180	0.205	0.190
Rainfall (mm)	460.8	204.9	248.6	258.2	401.8	215.2	321.1	269.7	

[1]Data are treatment means averaged over 4 replicates; [a] Long rain season (March-May); [b]Short rain season (October- December); [c]Normally planted in the short rain season only; [d]Standard error of treatment means; *No crop residues were incorporated; †2 t ha^{-1} of crop residues were incorporated; ‡4 t ha^{-1} of crop residues were incorporated.

Table 6b. Maize stover yield obtained per season from different maize-pigeonpea cropping systems and crop residue management options from 2010 to 2013.

	Maize stover yield (t ha^{-1})[1]								
	2010		2011		2012		2013		Mean stover yield / season
Cropping system	LR[a]	SR[b]	LR	SR	LR	SR	LR	SR	
Maize sole crop + 0 tons (control)	1.02	1.02	2.19	1.00	1.13	1.07	1.19	1.13	1.22
Mbaazi I/maize intercrop + 0 t ons*	1.12	1.06	1.65	1.16	1.58	1.13	1.56	0.96	1.28
Mbaazi I/maize intercrop + 2 tons†	1.47	1.22	1.89	1.35	1.62	1.13	1.71	1.16	1.44
Mbaazi I/maize intercrop + 4 tons‡	1.90	1.37	2.07	1.39	1.78	1.93	1.84	1.88	1.77
Kat 60/8/maize intercrop + 0 tons	1.05	1.57	1.58	1.37	1.53	1.15	1.50	1.04	1.35
Kat 60/8/maize intercrop + 2 tons	1.62	1.78	2.07	1.91	1.73	1.29	1.86	1.30	1.70
Kat 60/8/maize intercrop + 4 tons	2.06	2.10	2.44	1.95	1. 82	1.62	1.97	1.77	1.99
Mbaazi II[c]/maize intercrop + 0 tons	-	1.02	-	1.57	-	1.51	-	1.31	1.35
Mbaazi II/maize intercrop + 2 tons	-	1.12	-	1.76	-	1.65	-	1.41	1.49
Mbaazi II/maize intercrop + 4 tons	-	2.09	-	1.94	-	1.88	-	2.41	2.08
SED	0.26	0.22	0.15	0.17	0.27	0.18	0.13	0.23	0.32
Rainfall (mm)	460.8	204.9	248.6	258.2	401.8	215.2	321.1	269.7	

[1]Data are treatment means averaged over 4 replicates; [a] Long rain season (March-May); [b] Short rain season (October- December); [c]Normally planted in the short rain season only; *No crop residues were incorporated; †2 t ha^{-1} of crop residues were incorporated; ‡4 t ha^{-1} of crop residues were incorporated.

Intercropping maize with the three pigeonpea varieties without ploughing back crop residues reduced ($p \leq 0.05$) average maize grain yields per season by 11% (0.9 to 0.8 t ha^{-1}). However, average stover yields increased ($p \leq 0.05$) by 8-17%, presumably due to the high rainfall received during the study. The drop in maize grain yield could be attributed to diminishing soil fertility due to continuous nutrient mining by crops without any restitution. Ploughing back 2 t ha^{-1} of crop residues had no significant effect on maize grain yield, however, it significantly ($p \leq 0.05$) increased stover yields by 17-42%. Similarly, stover yields increased ($p \leq 0.05$) by 50 (from 1.2 to 1.8 t ha^{-1}), 67 (from 1.2 to 2.0 t ha^{-1}) and 75 % (from 1.2 to 2.1 t ha^{-1}) per season under maize-Mbaazi I, maize-Kat 60/8 and maize-Mbaazi II intercrops, respectively, when 4 t ha^{-1} of crop residues was ploughed back. Mean maize grain yields increased ($p \leq 0.05$) by 44 % (from 0.9 to 1.3 t ha^{-1}), 78% (from 0.9 to 1.6 t ha^{-1}) and 111% (from 0.9 to 1.9 t ha^{-1}) per season when maize was intercropped with the short, medium and long duration pigeonpea, respectively. The increase in both grain and stover yields could be attributed to improvement in soil nutrient supply and soil physical properties due to decomposition of the crop residues (Chirwa *et al*., 2004; Akanvou *et al*., 2002; Kwesiga *et al*., 2003; Degranade, 2001). However, the high increase in maize yield realized under Mbaazi II (long duration pigeonpea) compared to the rest could be attributed to its ability to mobilize and avail extra N through biological nitrogen fixation and decomposition of its massive litterfall (Table 7b) (Snapp and Silim, 2002; Silim *et al*., 2005; Myaka *et al*., 2006; Adu-Gyamfi *et al*., 2007; Kumar *et al*., 2011). These results corroborate findings of Kumar and Goh (2000) that the magnitude of the yield increase of cereals in such systems depends on the amount of materials returned to the soil. Similar results were reported by Wanderi *et al* (2011) from a study in Thika near Nairobi where maize grain and stover yields increased by about 15% and 30%, respectively, under maize-long duration pigeonpea intercrop. Chirwa *et al*.(2004), Mapfumo and Mtambanengwe (2004), Rao and Mathuva (2000), Adjei-Nsiah *et al* (2007), Degrande (2001), Akanvou *et al.*(2002), Abunyewa and Karbo (2005) and Chamango (2001) also reported significant improvement in maize yields attributable to pigeonpea, albeit from long duration pigeonpea fallows. They attributed the increase in maize (cereal) yield to improvement in soil chemical and physical properties due to decomposition and mineralization of pigeonpea's massive litterfall. However, Silim *et al.* (1997) reported a significantly lower yield of intercropped maize compared to its sole crop from a study in semi-arid Eastern Kenya.The disparity could be attributed to differences in the amount of crop residues ploughed back.

3.3.4.2. Pigeonpea yield

Pigeonpea yields obtained per season from different maize-pigeonpea cropping systems and crop residue management options are presented in Tables 7a and 7b. The short (Mbaazi I) and medium (Kat 60/8) duration pigeonpea performed dismally when intercropped with maize as their average yields dropped ($p \leq 0.05$) by 80-90%. The reduction in yield could be attributed to maize's longer duration in the field since the longer the duration of the cereal, the lower the pigeonpea yield (Tarhalkar and Rao, 1981; Ali, 1990). However, long duration pigeonpea (Mbaazi II) grain and stalk yields increased ($p \leq 0.05$) by 18-27% and 20-53%, respectively, especially when crop residues were ploughed back. The increase in the long duration pigeonpea yield could be due to its phenological complementarity with maize and its ability to mobilize extra nutrients N and access water from deeper soil horizons due to its strong deep root system and massive litterfall (McCown *et al.*, 1992; Myaka *et al.*, 2006; Snapp and Silim, 2002; Mapfumo and Mtambanengwe, 2004; Silim *et al.*, 2005; Kumar *et al.*, 2011). Natarajan and Wiley (1981) reported similar results from a study in India in which the pigeonpea component of a cereal (sorghum)-pigeonpea intercrop suffered considerable competition from the cereal (sorghum) initially, but recovered after the cereal (sorghum) was harvested and produced seed yields equivalent to 70% of the sole crop. Other workers such as Tarhalkar and Rao (1981), Ali (1990), Egbo, and Ngumalen (2010) also reported that intercropping cereals with early-maturing pigeonpea often leads to drastic reduction in pigeonpea yield. It is apparent from this study that intercropping maize with pigeonpea, especially the long duration variety, and ploughing back crop residues improves soil fertility leading to significant increase in maize and pigeonpea yields.

Table 7a. Pigeonpea grain yield obtained per season from different pigeonpea-maize cropping systems and crop residue management options from 2010 to 2013.

	Pigeonpea grain yield (t ha^{-1})[1]								
	2010		2011		2012		2013		Mean
Cropping system	LR[a]	SR[b]	LR	SR	LR	SR	LR	SR	grain yield/ season
Mbaazi I sole crop + 0 tons*	0.87	0.88	0.98	0.77	0.69	1.04	0.93	0.99	0.90
Kat 60/8 sole crop + 0 tons	1.02	1.01	0.98	1.08	1.02	1.08	1.03	0.96	1.02
Mbaazi II[c] sole crop + 0 tons	-	1.00	-	0.99	-	1.19	-	1.36	1.14
Mbaazi I/maize intercrop + 0 tons	0.19	0.01	0.04	0.12	0.09	0.02	0.05	0.05	0.07
Mbaazi I/maize intercrop + 2 tons†	0.19	0.03	0.15	0.12	0.16	0.02	0.10	0.06	0.10
Mbaazi I/maize intercrop + 4 tons‡	0.25	0.07	0.17	0.13	0.15	0.03	0.14	0.09	0.13
Kat 60/8/maize intercrop + 0 tons	0.20	0.02	0.04	0.03	0.08	0.04	0.06	0.05	0.07
Kat 60/8/maize intercrop + 2 tons	0.22	0.03	0.07	0.17	0.14	0.08	0.07	0.05	0.10
Kat 60/8/maize intercrop + 4 tons	0.23	0.04	0.11	0.24	0.19	0.09	0.07	0.06	0.13
Mbaazi II/maize intercrop + 0 tons	-	1.25	-	0.99	-	1.09	-	1.25	1.20
Mbaazi II/maize intercrop + 2 tons	-	1.45	-	1.13	-	1.15	-	1.36	1.32
Mbaazi II/maize intercrop + 4 tons	-	1.53	-	1.14	-	1.35	-	1.40	1.43
SED[d]	0.18	0.32	0.20	0.24	0.17	0.30	0.21	0.32	0.29
Rainfall (mm)	460.8	204.9	248.6	258.2	401.8	215.2	321.1	269.7	

[1]Treatment means of four replicates; [a]Long rain season(March-May); [b]Short rain season (October- December); [c]Normally planted in short rain season only; [d]Standard error of treatment means; *No crop residues were incorporated; †2 t ha^{-1} of crop residues were incorporated; ‡4 t ha^{-1} of crop residues were incorporated.

Table 7b. Amount of pigeonpea stalks obtained per season from different pigeonpea-maize cropping systems and crop residue management options from 2010 to 2013.

Cropping system	Pigeonpea stalks yield (t ha^{-1})[1]								
	2010		2011		2012		2013		Mean stalk yield/ season
	LR[a]	SR[b]	LR	SR	LR	SR	LR	SR	
Mbaazi I sole crop + 0 tons*	1.00	0.99	1.00	1.00	0.93	1.24	1.09	1.07	1.04
Kat 60/8 sole crop + 0 t ons	1.95	1.33	1.05	1.21	1.41	1.37	1.29	1.14	1.35
Mbaazi II[c] sole crop + 0 tons	-	1.48	-	1.24	-	2.24	-	2.75	1.93
Mbaazi I-maize intercrop + 0 t ons	0.31	0.12	0.11	0.18	0.23	0.07	0.24	0.12	0.17
Mbaazi I-maize intercrop + 2 tons†	0.36	0.32	0.26	0.18	0.31	0.07	0.37	0.17	0.26
Mbaazi I/maize intercrop + 4 tons‡	0.52	0.48	0.28	0.19	0.52	0.09	0.44	0.18	0.34
Kat 60/8-maize intercrop + 0 tons	0.39	0.09	0.16	0.06	0.25	0.35	0.24	0.14	0.21
Kat 60/8-maize intercrop + 2 tons	0.40	0.15	0.35	0.26	0.31	0.35	0.26	0.16	0.28
Kat 60/8-maize intercrop + 4 tons	0.44	0.18	0.46	0.40	0.58	0.45	0.31	0.18	0.37
Mbaazi II-maize intercrop + 0 tons	-	1.53	-	2.35	-	2.67	-	2.84	2.35
Mbaazi II-maize intercrop + 2 tons	-	2.01	-	2.57	-	2.69	-	3.01	2.57
Mbaazi II-maize intercrop + 4 tons	-	2.54	-	2.92	-	2.97	-	3.26	2.92
SED[d]	0.37	0.43	0.19	0.54	0.20	0.58	0.21	0.65	0.53
Rainfall (mm)	460.8	204.9	248.6	258.2	401.8	215.2	321.1	269.7	

[1]Treatment means of four replicates; [a]Long rain season (March-May); [b]Short rain season (October- December); [c]Normally planted in short rain season only; [d]Standard error of treatment means; *No crop residues were incorporated; †2 t ha^{-1} of crop residues were incorporated; ‡4 t ha^{-1} of crop residues were incorporated.

3.4. Conclusion

All the five pigeonpea varieties tested in this study were good nitrogen-fixers, with or without inoculation with *Rhizobia*. However, Mbaazi II fixed more Nitrogen than Mbaazi I and Kat 60/8 when intercropped with maize. Farmers are therefore encouraged to adopt them to supply N and increase cereal yields.

CHAPTER FOUR

4.0. THE EFFECT OF PIGEONPEA-MAIZE INTERCROPPING SYSTEMS ON SOIL CARBON, NITROGEN, PHOSPHORUS AND EXCHANGEABLE BASES

Abstract

Little research has been conducted in Kenya to ascertain and exploit the ability of pigeonpea to improve soil fertility and increase cereal yields. An experiment was conducted at Katumani Research Centre between 2009 and 2013 to evaluate the effects of pigeonpea on soil fertility and productivity of maize cropping systems in semi-arid Kenya. The experiment was established as a split-split plot design with sole and intercrops of maize and pigeonpea varieties drawn from three maturity groups and three crop residue application rates as the treatments. Results showed that intercropping maize with pigeonpea reduced ($p \leq 0.05$) soil organic carbon and total soil N from 1.4 and 0.2% in 2009 to less than 1 and 0.1%, respectively, in 2013. Intercropping maize with long duration pigeonpea (Mbaazi II) and ploughing back 4 t ha^{-1} of crop residues had no significant effect on available P. However, it increased ($p \leq 0.05$) available P from 26 ppm at the start of the study to 50 ppm and 47 ppm in eight seasons under maize-Mbaazi I and maize-Kat 60/8 intercrops, respectively. Exchangeable K, Mg and Ca also declined significantly ($p \leq 0.05$). Intercropping maize with long duration pigeonpea and ploughing back 4 t ha^{-1} of crop residues offers the best option since it gave higher maize (1.9 t ha^{-1}) and pigeonpea (1.4 t ha^{-1}) grain yields per season and sufficient crop residues to feed the livestock and plough back to improve soil fertility.

Key words: cereal yields, crop residues, soil fertility, pigeonpea

4.1. Introduction

Arid and semi-arid lands (ASALs) account for over 80% of Kenya's landmass and support about a third of Kenya's population. This figure is expected to rise, given the current population growth rate of 3% (GoK, 2013a). However, majority of the people (> 65%) in ASALs live in abject poverty and rely on Government relief supplies. Soils in these areas are low in essential plant nutrients, particularly nitrogen (N) and phosphorus (P), while rainfall is low and erratic, hence undermine crop production. Cereal and legume yields from farmers' fields rarely exceed 1.0 and 0.5 t ha^{-1}, respectively, per season compared to over 2.0 t ha^{-1} obtained from research stations and in commercial farms in these regions. The situation is bound to worsen with the expected increase in variability and change in climate (Jaetzold *et al*., 2006; Thornton *et al*., 2009).

Although this situation can be reversed through the use of mineral fertilizers and livestock manure, their widespread application is limited by their prohibitive prices and low quantities and quality, respectively (Bationo and Waswa, 2011). The few farmers who apply mineral fertilizers, hardly use the recommended rates, and often it is utilized with poor efficiency due to environmental or soil-related factors (e.g. P-fixation by sesquioxides, leaching and volatilization of N) as well as management factors, such as poor timing or placement of fertilizer (Vanlauwe *et al*., 2010; Chichongue *et al*., 2013).

However, other studies indicate that including legumes such as pigeonpea in maize cropping systems can reverse the trend effectively and cheaply (Adu-Gyamfi *et al*., 2007; Audi *et al*., 2008; Gwata and Shimelis, 2013; Høgh-Jensen *et al*., 2007; Nagarajan *et al*., 2008; Shiferaw *et al*., 2008). Pigeonpea can improve soil fertility and increase maize yield by availing N to the companion or subsequent maize crop and by mobilizing large amounts of sparingly soluble P into organic forms, especially in N and P deficient soils predominant in semi-arid Eastern Kenya and the rest of Africa (Adu-Gyamfi *et al*., 2007). In Kenya, however, little research has been made to ascertain and exploit this opportunity.

The Kenya Agricultural Research Institute (now Kenya Agricultural and Livestock Research Organization (KALRO), jointly with the International Crop Research Institute for Semi-Arid Tropics (ICRISAT) and the University of Nairobi have over the years developed and released numerous pigeonpea varieties suitable for Kenya's semi-arid lands. However, these efforts focused mainly on developing high yielding varieties that are resistant to *Fusarium* wilt and adaptable to a broad range of ecological conditions (Shiferaw *et al*., 2008). There have been few studies on how their inclusion in the cereal-based cropping systems influences soil N and P and long-term sustainability of these production systems. Therefore the objectives of this study were: (1) To determine the effect of maize-pigeonpea cropping systems on soil carbon, total nitrogen, available phosphorus and exchangeable potassium, calcium and magnesium, and (2) To evaluate the effect of pigeonpea on maize yields.

4.2. Materials and methods

4.2.1. Study area

The study was conducted from 2009 to 2013 at KALRO - Katumani Research Centre in Machakos County, 80 km South-East of Nairobi (37˚ 14′ E and 1˚ 35′ S) (Fig.1). Katumani, with a bimodal rainfall pattern, receives an average of 711 mm annually, and is about 1600m above sea level. Average seasonal rainfall is between 250 and 400mm, with long rains (LR) falling from mid-March to May and short rains (SR) from October to December (Jaetzold *et al*., 2006). Inter-seasonal rainfall variation is large with coefficient of variation ranging between 45 and 58% (Keating *et al*., 1992). Therefore, the timing and relative lengths of each growing period vary substantially. Any delay in planting maize at the start of the wet season, brings risks of significant losses in yield, almost proportional to the time delay (Keating *et al*., 1992). However, SR tends to be more reliable for crop production than LR (Jaetzold *et al*., 2006). Temperatures range between 17 and 24^{o}C with February and September being the hottest months of the year. Mean annual temperature is 20^{o}C. Evaporation rates (ETo) are high and exceed the amount of rainfall (r) except in the month of November. Mean potential evaporation is in the range of 1820 to 1840 mm per year, whilst evapotranspiration is estimated to be 1239 mm (Gicheru, 1996), giving an r/ETo ratio of 0.57. The terrain ranges from flat to hilly with slopes varying from 2 to 20% (Gicheru and Ita, 1987). Katumani falls under agro-climatic zone IV, with a low potential for rainfed agriculture (Jaetzold *et al.*, 2006).

Soils in Katumani are predominantly Luvisols (FAO/UNESCO, 1997; WRB, 2006) derived from granitic parental material (Gicheru and Ita, 1987). They have weak surface structures due to low organic matter and high sand content, and are friable, deep to very deep, well-drained and dark red to reddish brown (Gicheru and Ita, 1987). Soil at the experimental site have moderate levels of organic C (1.4%) and sufficient quantities of P (> 300 ppm), K (229 ppm), Mg (177 ppm) and Ca (1256 ppm) to sustain a healthy maize and pigeonpea crop, without any fertilizer application. However, soils have low total N (0.15%) and are slightly acidic with a pH of 5.52 (Okalebo *et al.*, 2002). Given that both maize and pigeonpea thrive best at soil pH of 5.5 to 8.0 (Jaetzold *et al.*, 2006), soil at the study site was appropriate. The experimental site was a grazing field for many years. It was cleared of weeds and sparse bushes, and cropped uniformly with maize in the 2009 LR season to even it out and to block the field layout before setting up the experiement. All the crop residues were removed from the field after harvesting to eliminate any confounding effect.

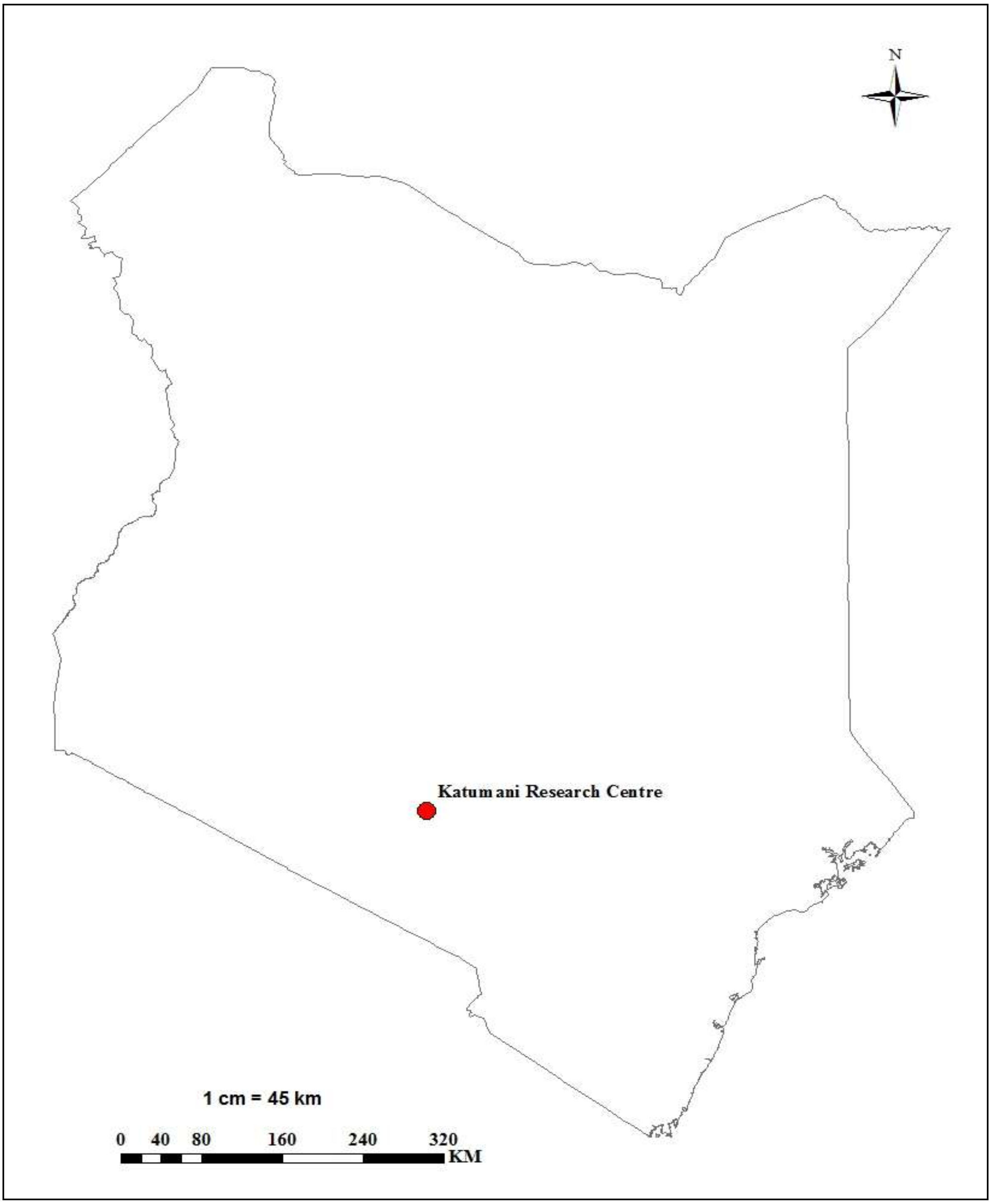

Fig.1. Location of the study site

Mixed farming systems involving food crops and livestock are characteristic of the region. Crops grown are predominantly drought-escaping or early maturing varieties of pigeonpea, maize, beans, sorghum and millet (Jaetzold *et al.*, 2006). Due to the erratic nature of rainfall, most farmers around Katumani and the larger semi-arid Eastern Kenya prefer to intercrop maize with at least a legume (pigeonpea, beans or cowpeas) on the same land. This is often done either in alternate or in multiple rows, and is seen by many farmers as a form of security against total crop failure. However, rather than devote their entire arable land to either pure-stand cropping or intercropping, most farmers often dedicate one piece to pure-stand cropping and the remaining area to intercropping in a bid to spread the risk . Long duration pigeonpea is normally planted during SR in October-November and harvested in August-September the following year. Medium and short duration varieties can be planted and harvested in one season (Audi *et al.*, 2008; Nagarajan *et al.*, 2008; Shiferaw *et al.*, 2008). Crop combinations, planting patterns and plant populations of pigeonpea and other crops vary considerably, depending on the soil type, climate and farmer's preferences. However, dominant pigeonpea cropping systems practiced in the region include: pigeonpea intercropped with maize, sorghum, millets, cowpea and green gram; pigeon pea and cowpea intercrops; and maize/bean/pigeon pea intercrops (Audi *et al.*, 2008; Nagarajan *et al.*, 2008; Shiferaw *et al.*, 2008). There is significant conflict between livestock and soil fertility enhancing activities in the area. Crop residues, maize stover and pigeonpea stalks, could be returned to the field to curb run-off and supply nutrients for future crops; however, they are commonly used as livestock feed and fuelwood, particularly during the dry season when there is scarcity (Audi *et al.*, 2008).

4.2.2. Experimental design

The experiment was established during the 2009 SR season as a split-split plot design, with pigeonpea varieties, cropping systems and crop residue application rates as the main plot, sub-plot, and sub-sub-plot, respectively. Treatments included sole and intercrops of maize and pigeonpea varieties drawn from three maturity groups (short, medium and long duration pigeonpeas), three crop residue (pigeonpea stalks and maize stovers) application rates and sole maize crop and a bare plot as controls. Treatments were laid out in 4.8 m long x 4.5 m wide plots with an inter-plot spacing of 1.5 m and replicated four times. Pigeonpea stalks and maize stovers were weighed, chopped into 5 to 10 cm pieces and placed into the soil to a depth of 15cm at the rate of 0, 2 and 4 t ha^{-1}, respectively. This was done every season after land preparation to allow sufficient time for the crop residues to decompose. Crop residue application rates and cropping systems used, represent as closely as possible those practiced by farmers and take into account the competing uses for crop residues in the ASALs. A total of 18 treatments were investigated using a bare plot and sole maize crop as controls and are summarized in Table 8.

Table 8. Summary of treatments investigated in the study, in a split-split plot design with pigeonpea varieties, cropping systems and crop residue application rates as the main plot, sub-plot, and sub-sub-plot, respectively.

Treatment	Description
$T0_a$	Virgin land/ bare plot (control 1)
$T0_b$	Sole maize, no maize stover incorporated (control 2)
T1	Short duration pigeonpea sole crop, no pigeonpea residues incorporated
T2	Short duration pigeonpea sole crop + 2 t ha^{-1} pigeonpea residues incorporated
T3	Short duration pigeonpea sole crop + 4 t ha^{-1} pigeonpea residues incorporated
T4	Maize/short duration pigeonpea intercrop, no maize stover or pigeonpea residues incorporated
T5	Maize/short duration pigeonpea intercrop + 2 t ha^{-1} maize stover + 2 t ha^{-1} pigeonpea residues incorporated
T6	Maize/short duration pigeonpea intercrop + 4 t ha^{-1} maize stover + 4 t ha^{-1} pigeonpea residues incorporated
T7	Medium duration pigeonpea sole crop, no pigeonpea residues incorporated
T8	Medium duration pigeonpea sole crop + 2 t ha^{-1} pigeonpea residues incorporated
T9	Medium duration pigeonpea sole crop + 4 t ha^{-1} pigeonpea residues incorporated
T10	Maize/medium duration pigeonpea intercrop, no maize stover or pigeonpea residues incorporated

T11	Maize/medium duration pigeonpea intercrop + 2 t ha^{-1} maize stover + 2 t ha^{-1} pigeonpea residues incorporated
T12	Maize/medium duration pigeonpea intercrop + 4 t ha^{-1} maize stover + 4 t ha^{-1} pigeonpea residues incorporated
T13	Long duration pigeonpea sole crop, no pigeonpea residues incorporated
T14	Long duration pigeonpea sole crop + 2 t ha^{-1} pigeonpea residues incorporated
T15	Long duration pigeonpea sole crop + 4 t ha^{-1} pigeonpea residues incorporated
T16	Maize/long duration pigeonpea intercrop, no maize stover or pigeonpea residues incorporated
T17	Maize/long duration pigeonpea intercrop + 2 t ha^{-1} maize stover + 2 t ha^{-1} pigeonpea residues incorporated
T18	Maize/long duration pigeonpea intercrop + 4 t ha^{-1} maize stover + 4 t ha^{-1} pigeonpea residues incorporated

Maize variety KDV1 was selected for the study owing to its good adaptability, early maturity (120 to 150 days to mature) and ability to yield highly under semi-arid conditions. Mbaazi 1 and KAT 60/8 were used for the short (100 days) and medium (150 days) duration pigeonpea varieties, respectively, due to their early maturity and high yields. Mbaazi II was used as the long duration variety owing to its resistance to common pests and diseases and high yield. It takes 180-220 days to mature. Generally, the three pigeonpea varieties are also popular among farmers and their seed is readily available. To obtain an integrated view of the legume effect, sole maize was used as the control.

Land was prepared using a hand hoe at the beginning of each cropping season, and crops sown at the on-set of the rains. Pigeonpea was planted at spacings of 90 x 60 cm, 75 x 30 cm and 50 x 25 cm for the long, medium and short duration varieties, respectively, at a rate of 2 seeds per hill. The two plants were thinned to one two weeks after emergence. Maize was planted with triple super phosphate (TSP) fertilizer at the recommended rate of 40 kg P_2O_5 ha^{-1} at spacing of 90c x 30cm. However, in the intercrops, one row of pigeonpea was planted after every row of maize to replicate the farmers' practice. This way, it was assumed nitrogen was the only macronutrient limiting maize yields.

Pigeonpea was protected from major pests on a 'minimum-protection' basis, as many farmers spray insecticides during flowering/podding, and to avoid confounding the potential soil fertility benefits of legumes with variable pest infestations. They were sprayed two times per season during flowering and podding with Dimethoate^{TM} (dimethoate) at 0.5L ha^{-1} per spray to control pod borer (*Helicoverpa armigera*) and pod fly (*Melanagromyza chalcosoma*). Bulldock^{TM} insecticide (beta-cyfluthrin) was applied on maize once every season before tasseling to control stalk borers. Plots were kept weed-free by weeding regularly using a hand hoe, depending on weed emergence/intensity and characteristics. The study was conducted for four LR and four SR seasons (8 seasons) from October 2009 to July 2013.

4.2.3. Soil and plant sampling

Soil samples were taken prior to setting up the trials and after harvesting the 2013 LR season crop (after eight cropping seasons). Soil samples were collected in a transect across the experimental site using a 600 cm^3 soil auger at depths of 0-20, 20-40, 40-60, 60-80, 80-100 and 100-120 cm. Soils from each depth were composted and mixed thoroughly in a bucket, and quartered to obtain a representative sample. The samples were air-dried, ground using a mortar and pestle, and passed through a 2 mm sieve for analysis of N, P Ca, Mg and K.

Maize and pigeonpea were harvested at full maturity, when the entire maize stalks are completely dry and pigeonpea pods brownish in colour. Plants lying within one metre of each side of the plot were omitted from the sample harvest to eliminate any plot border effects; the harvest area was 7 m^2. Plants within the harvest area were counted, harvested and weighed. Sub-samples of maize and pigeonpea plants were taken from the total number of plants harvested and divided into cobs and stover, and pods and stalks for maize and pigeonpea data collection, respectively. All samples were oven-dried to constant weight at 60°C and ground to a fine powder using a Wiley Mill. Maize and pigeonpea grains were dried at 12.5% moisture content; the ratio of dry weight to fresh weight and plot fresh weight used to estimate maize and pigeonpea grain and biomass yields in tonnes per hectare.

4.2.4. Soil and plant analysis

Plant samples at harvest were analyzed for N, P, Ca, Mg and K content, whilst soil samples at the onset and at the end of eight seasons were analysed for pH, organic C, total N, available P, total P and exchangeable bases (K, Mg and Ca). Soil pH was measured in water (1:2.5 soil: water w/v) using a pH meter and organic carbon by the Walkley and Black method as described by Nelson and Sommers (1982). Total N was determined by the Kjeldhal method as described by Bremner and Mulvaney (1982). Available P was measured using Bray 2 method as described by Olsen and Sommers (1982). Exchangeable Ca and Mg were determined using Atomic Absorption Spectroscopy (AAS). Na and K were determined by flame photometry using a flame photometer.

4.2.5. Data analysis

All data on maize and pigeonpea yields, and soil properties were subjected to a two-way analysis of variance (ANOVA) using GENSTAT software version 14.2 (GENSTAT, 2016). Mean comparisons for the individual treatments was done using both Least Significant Difference of means (LSD, $p \leq 0.05$) and the Duncan Multiple Range Test (DMRT) owing to the large number of some of the treatments.

4.3. Results and discussion

4.3.1. Effect of maize-pigeonpea cropping systems on soil carbon, total nitrogen, available phosphorus and exchangeable bases

Changes in soil chemical properties in the study area after eight seasons of continuous cropping are presented in Table 9.

Table 9. Changes in soil chemical properties in Katumani after eight seasons of continuous cropping, with different pigeon pea varieties, cropping systems and crop residue application rates.

Cropping system	Chemical properties[1]					
	% Organic C	% Total N	Ext. P (ppm)	Exch. K (ppm)	Exch. Mg (ppm)	Exch. Ca ppm)
Control (virgin/bare land)	1.4^{a}	0.15^{a}	26^{d}	229^{a}	177^{a}	1259^{a}
Mbaazi I/maize intercrop + 0 tons*	0.8^{bcd}	0.09^{bc}	57^{abc}	80^{c}	113^{bc}	650^{b}
Mbaazi I/maize intercrop + 2 tons†	0.8^{bcd}	0.08^{c}	43^{abc}	93^{c}	143^{b}	1080^{b}
Mbaazi I/maize intercrop + 4 tons‡	0.8^{bcd}	0.08^{c}	50^{abc}	100^{c}	117^{bc}	873^{b}
Kat 60/8/maize intercrop+0 tons	0.9^{b}	0.10^{b}	37^{bcd}	77^{c}	117^{bc}	987^{b}
Kat 60/8/maize intercrop + 2 tons	0.8^{bcd}	0.09^{bc}	65^{a}	93^{c}	113^{bc}	633^{b}
Kat 60/8/maize intercrop + 4 tons	0.9^{b}	0.09^{b}	47^{abc}	130^{b}	123^{bc}	640^{b}
Mbaazi II/maize intercrop + 0 tons	0.8^{bcd}	0.08^{bc}	22^{d}	87^{c}	117^{bc}	650^{b}
Mbaazi II/maize intercrop + 2 tons	0.7^{d}	0.08^{c}	30^{bcd}	100^{c}	117^{bc}	757^{b}
Mbaazi II/maize intercrop + 4 tons	0.8^{bcd}	0.08^{bc}	28^{cd}	93^{c}	100^{c}	600^{b}

[1]Data are treatment means averaged over four replicates, except for the control; Means followed by different letter(s) within the same column are significant at 5% level of probability; *No crop residues were incorporated; †2 t ha^{-1} of crop residues were incorporated; ‡4 t ha^{-1} of crop residues were incorporated.

4.3.1.1. Soil organic carbon (SOC)

Intercropping maize with the short duration pigeonpea (Mbaazi I) without ploughing back crop residues reduced ($p \leq 0.05$) SOC from 1.4% at the onset of the study to 0.8% after eight cropping seasons. A similar trend was observed with the medium duration variety (Kat 60/8) where SOC declined significantly ($p \leq 0.05$) from 1.4% in 2010 to 0.9% in 2013 (after eight cropping seasons). Similarly, intercropping maize with the long duration pigeonpea (Mbaazi II) significantly ($p \leq 0.05$) reduced SOC from 1.4% at the start of the experiment to 0.8%

after eight seasons. Ploughing back 2-0 t ha^{-1} (1.0 t ha^{-1} each) of pigeonpea and maize crop residues did not decelerate the reduction in SOC as it declined ($p \leq 0.05$) from 1.4% in 2010 to 0.8% under both maize-Mbaazi I and maize-Kat 60/8 intercrops in 2013 (after eight seasons). The same trend was observed with the long duration variety (Mbaazi II) where SOC dropped significantly ($p \leq 0.05$) from 1.4% at project inception to 0.7% after eight continuous cropping seasons. Retaining and incorporating 4 t ha^{-1} of pigeonpea and maize crop residues into the soil also did not decelerate the decline in SOC as it dropped significantly ($p \leq 0.05$) from 1.4% to 0.8, 0.9 and 0.8% after eight continuous cropping seasons under maize-Mbaazi I, maize-Kat 60/8 and maize-Mbaazi II intercrops, respectively. There were no significant differences in SOC between any of the three pigeonpea-maize cropping systems. The drop in SOC could be attributed to rapid mineralization and dissipation of soil organic matter due to continuous cropping without addition of organic materials (Mugwe *et al*., 2009; Itabari *et al*., 2011) and high temperatures. These results agree with the findings by Rao and Mathuva (2000), who reported a significant decline in soil organic C after 5 years of maize-pigeonpea cropping in Machakos, where soil organic C declined by about 6%. The study, however, did not measure the contribution of residue management to soil carbon stocks of the cropping system and was based on the traditional long duration pigeonpea variety only. Similarly, working in Ghana, Yeboah *et al*. (2004) reported a 2.5% decline in mean organic carbon content of soils after just one year of pigeonpea cultivation. Conversely, also in Ghana, Abunyewa and Karbo (2005) reported a 30.5% increase in soil organic carbon on pigeonpea fallow plots after a two-year fallow period. The disparity in pigeonpea contribution to SOC in these two scenarios was due to differences in the amount of pigeonpea biomass returned to the soil. However, working in Malawi, Chirwa *et al*. (2006) found no change in SOC when pigeonpea was included in agroforestry systems. Similarly, Adu-Gyamfi *et al*. (2007) reported no significant change in total soil C after two seasons of maize-pigeonpea intercropping in Malawi and Tanzania. They noted, however, that in Tanzania the maize-pigeonpea intercrop tended to accumulate more C in the upper soil layer, whilst at Nyambi in Malawi it was the reverse, total C content decreased in intercropped plots compared to sole maize plots.

These results differ significantly with those reported by Singh *et al*. (2005) from a study in India, where inclusion of pigeonpea in cereal (wheat) cropping systems reportedly enhanced carbon accumulation in the soil profile by 13.9%, after three years of continuous cropping, especially when N and P fertilizers were applied. Similarly, Singh and Dwivedi (2006) reported increases in soil organic carbon of 13% at 0-15 cm, 11% at 15-30cm and 9 % at 30-45cm soil depth after three years of pigeonpea-cereal cropping in the same region. Similar results have been reported by Diekow *et al*. (2005) for a long-term trial in Brazil, in which maize-pigeonpea cropping systems increased soil C stocks by 26% after 17 years of cropping. Tolanur and Badanur (2003) also reported a significant increase in soil C after just one year of pigeonpea-cereal (pearl millet) cropping in India. These authors attributed the increase in soil C to massive litter fall from pigeonpea. This implies that the 2 or 4 t ha^{-1} of pigeonpea and maize crop residues returned to the soil in our study were insufficient to contribute to SOC. It also means that pigeonpea's contribution to SOC build-up is site-specific and might not depend on residue management and the duration of the crop in the field alone.

4.3.1.2. Soil nitrogen

Soil N also declined significantly ($p \leq 0.05$) from 0.15% at the start of the experiment to 0.09% in eight seasons, when maize was intercropped with the short (Mbaazi I) and medium (Kat 60/8) duration pigeonpea, without ploughing back any crop residues. The trend was the same with the long duration pigeonpea (Mbaazi II), where soil N declined significantly ($p \leq 0.05$) from 0.15% at inception to 0.08% after eight seasons. Ploughing back 2t ha^{-1} of pigeonpea and maize crop residues did not hamper the decline in soil N, as it dropped significantly ($p \leq 0.05$) from 0.15 to 0.08, 0.09 and 0.08% after eight continuous cropping seasons, when maize was intercropped with the short (Mbaazi I), medium (Kat 60/8) and long (Mbaazi II) duration pigeonpea varieties, respectively. Similarly, retaining and incorporating 4t ha^{-1} of pigeonpea and maize crop residues in the soil did not decelerate the drop in soil N, as it reduced significantly ($p \leq 0.05$) from 0.15 to 0.08, 0.09 and 0.08% after eight seasons under maize-Mbaazi I, maize-Kat 60/8 and maize-Mbaazi II, respectively. The drop in soil N could be attributed to high biomass production by both, maize and pigeonpea, hence high N demand, immobilization of N by soil micro-organisms due to the high C:N ratio of the maize stovers and leaching of nitrates (NO_3) to lower depths beyond the rooting depth of maize and pigeonpea due to high rainfall received during the study (Tables 6a, 6b, 7a and 7b) (Chirwa *et al.*, 2004; Sakala *et al.*, 2000; Mafongoya *et al.*, 2000). There were no significant differences in soil N between any of the three pigeonpea-maize cropping systems. These results agree with those of Singh and Dwivedi (2006) who also reported massive depletion of N when pigeonpea was intercropped with cereals (wheat) in India, where 121.2-135.2 kg N ha^{-1} was removed and a meagre 38.4 to 41.6 kg N ha^{-1} recycled from stubble, nodules and leaf litter by pigeonpea. Similarly, it corroborates findings by Adu-Gyamfi *et al.* (2007), where exporting all above-ground material gave a mean N budget of -26.1 kg ha^{-1} for sole maize crop and -40.3 kg ha^{-1} for maize-pigeonpea intercrop at two locations in Malawi, and -50.1 kg ha^{-1} for sole maize crop and -51.1 kg ha^{-1} for maize-pigeonpea intercrop at two sites in Tanzania. Conversely, retaining and incorporating all the aboveground material of maize and pigeonpea, except the edible parts, into the soil gave a positive value of 30.5 kg N for the maize-pigeonpea intercrop and a less negative one (-8.9 kg N) for the sole maize crop in Malawi, and a more negative value (-35.4 kg N) for sole maize, compared to the intercrops (-5.9kg N) in Tanzania. The huge disparity in N budgets between the two countries was attributed to low and high maize grain yields realized in Malawi and Tanzania, respectively (Adu-Gyamfi *et al.*, 2007). Kumar Rao and Dart (1987) also reported negative budgets for pigeonpea cropping systems in India. However, Yeboah *et al.* (2004) and Chirwa *et al.* (2006) reported no change in total soil N after pigeonpea cultivation in Ghana and Malawi, respectively. Nonetheless, Rego *et al.* (2003) reported positive N for a two-year sorghum-pigeonpea-castor rotation system in farmers' fields in India, Abunyewa and Karbo (2005) reported a 48.5% increase in total soil N on pigeonpea fallow plots after a two-year fallow period in Ghana. Diekow *et al.* (2005) reported a 28% increase in soil N stock after 17 years of maize-pigeonpea cropping in Brazil Also, Tolanur and Badanur (2003) reported a significant increase in soil N after one year of pigeonpea- pearl millet cropping in India. This implies that pigeonpea's contribution to soil N depends more on the initial soil N content and to some extent, the companion crop.

4.3.1.3. Soil phosphorus

Intercropping maize with the short duration pigeonpea (Mbaazi I) without ploughing back any crop residues, increased ($p \leq 0.05$) available P by 119% (from 26 to 57 ppm) in eight seasons. The increase in available P could be attributed to pigeonpea's ability to mobilize P from deep soil horizons and bring it near the surface (Snapp and Silim, 2002; Sakala *et al.*, 2003). However, intercropping maize with the medium (Kat 60/8) and long (Mbaazi II) duration pigeonpea had no significant effect on available P. Ploughing back 2 t ha^{-1} of crop residues increased ($p \leq 0.05$) available P by 65 and 150% in eight seasons, when maize was intercropped with the short (Mbaazi I) and medium (Kat 60/8) duration pigeonpea varieties, respectively. Intercropping maize with the long duration variety (Mbaazi II) and ploughing back 2 t ha^{-1} of crop residues had no significant effect on available P. Retaining and incorporating 4 t ha^{-1} of crop residues also increased ($p \leq 0.05$) available P by 92 and 81% in eight seasons under maize-Mbaazi I and maize-Kat 60/8 intercrop, respectively. The increase in available P under the two varieties could be attributed to rapid decomposition and mineralization of the crop residues ploughed back (Abunyewa and Karbo, 2005; Yeboah *et al.*, 2004). However, intercropping maize with the long duration variety (Mbaazi II) and ploughing back 4 t ha^{-1} of crop residues had no significant effect on available P, and this could be attributed to its tendency to utilize most of the nutrients it mobilizes, due to its high biomass production and long duration in the field (Peoples and Herridge, 1990; Rego and Rao, 2000). These results agree with Rego *et al.* (2003) and Tolanur and Badanur (2003), who reported positive P budgets for sorghum-pigeonpea-castor rotation and pigeonpea-pearl millet cropping systems in farmers' fields in India, after two and one year, respectively. However, they contrast sharply with the findings by Rao and Mathuva (2000), who reported a significant decline in extractable P after 6.5 years of maize-pigeonpea cropping in Machakos, where extractable P declined from the initial 16 to 11ppm by the end of 6.5 years. The researchers also noted that pigeonpea-maize intercrop recycled a meagre 1.6 kg P ha^{-1} per year through litterfall. Unlike this study, their results were based on the traditional long duration pigeonpea variety and did not factor in the contribution of residue management to extractable soil P. Yeboah *et al.* (2004) also reported a 26% decline in available P after one year of pigeonpea cultivation in Ghana. Similarly, Singh *et al*. (2005) reported massive depletion of P when pigeonpea was intercropped with cereals (wheat) in India. Available P diminished by 16% in the first year, 22% in the second, and 29% in the third year. It is apparent that, depending on the companion crop and duration in the field, pigeonpea may deplete or increase soil available P.

4.3.1.4. Exchangeable bases (potassium, magnesium and calcium) in soil

The exchangeable potassium (K) declined significantly ($p \leq 0.05$) by 65% (from 229 to 80 ppm), 66% (from 229 to 77 ppm) and 62% (from 229 to 87 ppm) in eight seasons under maize-Mbaazi I, maize-Kat 60/8 and maize-Mbaazi II intercrops, respectively, when no crop residues were ploughed back. Ploughing back 2 or 4 t ha^{-1} of crop residues markedly arrested the decline in soil exchangeable K to 59-56, 59-43 and 56-59% in eight seasons under maize-Mbaazi I, maize-Kat 60/8 and maize-Mbaazi II intercrops, respectively. A similar trend was exhibited by exchangeable magnesium (Mg), where it significantly dropped ($p \leq 0.05$) by 36% (from 177 to 113ppm), 34% (from 177 to 117ppm) and 34% (from 177 to 117 ppm) in eight seasons under maize-Mbaazi I, maize-Kat 60/8 and maize-Mbaazi II intercrops, respectively, when no crop residues, were retained and incorporated in the soil. Ploughing back 2 or 4t ha^{-1} of crop residues did not deter soil exchangeable Mg from diminishing, as it declined ($p \leq 0.05$) by 19-34, 36-31 and 34-44% after eight seasons of continuous cropping under maize-Mbaazi I, maize-Kat 60/8 and maize-Mbaazi II intercrops, respectively. Similarly, exchangeable calcium (Ca) declined ($p \leq 0.05$) by 48% (from 1259 to 650 ppm), 22% (from 1259 to 987 ppm) and 48 % (from 1259 to 650 ppm) after eight seasons of continuous cropping under maize-Mbaazi I, maize- Kat 60/8 and maize-Mbaazi II intercrops, respectively, when no crop residues were ploughed back. The situation was the same when 2 or 4t ha^{-1} of crop residues were ploughed back; exchangeable Ca dropped ($p \leq 0.05$) by 14-31, 50-49 and 40-52% under maize-Mbaazi I, maize-Kat 60/8 and maize-Mbaazi II intercrops, respectively. The drop in these exchangeable bases (K, Mg and Ca) could be attributed to high biomass production by maize (Tables 3a and 3b) and pigeonpea (Tables 4a and 4b), hence high K, Mg and Ca demand. However, the reduction in the decline of soil exchangeable K could be attributed to improvement in K fertility, due to decomposition and mineralization of the crop residues ploughed back (Abunyewa and Karbo, 2005; Yeboah *et al*., 2004). There were no significant differences in exchangeable bases between any of the three pigeonpea-maize cropping systems, implying that all the three pigeonpea varieties lacked the capacity to mobilize exchangeable bases in the soil. These results contrast sharply with findings by Mapfumo and Mtambanengwe (2004), who in a two-year study in northeast of Zimbabwe to determine the rotational effects of pigeonpea of different maturity genotypes on maize yields observed that application of pigeonpea residues improveed K, Mg and Ca in the soil. However, unlike our study site which had sufficient amounts of exchangeable bases, the site in Zimbabwe was nutrient-depleted hence the positive response.

It is apparent from this study that, incorporating pigeonpea in low input maize-based cropping systems predominant in semi-arid eastern Kenya did not improve soil fertility as envisaged. Soil organic matter and nitrogen declined significantly regardless of the pigeonpea variety and amount of crop residues returned to the soil. Available P increased significantly but this was because of the inherently high P levels at the study site. Exchangeable bases, such as potassium, calcium and magnesium also declined significantly. Whilst this decline may be attributed to high nutrient demands due to high maize and pigonepea yields reported during the study, it is apparent that factors other than cropping system, residue management and the duration of the crop in the field influenced the contribution of pigeonpea to soil fertility improvement in this study. Most probably, it was influenced by the intial soil fertility status of the study site. This confirms that pigeonpea's contribution to soil fertility improvement is site-specific and perhaps helps to explain why, despite being the fourth largest producer of pigeonpea in the world, most pigeonpea growing areas in the country are among the most degraded in the region.

4.3.2. Effect of intercropping and crop residue incorporation on maize and pigeonpea yields

4.3.2.1. Maize yield

Maize yields obtained per season from different maize-pigeonpea cropping systems and crop residue management options are presented in Tables 6a and 6b in Chapter Three. Growing maize alone without returning any stovers to the soil yielded 0.948 t ha^{-1} of grain and 1.217

t ha^{-1} of stover per season. Yields were higher in the LR compared to SR season (Tables 6a and 6b), probably due to to high rainfall received in the long season compared to the short season. They were also higher than what most farmers in the region obtain from their farms (less than 0.5t ha^{-1} per season) and could be attributed to good agronomic practices, such as timely planting and weeding, correct spacing, use of certified early maturing maize seed and protection against maize stalk borers applied in this study. The high yields in the LR seasons also indicate that, unlike typical farmers's fields, the study site was not nutrient-depleted. This implies that farmers in the region can double their maize grain yields in good seasons without applying fertilizer, especially in newly opened farms, provided they adhere to other sound agronomic practices, such as timely planting and weeding, correct spacing, use of certified early maturing maize seed and protecting against maize stalk borers. Low grain yields in the short seasons (less than 1.0 t ha^{-1}) reflect what most farmers in the region get (less than 0.5 t ha^{-1} per season) and could be due to the relatively low rainfall received in those seasons compared to the long seasons.

Ploughing back crop residues had a significant effect on both maize grain and stover yields across seasons and cropping systems. For instance, intercropping maize with the short, medium and long duration pigeonpea varieties without ploughing back crop residues reduced mean maize grain yields per season by 13% (0.948 to 0.821 t ha^{-1}), 14% (0.948 to 0.812 t ha^{-1}) and 20% (0.948 to 0.760 t ha^{-1}), respectively. The reduction in grain yield could be attributed to low availability of essential nutrients due to continuous cropping without any nutrient restitution. However, mean stover yields per season increased by 4.8% (from 1.217 to 1.276 t ha^{-1}), 10.7% (from 1.217 to 1.347 t ha^{-1}) and 11% (from 1.217 to 1.352 t ha^{-1}) under maize-Mbaazi I, maize-Kat 60/8 and maize-Mbaazi II intercrops, respectively, presumably due to the high rainfall received during the study, especially in the long seasons. A similar trend was observed when 2 t ha^{-1} of crop residues were ploughed back, where mean grain yields per season dropped by 5% (from 0.948 to 0.898 t ha^{-1}) and 4% (from 0.948 to 0.907 t ha^{-1}) under maize-Mbaazi I and maize-Kat 60/8 intercrops, respectively, but increased marginally by 3% (from 0.948 to 0.980 t ha^{-1}) under maize-Mbaazi II intercrop. On the contrary, mean stover yields per season increased significantly by 18.5% (from 1.217 to 1.443 t ha^{-1}), 39% (from 1.217 to 1.696 t ha^{-1}) and 22.2% (from 1.217 to 1.487 t ha^{-1}) under maize-Mbaazi I, maize-Kat 60/8 and maize-Mbaazi II intercrops, respectively. The reduction in the decline of grain yields and significant increase in stover yield could be attributed to improvement in soil fertility due to decomposition and mineralization of the crop residues (Akanvou *et al*., 2002; Degranade, 2001). These results agree with Silim *et al*. (1997) who noted from a study in semi-arid Eastern Kenya that the yield of intercropped maize was substantially lower than its sole crop, especially in seasons when moisture supply was limiting. Ploughing back 4 t ha^{-1} of crop residues increased mean grain yields significantly by 35% (from 0.948 to 1.289 t ha^{-1}), 70% (from 0.948 to 1.616 t ha^{-1}) and 97% (from 0.948 to 1.864 t ha^{-1}) per season under maize-Mbaazi I, maize-Kat 60/8 and maize-Mbaazi II intercrops, respectively. Similarly, it increased stover yields by 45% (from 1.217 to 1.769 t ha^{-1}), 63% (from 1.217 to 1.986 t ha^{-1} and 71% (from 1.217 to 2.080 t ha^{-1}) per season when maize was intercropped with the short, medium and long duration pigeonpea, respectively. The significant increase in both grain and stover yields could be attributed to improvement in soil nutrient supply and soil physical properties such as bulk density, infiltration and water-holding capacity due to decomposition of the crop residues (Chirwa *et al*, 2004), however, the high increase in yield by Mbaazi II (long duration pigeonpea) compared to the rest could be attributed to its ability to mobilize and avail extra nutrients from deep soil horizons due to its deep root system and massive litterfall (Snapp and Silim, 2002; Silim *et al*., 2005; Myaka *et al*., 2006; Adu-Gyamfi *et al*., 2007; Kumar *et al*., 2011). These results corroborate findings of Kumar and Goh (2000) that the magnitude of the yield increase of cereals in such systems depends on the amount of materials returned to the soil. Similar results were reported by Wanderi *et al.* (2011) from a study in Thika near Nairobi where maize grain and stover yields increased by about 15 and 30%, respectively, under maize-long duration pigeonpea intercrop. Other authors such as Chirwa *et al*. (2004), Mapfumo and Mtambanengwe (2004), Rao and Mathuva (2000), Adjei-Nsiah *et al.* (2007), Degrande (2001), Akanvou *et al.* (2002), Abunyewa and Karbo (2005) and Chamango (2001) reported significant improvement in maize grain yields attributable to pigeonpea, but mostly based on long duration pigeonpea fallows. They attributed the increase in maize yield to improvement in soil chemical and physical properties due to decomposition and mineralization of pigeonpea's massive litterfall.

Thus, it is possible to increase maize grain yields from < 0.5 t ha^{-1} per season currently obtained by most farmers in semi-arid Eastern Kenya to 1.289 t ha^{-1}, 1.616 t ha^{-1} and 1.864 t ha^{-1} cheaply by intercropping maize with the short, medium and long duration pigeonpea, respectively, and by ploughing back 4 t ha^{-1} (2 t ha^{-1} each) of pigeonpea and maize crop residues every season to improve soil fertility. However, intercropping maize with the long duration pigeonpea and ploughing back 4 t ha^{-1} of crop residues offers the best option as it increases maize grain yields significantly and generates sufficient stover to plough back and feed the livestock. Framers should therefore be encouraged to adopt this practice to avert land degradation and food insecurity.

4.3.2.2. Pigeonpea yield

Pigeonpea yields obtained per season from different maize-pigeonpea cropping systems and crop residue management options are presented in Tables 7a and 7b in Chapter Three. Pigeonpea yield varied significantly across varieties, seasons, cropping systems and residue management options. For instance, the short (Mbaazi I), medium (Kat 60/8) and long

(Mbaazi II) duration pigeonpea varieties yielded 0.895, 1.023 and 1.136 t ha^{-1} of grain, respectively, per season when grown without ploughing back crop residues. The same trend was observed in biomass yields where 1.04, 1.345 and 1.927 t ha^{-1} of pigeonpea stalks was obtained from the short (Mbaazi I), medium (Kat 60/8) and long (Mbaazi II) duration pigeonpea variety, respectively, per season. These higher yields compared to what most farmers farmers obtain from their farms (less than 0.5 t ha^{-1} of grain per season) could be attributed to the good agronomic practices such as timely planting and weeding, correct spacing, use of certified early maturing maize seed and protection against maize stalk borers applied in this study. However, the significantly higher yields by Mbaazi II (the long duration variety) compared to other varieties (Mbaazi II and Kat 60/8) could be due to its phenological complementarity with maize and its ability to mobilize nutrients from deeper soil horizons due to its deep root system and massive litterfall (McCown *et al.*, 1992; Myaka *et al.*, 2006).

Intercropping the short (Mbaazi I) and medium (Kat 60/8) duration pigeonpea with maize without ploughing back crop residues reduced their average grain yields per season by 92% (from 0.895 to 0.071 t ha^{-1}) and 94% (from 1.023 to 0.065 t ha^{-1}), respectively. However, long duration pigeonpea (Mbaazi II) grain yield increased marginally by 5.5% (from 1.136 to 1.199 t ha^{-1}). Similarly, relative to the control, mean pigeonpea stalk yield per season dropped by 83.5 and 84.5% under maize-Mbaazi I and maize-Kat 60/8 intercrop, respectively, but increased ($p \leq 0.05$) by 21.8% under maize-Mbaazi II intercrop. The reduction in the short and medium duration pigeonpea grain and stalk yields could be attributed to maize's longer duration in the field, since the longer the duration of the cereal, the lower the pigeonpea yield (Tarhalkar and Rao, 1981; Ali, 1990). However, the increase in the long duration pigeonpea yield could be due to its longer duration in the field, which allowed it to recover from the initial slow growth after the maize was harvested and also its ability to mobilize extra nutrients from deeper soil horizons due to its deep root system (Snapp and Silim, 2002; Mapfumo and Mtambanengwe, 2004; Silim *et al.*, 2005; Kumar *et al.*, 2011). Similar results were reported by Natarajan and Wiley (1981) from a study in India, in which the pigeonpea component of a cereal (sorghum)-pigeon pea intercrop suffered considerable competition from the cereal initially, but recovered after the cereal was harvested and produced seed yields equivalent to 70% of the sole crop.

Ploughing back 2t ha^{-1} of crop residues reduced the decline in average pigeonpea grain yields per season to 88.4 and 90.3% under maize-Mbaazi I and maize-Kat 60/8 intercrops, respectively, before increasing by 15.9% under maize-Mbaazi II intercrop. The average pigeonpea stalk yields per season also declined by 75.5 and 79.2% under maize-Mbaazi I and maize-Kat 60/8 intercrops, respectively, before increasing by 33.4% under maize-Mbaazi II intercrop. Retaining and incorporating 4 t ha^{-1} of crop residues in the soil hampered further drop in mean pigeonpea grain yield per season to 85.8 and 87.4% under maize-Mbaazi I and maize-Kat 60/8 intercrops, respectively, but increased it by 25.6% under maize-Mbaazi II intercrop. Average stalk yields per season declined by 67.5 and 72.2% under maize-Mbaazi I and maize-Kat 60/8 intercrops, respectively, but increased by 51.6% under maize-Mbaazi II intercrop. The deceleration in the decline in the short and medium duration pigeonpea yields and increase in long duration pigeonpea yield could be attributed to improvement in soil fertility, due to mineralization of the added crop residues. These results agree with those of Tarhalkar and Rao (1981), and Ali (1990) who indicated that intercropping cereals with early-maturing pigeonpea often led to reduction in pigeonpea yield. Similar results were reported by Egbo and Ngumalen (2010) from a two-year study in Nigeria, where intercropping decreased the number of pods per plant, dry pod weight and grain yield of the pigeonpea component, as well as the panicle length, panicle weight and dry grain yield of the cereal component. It is apparent from this study that, irrespective of how much crop residues is returned to the soil, both short and medium duration pigeonpea are not the best candidates for incorporation into maize-based cropping systems in the study area, since doing so depressed their grain and stalk yields significantly. However, due to its phenological complementarity with maize, long duration pigeonpea is the best option for intercropping with maize. Long duration pigeonpea is able to give higher yields with or without ploughing back crop residues, because its deep root system allows it to mobilize extra nutrients from deeper soil horizons, besides its ability to recycle massive litterfall.

4.4. Conclusions

Intercropping maize with short and medium duration pigeonpea varieties in water-deficit environment of Katumani is not feasible, as it depresses both grain and biomass yields. However, intercropping the short (Mbaazi I) and medium (Kat 60/8) duration pigeonpea varieties with maize and ploughing back 4 t ha^{-1} of crop residues can increase maize yields from what is currently obtained by most farmers in semi-arid Eastern Kenya, up to 1.6t ha^{-1} per season. Nevertheless, farmers would be hesitant to adopt this option, since they prefer a system that would guarantee them both bumper maize and pigeonpea yields. Thus, intercropping maize with long duration pigeonpea and ploughing back 4 t ha^{-1} of crop residues would be the best option, since it is able to give higher maize and pigeon pea yields, and sufficient crop residues to feed the livestock and plough back to improve soil fertility. The contribution of pigeonpea-maize cropping systems to soil fertility improvement in semi-arid areas might depend more on the intial soil fertility status, besides the cropping system, residue incorporation and the duration of the crop in the field.

CHAPTER FIVE

5.0. THE EFFECT OF PIGEONPEA AND CROP RESIDUES ON SOIL PHYSICAL PROPERTIES AND MAIZE YIELD

Abstract

Land degradation and low rainfall seriously constrain agricultural production in arid and semi-arid areas. A study was conducted at Katumani Research Centre between 2009 and 2013 to investigate the effect of pigeonpea and crop residues on soil physical properties and maize yields. Sole- and inter-crops of maize and pigeonpea varieties drawn from three maturity groups and three crop residue application rates were evaluated in a split-split plot design with pigeonpea varieties, cropping systems and crop residue application rates as the main plot, sub-plot and sub-sub-plot, respectively. The treatments were laid out in 4.8 m long × 4.5m wide plots and replicated four times. Soils were analysed for texture, bulk density, aggregate stability, soil water content and soil organic carbon. Results showed that all the maize-pigeonpea cropping systems tested in this study accumulated very low soil organic carbon (< 1%) and hence, did not improve soil physical properties. Instead, they increased soil bulk density beyond the prescribed range for non-restricted plant growth and reduced soil aggregation thereby exposing soils to degradation. However, they did not alter texture of the soils at the study site. Intercropping maize with the three pigeonpea varieties, especially the long duration variety (Mbaazi II), requires more water compared to maize and pigeonpea sole crops. This can be addressed by conserving more water in the profile by ploughing back crop residues. Mbaazi II-maize intercrop offers the best option for farmers in marginal areas like Katumani since it gave the highest maize (1.9 t ha^{-1}) and pigeonpea (1.4 t ha^{-1}) grain yields and produced sufficient maize stover (2.1t ha^{-1}) and pigeonpea stalks (2.9 t ha^{-1}) to plough back and feed the livestock.

Key words: aggregate stability, maize yields, crop residues, pigeonpea

5.1. Introduction

Dominant features of agricultural production systems in arid and semi-arid lands (ASAL) in Kenya are land degradation and low crop yields (GoK, 2013a; Gicheru *et al*., 2004). Cereal and legume yields from farmers' fields rarely exceed 1t and 0.5t ha^{-1}, respectively, per season compared to over 2t ha^{-1} obtained from research stations and in commercial farms in these areas (Recha *et al*.,2012; Jaetzold *et al*., 2006). Majority of the people (> 65%) in ASALs live in abject poverty and rely on government relief supplies. Several authors (Recha *et al*., 2012; Itabari *et al*., 2011, 2004; Jaetzold *et al*., 2006) have described the situation evident on most farms in these areas as a 'poverty trap', in which the high subsistence population living on degraded soils receives low income, affords low or no farm inputs and consequently get low crop yields. The widespread land degradation in these areas is attributable to agricultural mismanagement, overgrazing and deforestation due to population pressure which has forced farmers to use land more intensively and to cultivate on marginal land (Gichangi *et al*., 2016; Itabari *et al*., 2011, 2004). Progressive land degradation is not only a threat to national food security, but also promotes climate change by denuding vegetative ground cover and depleting soil organic matter (SOM), thereby reducing their capacity to regulate atmospheric gas pools (Lawal *et al*., 2009; Steiner, 1996).

Low yields on the other hand are partly due to diminishing soil fertility, but mostly due to low and unreliable rainfall. The soils have low organic matter content due to poor natural vegetation cover and removal of crop residues for livestock feed. They also have low water-holding capacity, poor nutrient status and, are susceptible to erosion and surface sealing and capping due to poor structural development. Besides its unreliability, rainfall in the ASALs occurs in high intensity storms that result in excessive soil and water losses through erosion and run-off, especially at the start of the rainy season when most croplands are bare due to removal of crop residues. Frequent water deficits occur within the growing season and on average, there is a crop failure in two out of every five seasons. Run-off water also carries away dissolved nutrients, further reducing the capacity of the soil to support plant growth (Itabari *et al.*, 2011).

Studies indicate that including legumes such as pigeonpea in maize cropping systems can effectively reverse the above scenario (Adu-Gyamfi *et al.*, 2007; Audi *et al.*, 2008; Gwata and Shimelis, 2013; Høgh-Jensen *et al.*, 2007; Nagarajan *et al.*, 2008; Shiferaw *et al.*, 2008; USAID, 2010). Pigeonpea provides several important benefits. The crop is drought-tolerant and can produce yields in seasons when other crops fail. It is therefore an important food security crop for the ASALs. The protein-rich grain is an important component in the diet of subsistence farmers, who eat mainly low-protein cereals and root crops. Pigeonpea stems supplement an often deficient fuelwood situation. Further, pigeon pea is one of the few crops with the potential to ameliorate soils with minimal labour inputs, low seed costs and little or no fertiliser inputs, compared to other green manure and agroforestry species (Snapp *et al.*, 1998; Sakala *et al.*, 2003). It increases SOM substantially through leaf biomass and senescent material produced at a rate of 1–4.5 t ha^{-1} (Snapp and Silim, 2002; Omanga *et al.*, 1990). This SOM improves soil structure and soil water-holding capacity; and supplies essential nutrients, N and P, through mineralisation. However, like other legumes, its contribution to SOM is site-specific and therefore depends on the growing conditions, residue management and the duration of the crop in the field (Mafongoya *et al.*, 2000; Snapp *et al.*, 1998). Pigeonpea also enriches the soil through nitrogen fixation and being a deep-rooted crop, mobilises nutrients, particularly phosphorus, from the deep soil horizons (Ae *et al.*, 1990; Omanga *et al.*, 1990; Snapp and Silim, 2002). In addition, intercropping pigeonpea with cereals enhances soil coverage, reduces soil erosion and boosts cereal yields tremendously (Myaka *et al.*, 2006;

Mapfumo and Mtambanengwe, 2004). It is an important component of traditional farming systems common in marginal areas where fertiliser use is minimal (Silim *et al*., 1990). However, whilst substantial work has been done on the nitrogen-fixing properties of pigeonpea and the effect of exporting or incorporating pigeonpea crop residues on soil nutrients (Adu-Gyamfi *et al*., 2007; Myaka *et al*., 2006; Sakala *et al*., 2000; Rao and Mathuva, 2000), there is scarcity of information on the effect of pigeonpea cropping systems and residue management practices on soil physical properties. This has been attributed to the time-consuming, cumbersome and expensive nature of most soil physical analyses (Chirwa *et al*., 2004).

Over the years, the Kenya Agricultural Research Institute (now Kenya Agricultural and Livestock Research Organization (KALRO)), jointly with the International Crop Research Institute for Semi-Arid Tropics (ICRISAT) and the University of Nairobi have developed and released numerous pigeonpea varieties suitable for Kenya's semi-arid lands. However, these efforts focused mainly on developing high yielding varieties that are resistant to *Fusarium* wilt and adaptable to a broad range of ecological conditions (Shiferaw *et al*., 2008; USAID, 2010). There have been few studies on how their inclusion in the maize-based cropping systems influences soil physical properties and long-term sustainability of these production systems. The objective of this study therefore, was to determine the effect of pigeonpea-maize cropping systems on soil physical properties and maize yields.

5.2. Materials and methods

5.2.1. Description of the study site

The study was conducted at the Kenya Agricultural and Livestock Research Organization (KALRO) Katumani Research Centre in Machakos County, 80km south-east of Nairobi (longitude: 37˚14´E and latitude: 1˚ 35´S) from 2009 to 2013. Katumani has bimodal rainfall pattern and receives an average of 711mm annually. The long rains (LR) occur from March to May and the short rains (SR) from October to December with peaks in April and November, respectively (Recha *et al*., 2012; Jaetzold *et al*., 2006). Inter-seasonal rainfall variation is large with coefficient of variation ranging between 45 and 58% (Keating *et al*., 1992). Therefore, the timing and relative lengths of each growing period vary substantially such that any delays in planting, particularly of maize, at the start of the wet season brings risks of significant yield losses, almost proportional to the time delay (Keating *et al*., 1992). However, the second season (short rains) rains are more reliable for crop production (Recha *et al*., 2012). Temperatures range between 17 and 24^{o}C with February and September being the hottest months. The mean annual temperature is 20^{o}C. Evaporation rates are high and exceed the amount of rainfall, most of the year, except in the month of November. The mean potential evaporation ranges between 1820 and 1840mm per year whilst evapotranspiration is estimated at 1239mm (Gicheru, 1996) giving an r/ETo ratio of 0.57. Katumani is 1600m asl and the terrain ranges from flat to hilly with slopes varying from 2 to 20 % (Gicheru and Ita, 1987). It falls under agro-climatic zone IV that has a low potential for rainfed agriculture (Jaetzold *et al.*, 2006).

The dominant soils are chromic Luvisols (FAO/UNESCO, 1997; WRB, 2006), which are low inorganic C, highly deficient in N and P and to some extent, Zinc and generally a poor soil structure (NAAIAP, 2014). The site was a grazing field for many years prior to the study. It was cleared of weeds and sparse bushes and cropped uniformly with maize in the 2009 long rain season to even it out and to block the field layout before setting up the experiment. All the crop residues were removed from the field after harvesting to eliminate any confounding effect.

5.2.2. Treatments and experimental design

The experiment was established during the 2009 short rain season in a split-split plot arrangement with pigeonpea varieties, cropping systems and crop residue application rates as the main plot, sub-plot, and sub-sub-plot, respectively. The treatments included sole and intercrops of maize and pigeonpea varieties drawn from three maturity groups (short, medium and long duration pigeonpeas), three crop residue application rates (0, 2 and 4 t ha^{-1}), and virgin land (bare plot) and maize sole crop as controls. The treatments were laid out in 4.8 m x 4.5 m plots with an inter-plot spacing of 1.5m and replicated four times in a randomized complete block design. Pigeonpea stalks and maize stovers were weighed, chopped into 5-10cm pieces and placed into the soil to a depth of 15 cm at the rate of 0, 2 and 4 t ha^{-1}, respectively, every season after land preparation to allow crop residues to decompose. These crop residue application rates and cropping systems represent as closely as possible those practiced by farmers and take into account the competing uses for crop residues in the ASALs. A total of 18 treatments were investigated using a bare plot and sole maize crop as the controls and are summarized in Table 8 in Chapter Four.

Maize variety KDV1 was selected for the study owing to its good adaptability, early maturity (120 -150 days to mature) and yields highly under semi-arid conditions. Mbaazi 1 and KAT 60/8 were used for the short and medium duration pigeonpea varieties, respectively, due to their early maturity and high yields. They take on average 100 and 150 days, respectively. Mbaazi II was used as the long duration variety owing to its resistance to common pests and diseases and high yield. It takes 180-220 days to mature. Generally, the three pigeonpea varieties are popular among farmers and their seeds are readily available. Virgin land (bare plot) and maize sole crops were used as the controls.

The land was prepared using a hand hoe at the beginning of each cropping season and crops sown at the on-set of the rains. Pigeonpea was planted without fertilizer additions at spacing of 90 cm x 60 cm, 75 cm x 30 cm and 50 cm x 25 cm for the long, medium and short duration varieties, respectively, at 2 seeds per hill and thinned to one two weeks after emergence. Maize was planted with Triple Super Phosphate (TSP) fertilizer at the recommended rate of 40 kg P_2O_5 ha^{-1} at spacing of 90cm x 30cm. However, in the intercrops, one row of pigeonpea was planted after every row of maize to replicate the farmers' practice.

Pigeonpea was protected from pests on a 'minimum-protection' basis, twice per season with Dimethoate™ (dimethoate) at 0.5L ha^{-1} to control pod borer (*Helicoverpa armigera*) and pod fly (*Melanagromyza chalcosoma*). Bulldock™ pesticide (beta-cyfluthrin) was applied on maize once every season to control stalk borers. The plots were kept weed-free by weeding regularly depending on weed emergence/intensity and characteristics. The study was conducted for four long rain and four short rain seasons (8 seasons) from October 2009 to July 2013.

5.2.3. Data collection

5.2.3.1. Soil moisture measurements

Soil moisture measurements were taken fortnightly from sowing to maturity using the gravimetric method outlined in Anderson and Ingram (1993) to monitor changes in soil moisture content with pigeonpea and maize growth and crop residue retention. Soil samples were taken at 20, 40, 60, 80 and 100cm depths from four spots across each plot using a 600 cm^3 soil auger and transferred into small metal moisture cans of known weights which were capped to prevent moisture loss. The samples were weighed using a portable battery-operated electronic balance to determine their fresh weights and dried in an oven at 105°C for 24 hours to determine their dry weight. Soil water content was calculated by subtracting the sample oven-dry weight from its fresh weight and dividing the difference by the oven- dry weight.

5.2.3.2. Determination of soil texture, aggregate stability, organic carbon and bulk density

Soil samples were taken from each experimental plot prior to the start of the experiment in the 2009 short rain season and also at the end of the 2013 long rain season (i.e. after eight cropping seasons). Soil samples were collected in a transect across each plot using a 600cm^3 soil auger to a depth of 0-20cm. Soils from each plot were composted and mixed thoroughly in a bucket, quartered to obtain a representative sample and air-dried. The air-dry composite sample was then split into two sub-samples:one sub-sample was gently broken down along natural planes of weakness, passed through a 5mm sieve and analyzed for texture and aggregate stability using the hydrometer (Anderson and Ingram, 1993) and wet sieving (Cambardella and Elliott,1993) methods, respectively; whilst the other sub-sample was ground using a mortar and pestle, passed through a 2mm sieve and analyzed for organic carbon using the Walkley and Black method as described by Nelson and Sommers (1996). Bulk density was determined using the core sampling method as described by Blake and Hartge (1986).

5.2.3.3. Plant sampling

Maize and pigeonpea were harvested at full maturity when the entire maize stalks are completely dry and pigeonpea pods are brownish. Plants lying within one metre of each side of the plot were omitted from the sample harvest to eliminate any plot border effects; giving a harvest area of 7 m^2. Plants within the harvest area were counted, harvested and weighed using a precision weighing balance ±0.001g. Sub-samples of maize and pigeonpea materials from the total number of plants harvested were divided into cobs and stover, and pods and stalks for maize and pigeonpea data collection, respectively. Maize and pigeonpea grains were dried at 12.5% moisture content and the ratio of dry weight to wet weight and plot wet weight used to estimate maize and pigeonpea grain and biomass yields in tonnes per hectare.

5.2.4. Data Analysis

Data on bulk density, soil aggregate stability, soil organic C, and maize and pigeonpea yields were subjected to analysis of variance (ANOVA) using GENSTAT software version 14.2 (GENSTAT, 2016). Because of the large number of treatments involved, mean comparisons for the individual treatments was done using both Least Significant Difference of means (LSD, $p \leq 0.05$) and the Duncan Multiple Range Test (DMRT).

5.3. Results and discussion

5.3.1. Soil texture

Particle size analysis results indicate that soils at the study site were sandy clay loam in texture (69% sand, 26% clay and 5% silt) in the 0-20cm depth. The textural results agree with Gichangi *et al* (2016) who reported a sandy clay loam texture in the 0-30cm depth and clay in the lower depths in a study conducted in Katumani about 400m from our site. Other researchers such as Gicheru and Ita (1987), Kilewe (1987) and Okwach (1994) also reported sandy clay loam texture in the topsoil of many sites in Katumani and this could be due to widespread occurrence of granitic and gneissic parent material, downward eluviation of clay, erosion of finer soil particles by massive run-off, and chemical destruction of kaolinite in the topsoil (Jaetzold *et al*., 2006; Brady and Weil, 2009). The clay content in the topsoil was low (26%), but it is likely to have increased with depth going by the previous reports. The soils had a high sand content (69%), an indication that they were weakly structured, friable, highly erodible and susceptible to surface capping under raindrop impact resulting in poor infiltration of rainwater leading to high run-off, serious erosion and loss of nutrients (Jaetzold *et al*., 2006; Okwach, 1994; Gicheru and Ita, 1987).

5.3.2. Soil aggregate stability, bulk density and organic carbon content

Soil aggregate stability refers to the ability of soil aggregates to remain intact when subjected to some stress. Aggregate stability is a crucial soil attribute that influences soil water movement and storage, aeration, erosion, biological activity and the growth of crops (Spohn and Giani, 2011; Pohl *et al*., 2012). Maintaining high soil aggregate stability is essential for preserving soil productivity, minimizing soil erosion and degradation and minimizing environmental pollution derived from soil degradation as well. Thus, maintaining high soil aggregate stability is a requisite for sustainable use of soil and for sustainable agriculture. Soil aggregate stability is very sensitive to changes in land management and is strongly correlated with soil erodibility. It is therefore widely used as an indicator of soil degradation (Mills and Fey, 2003; Wick *et al*., 2009; Fonte *et al*., 2014). The importance of soil organic matter (SOM) in stabilizing soil aggregates has been well documented (Six *et al*., 2000, 2004; Bronick and Lal, 2005). SOM is an important binding agent for aggregation therefore the higher the SOM content the greater the stability of soil aggregates, especially in mineral soils (Onweremada *et al*., 2007; Barreto *et al*., 2009; Lawal *et al*., 2009; Samahadthai *et al*., 2010). Conversely, loss of SOM reduces soil fertility, degrades soil structure and water holding capacity and eventually leads to land degradation. Soil bulk density is commonly used to measure soil compaction and is a function of soil organic matter and aggregate stability (Baldock and Nelson, 2000). A decrease in organic matter causes an increase in bulk density and a decrease in porosity which impedes free entry and movement of water and air, easy cultivation as well as germination and emergence of seedlings and growth of plant roots (Franzluebbers, 2002; Wall and Heiskanen, 2003; Celik, 2005). Changes in soil aggregate stability, bulk density and soil organic carbon content after 8 seasons of continuous pigeonpea-maize cropping are reported in Table 10.

Table 10. Effect of maize-pigeonpea cropping systems and crop residue incorporation on soil aggregation, bulk density and organic carbon content.

Treatment	Soil aggregate size distribution (%)[1] Macro-aggregates (> 250µm)	Micro-aggregates (< 250µm)	Bulk density (g cm^{-3})	Soil organic C (%)
Control (virgin land)	44.9[a]	54.8[f]	1.49[c]	1.4[a]
Maize sole crop + 0 tons*	36.8[ef]	63.0[ab]	1.68[a]	0.7[d]
Mbaazi I sole crop+0 tons	38.7[bcde]	60.9[bcd]	1.57[abc]	0.9[b]
Mbaazi I sole crop+ 2 tons†	38.0[cde]	61.9[abc]	1.56[abc]	0.8 [bcd]
Mbaazi I sole crop+ 4 tons‡	34.8[f]	64.8[a]	1.57[abc]	0.8 [bcd]
Kat 60/8 sole crop+ 0 tons	39.0[bcde]	60.9[bcd]	1.61[abc]	0.9[b]
Kat 60/8 sole crop+ 2 tons	36.3[ef]	63.5[ab]	1.58[abc]	0.8 [bcd]
Kat 60/8 sole crop+ 4 tons	38.7[bcde]	61.2[bcd]	1.56[abc]	0.8 [bcd]
Mbaazi II sole crop + 0 tons	39.1[bcde]	60.8[bcde]	1.56[abc]	0.8 [bcd]
Mbaazi II sole crop + 2 tons	40.8[bc]	59.0[de]	1.55[abc]	0.8 [bcd]
Mbaazi II sole crop + 4 tons	35.1[f]	64.2[a]	1.57[abc]	0.8 [bcd]
Mbaazi I/maize intercrop+0 tons	40.5[bc]	59.3[cde]	1.56[abc]	0.8[bcd]
Mbaazi I/maize intercrop + 2 tons	37.9[cde]	62.0[abc]	1.56[abc]	0.8[bcd]
Mbaazi I/maize intercrop + 4 tons	41.3[b]	58.6[de]	1.57[abc]	0.8[bcd]
Kat 60/8/maize intercrop+0 tons	40.1[bcd]	59.8[cde]	1.56[abc]	0.9[b]
Kat 60/8/maize intercrop + 2 tons	38.1[cde]	61.8[abc]	1.58[abc]	0.8[bcd]
Kat 60/8/maize intercrop + 4 tons	41.4[b]	57.6[ef]	1.57[abc]	0.9[b]
Mbaazi II/maize intercrop+0 tons	41.1[b]	58.5[de]	1.56[abc]	0.8[bcd]
Mbaazi II/maize intercrop + 2 tons	37.2[de]	62.5[abc]	1.55[abc]	0.7[d]
Mbaazi II/maize intercrop + 4 tons	39.0[bcde]	60.8[bcde]	1.57[abc]	0.8[bcd]

[1]Averaged over 4 replicates; Means followed by different letter(s) within the same column are significant at 5% level of probability; *No crop residues were incorporated; †2 t ha^{-1} of crop residues were incorporated; ‡4 t ha^{-1} of crop residues were incorporated.

Both soil organic carbon (SOC) and aggregate stability were higher under the control (virgin land) compared to cropped land, probably due to dense vegetation cover and minimal soil disturbance (Lawal *et al*., 2009). These results corroborate findings by Lawal *et al*. (2009), Spaccini *et al*. (2001), Bear *et al*. (1994) and Barzegar *et al* (1994) who reported that cultivation destroys soil structural stability and virgin soils have much higher aggregate stability than cultivated ones, especially where crop residues are removed as it was the case with some of the treatments in this study. The results also agree with reports by Chenu *et al*. (2000), Hamblin (1980), Dormaar (1983) and Angers and Mehuis (1989) who observed that upon cultivation the organic matter content of soils typically decreased with a corresponding decrease in aggregate stability. Growing maize alone continously for 8 seasons without ploughing back crop residues significantly ($P \leq 0.05$) reduced SOC from 1.4% to 0.7%. The proportion of macro- and micro-aggregates also declined and increased by 8% (from 44.9 to 36.8 %) and 9 % (from 54.8 to 63.8%), respectively, in the same period. The increase in the proportion of micro-aggregates could be due to dispersion of clay from the soil due to the growth of maize roots resulting in disintegration of macro-aggregates into micro-aggregates. Maize roots exude chelates and organic acids which remove polyvalent cations from the bonds between clay and organic matter thereby dispersing the clay which acts as a cementing agent (Reid *et al*., 1982). A similar trend was observed under pigeonpea sole crop where SOC declined from 1.4% to <0.9% and both macro- and micro-aggregates declined (from 44.9% to < 40%) and increased (from 54.8% to > 59%) by over 5%, respectively, across the three pigeonpea varieties. The decline in SOC under both maize and pigeonpea sole crops could be attributed to rapid mineralization and dissipation of SOM due to high rainfall and high temperatures (Itabari *et al*., 2004; Mugwe *et al*., 2009; Itabari *et al*., 2011) whilst the increase in micro-aggregation under pigeonpea sole crop may have been caused by the reduction in SOC and the breakdown of macro-aggregates into micro-aggregates by tillage during land preparation and weeding (Lawal *et al*., 2009). Contrary to observations by Lynch and Bragg (1995) and Oades (1993) that monocotyledonous plants such as maize are superior to dicotyledonous plants like pigeonpea in stabilizing soil aggregates, there were no significant differences in both macro- and micro-aggregate stability between maize and pigeonpea sole crops in this study. Similarly, there were no significant differences in aggregate stability between sole crops of the three pigeonpea varieties, especially when on crop residues were ploughed back. Ploughing back crop residues did not hamper the decline in SOC, neither did it decelerate the decline in soil aggregation, attesting to the fact that it takes time for organic matter levels to build up in the soil and influence soil physical properties. These results agree with those of Dowuona *et al*. (2011) from a study in Ghana who reported a marked decline in aggregate stability of soils under pigeonpea and other legumes compared to the natural fallow, despite addition of pigeonpea biomass.

Intercropping maize with pigeonpea significantly reduced SOC (from 1.4% to <0.9%), but decelerated the decline in aggregate stability by about 4%. Macro-aggregates declined from 45-41% whilst the micro-aggregates increased from 55-63%. The decelaration in the decline in aggregate stability could be attributed to extensive shallow root systems of maize and pigeonpea, especially the short and medium duration pigeonpea varieties. Roots serve as temporary binding agents (Tisdall and Oades, 1983). They enmesh fine soil particles into stable macro-aggregates; dry the localized soil environment around the roots, reorienting clay particles parallel to the axis of the root and drawing soil particles together; supply decomposable organic residues to soil; support a large microbial population in the rhizosphere; provide food for soil animals such as earthworms and mesofauna; and release polyvalent cations and increase the concentration of ions in the soil solution which promote soil aggregation (Franchini *et al*., 2007; Leifeld, *et al*., 2005; Amezketa, 1999). There were no significant differences in soil aggregate stability between intercrops of the three pigeonpea varieties. Similarly, ploughing back crop residues did not hamper the decline in soil aggregate stability, perhaps due to low soil organic matter accumulation because of rapid mineralization and dissipation of crop residues attributable to the high rainfall and temperatures (Lal *et al*., 2003; Marquez *et al.,* 2004; Denef *et al*., 2007). These results are in contrast with findings by Dowuona and Adjetey (2010) from a study in Ghana where pigeonpea plots had more stable aggregates than natural fallow and bare plots. The greater stability of soil aggregates under pigeonpea and other tree legumes was attributed to the protective cover of their canopy and binding action of their roots. In a related study in Zambia, Chirwa *et al*. (2004) reported the highest percentage of water stable aggregates in pigeonpea land use systems at 76.9% followed by natural fallow at 65.8%. The least was recorded in maize without fertilizer at 44%. The disparity was attributed to high organic matter content under pigeonpea cropping systems compared to maize with or without fertilizer. Other researchers (Lawal *et al*., 2009; Gichangi *et al*., 2016) also observed that continuous deposition of biomass improved aggregate stability, although their findings were based on litterfall from forest trees and pasture grasses. Generally, all the maize-pigeonpea cropping systems tested in this study generated high proportions of micro-aggregates compared to macro-aggregates, an indication that they were all susceptible to water erosion since micro-aggregates are generally easily eroded by water (Adesodun *et al*., 2005). This could explain why most pigeonpea growing areas in the country are among the most degraded areas in the region. Otherwise improved soil aggregation improves infiltration, aeration and root penetration, and increases crop yields (Spohn and Giani, 2011; Pohl *et al*., 2012).

Bulk density ranged from 1.49 to 1.68 g cm^{-3} which was higher than the prescribed range of 1.10-1.30g cm^{-3} for non-restricted plant growth (Landon, 1991). Generally, soil bulk density exceeding 1.6g cm^{-3} for such soils would impair root growth and curtail soil aeration through reduced porosity (Brady and Weil, 2009). However, the results agree with findings by Kilewe (1987) and Okwach (1994) who reported bulk densities of 1.52 and 1.45g cm^{-3}, respectively, in topsoils from studies in Katumani. Similarly, Gichangi *et al*. (2016) reported bulk densities of 1.32-1.45g cm^{-3} in topsoils from a study in Katumani, albeit under pasture grasses.

5.3.3. Soil water content

Katumani receives an average of 711mm of rain annually. However, during this study, about 665.7 mm was received in 2010, 506.8 mm in 2011, 617 mm in 2012 and 590.8mm in 2013. Thus, the amounts of rainfall received in the 8 seasons of experimentation were high and adequate to sustain maize and pigeonpea crop if well conserved. Soil water contents of the dominant maize-pigeonpea cropping systems and three residue application rates tested in this study for 8 cropping seasons are provided in Figure 2. As expected, bare plots conserved more water than the cropped plots because apart from surface evaporation, there was no crop to utilize the water allowing most of it to be retained in the profile (Freebairn *et al*., 1986; Ulsaker and Kilewe, 1984; Lal, 1975). They also had a much better soil structure than other treatments due to minimal soil disturbance (Table 10). Sole maize cropping system extracted the least amount of water from the profile compared to other cropping systems and most of it was extracted from the upper soil horizons. These results contrast with reports by Chirwa *et al*. (2004), Lal (1989) and Hulugalle and Ndi (1993) that pigeonpea cultivation leads to high cumulative water intake than maize sole crop, and could be due to maize's extensive but shallow root system and low population due to wide spacing hence low demand for water and nutrients (Rachie and Roberts, 1974; Sheldrake and Narayanan, 1979). Maize-Mbaazi II (long duration pigeonpea) intercrop emptied the profile the most followed by maize-Mbaazi I (short duration pigeonpea) and maize-Kat 60/8 (medium duration pigeonpea) in the second and third position, respectively. However, Mbaazi II-maize intercrop extracted most of its water from deeper horizons in the profile whilst Mbaazi I-maize and Kat 60/8-maize intercrops obtained most of their water from the upper soil layers. These results corroborate findings by Kay (1979) that root penetration and water extraction are deeper in late-maturing pigeonpea varieties compared to early maturing ones. The high water uptake by maize-Mbaazi II intercrop may be due to Mbaazi II's extensive deep root system, long maturity period, and high biomass production (Table 7b) hence high water demand (Kay,1979). Maize is generally harvested earlier leaving long duration pigeonpea varieties such as Mbaazi II to continue in the field. This enables the long duration pigeonpea to utilize residual moisture or any rain that comes after the maize is harvested. The moderately high water uptake by maize-Mbaazi I intercrop may be attributed to high plant population and rapid growth by both maize and Mbaazi I resulting in increased demand for water and nutrients (Mehrotra *et al*., 1977; Singh *et al*., 1983). The low water uptake by the maize-Kat 60/8 intercrop may be attributed to suppression of Kat 60/8 by maize. Ploughing back crop residues increased the amount of water conserved across the cropping systems, perhaps because of improvement in soil structure due to decomposition of crop residues (Table 10; Akanvou *et al*., 2002; Kwesiga *et al*., 2003; Degranade, 2001). These results corroborate reports by Cassel *et al*. (1995) that retaining crop residues on or near the soil surface enhanced rainwater infiltration. Otherwise extraction of soil water was detected to the full depth sampled, indicating pigeonpea's ability to extract water from deep into the profile. These results correspond with reports by other researchers who detected extraction at 120cm (De Vries, 1986), 150cm (Sheldrake and Narayanan, 1979), 180 cm (Sardar and Russell, 1981), and down to 220cm (Nene *et al*., 1990). Although this study did not estimate the rate of water extraction by roots, Sardar and Russell (1981) reported from a two-year maize–pigeonpea intercropping study in India, that rates of water extraction by roots ranged from 0.003 to 0.055 mm/cm/day and varied with time, depth in the profile, and available water content.

Similarly, although this study did not determine the water use efficiency (WUE) of the pigeonpea-maize cropping systems, other researchers (Saxena and Yadar, 1975; Sardar and Russell, 1981) observed that on average, pigeonpea uses about 20-25cm of water to produce about 1t ha^{-1} of grain under traditional production systems. However, because of high densities due to closer spacing intensively managed pigeonpea systems that involve short duration varieties have a higher water requirement (Mehrotra *et al*., 1977; Singh *et al*., 1983). Mehrotra *et al*. (1977) estimated water use by one such variety to be in the range of 55-60cm. Sardar and Russell (1981) found that maize had higher water use efficiency (WUE) than pigeonpea from a two-year maize–pigeonpea intercropping study in India. The low WUE by pigeonpea was attributed to low grain yields due to poor season. Thus, given the high maize and pigeonpea yields reported under maize-Mbaazi II intercrop in this study(Tables 6a, 6b,7a and 7b), it is probable that maize-Mbaazi II intercrop had a higher WUE compared to maize-Mbaazi I and maize-Kat 60/8 intercrops.

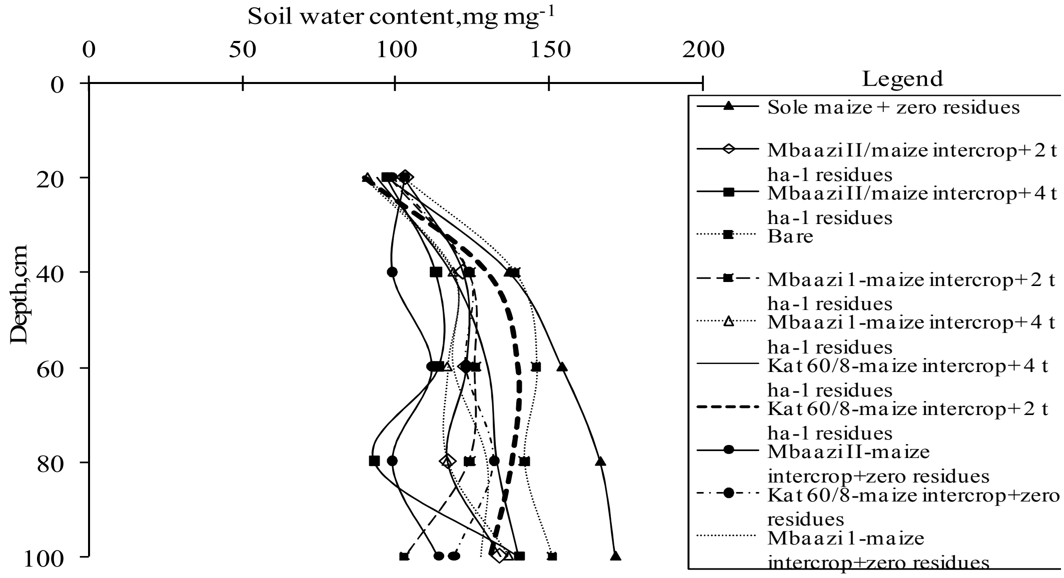

Fig.2. Effect of maize-pigeonpea cropping systems and incorporation of crop residues on soil water content in Katumani.

5.3.4. Maize and pigeonpea yields

5.3.4.1. Maize yield

Maize yields obtained from different maize-pigeonpea cropping systems and crop residue management options are reported in Table 6a and 6b in Chapter Three. Unlike what most farmers in the region harvest from their farms (less than 0.5 t ha^{-1} per season), growing maize sole crop without ploughing back stovers in this study yielded 0.9 t ha^{-1} of grain and 1.2 t ha^{-1} of stover per season. Since through its root exudates maize destroys soil structure (Reid *et* *al*., 1982; Table 10), the high yields could be attributed to other factors like good agronomic practices such as timely planting and weeding, correct spacing, use of certified early maturing maize seed and protection against maize stalk borers applied in this study. This means that by merely adhering to sound agronomic practices such as timely planting and weeding, correct spacing, use of certified early maturing maize seed and protecting against maize stalk borers, farmers in newly opened farms in the region can double their maize yields.

Intercropping maize with the short, medium and long duration pigeonpea varieties without ploughing back crop residues reduced average maize grain yields per season by 11% (0.9 to 0.8t ha^{-1}). However, average stover yields increased by 8-17%. The drop in maize grain yield and increase in stover yields could be attributed to scarcity of water to carry the crop through the grain filling stage because of low soil water retention capacity due to poor soil structure (Table 10). Due to low soil organic matter accumulation (Table 10), ploughing back 2 t ha^{-1} of crop residues did not improve soil structure (Table 10) and soil water content substantially (Figure 2) and hence had no significant effect on maize grain yield. However, it significantly increased stover yields by 17-42%. The significant increase in stover yield could be attributed to improvement in soil fertility due to decomposition and mineralization of the crop residues (Akanvou *et al*., 2002; Kwesiga *et al*., 2003; Degranade, 2001). These results differ with findings by Silim *et al*. (1998) who noted from a study in semi-arid Eastern Kenya, that the yield of intercropped maize was substantially lower than its sole crop. The disparity could be attributed to differences in the amount of crop residues ploughed back. Average grain yields also increased by 44% (from 0.9 to 1.3 t ha^{-1}), 78% (from 0.9 to 1.6 t ha^{-1}) and 111% (from 0.9 to 1.9 t ha^{-1}) per season under maize-Mbaazi I, maize-Kat 60/8 and maize-Mbaazi II intercrops, respectively, when 4 t ha^{-1} of crop residues was ploughed back. Stover yields increased too by 50% (from 1.2 to 1.8 t ha^{-1}), 67% (from 1.2 to 2.0 t ha^{-1}) and 75% (from 1.2

to 2.1t ha^{-1}) per season when maize was intercropped with the short, medium and long duration pigeonpea, respectively. Apart from improvement in soil nutrient supply, the huge increase in both grain and stover yields could be attributed to improvement in soil physical properties due to decomposition of the crop residues (Table 10; Figure 2; Chirwa *et al.*, 2004), however, the high increase in yield by Mbaazi II (long duration pigeonpea) compared to the rest could be attributed to its ability to mobilize and avail extra nutrients from deep soil horizons and improve soil structure due to its deep strong tap root system and massive litterfall (Table 10; Figure 2; Snapp and Silim, 2002; Silim *et al*., 2005; Myaka *et al*., 2006; Adu-Gyamfi *et al*., 2007; Kumar *et al*., 2011). These results corroborate findings of Kumar and Goh (2000) that the magnitude of the yield increase of cereals in such systems depends on the amount of materials returned to the soil. Similar results were reported by Wanderi *et al.* (2011) from a study in Thika near Nairobi where maize grain and stover yields increased by about 15% and 30%, respectively, under maize-long duration pigeonpea intercrop. Chirwa *et al.*(2004), Mapfumo and Mtambanengwe (2004), Rao and Mathuva (2000), Adjei-Nsiah *et al.* (2007), Degrande (2001), Akanvou *et al.* (2002), Abunyewa and Karbo (2005) and Chamango (2001) also reported significant improvement in maize yields attributable to pigeonpea, albeit from long duration pigeonpea fallows. They attributed the increase in maize (cereal) yield to improvement in soil chemical and physical properties due to decomposition and mineralization of pigeonpea's massive litterfall.

In a nutshell, intercropping maize with pigeonpea, especially the long duration variety, and ploughing back crop residues improves both soil physical and chemical properties leading to significant increase in maize grain yields and production of sufficient stover to plough back and feed the livestock.

5.3.4.2. Pigeonpea yield

Pigeonpea yield data is presented in Table 7a and 7b in Chapter Three. Compared to what most farmers obtain from their fields (less than 0.5 t ha^{-1} of grain per season), significantly higher grain yields were obtained in this study when the short (0.9t ha^{-1}), medium (1.0t ha^{-1}) and long (1.1 t ha^{-1}) duration pigeonpea varieties were grown as sole crops without ploughing back crop residues. About 1.0, 1.3 and 1.9 t ha^{-1} of pigeonpea stalks was harvested from the short (Mbaazi I), medium (Kat 60/8) and long (Mbaazi II) duration pigeonpea variety, respectively, too. These higher yields could be attributed to the good agronomic practices such as timely planting and weeding, correct spacing, use of certified early maturing maize seed and protection against maize stalk borers applied in this study. The significantly higher yields by Mbaazi II (the long duration variety) compared to the rest (Mbaazi II and Kat 60/8) could be due to its phenological complementarity with maize and its ability to mobilize nutrients and access water from deeper soil horizons due to its strong deep root system and massive litterfall (McCown *et al*, 1992; Myaka *et al*, 2006).

The short (Mbaazi I) and medium (Kat 60/8) duration pigeonpea performed dismally when intercropped with maize as their average yields dropped by 80-90%. The reduction in yield could be attributed to maize's longer duration in the field since the longer the duration of the cereal, the lower the pigeonpea yield (Tarhalkar and Rao, 1981; Ali, 1990). However, long duration pigeonpea (Mbaazi II) grain and stalk yields increased by 18-27% and 20-53%, respectively, especially when crop residues were ploughed back. The increase in the long duration pigeonpea yield could be due to its longer duration in the field which allowed it to recover from the initial slow growth after the maize was harvested and also its ability to mobilize extra nutrients and water from deeper soil horizons due to its strong deep tap root system (Snapp and Silim, 2002; Mapfumo and Mtambanengwe, 2004; Silim *et al*., 2005;

Kumar *et al*., 2011). Natarajan and Wiley (1981) reported similar results from a study in India in which the pigeonpea component of a cereal (sorghum)-pigeonpea intercrop suffered considerable competition from the cereal (sorghum) initially, but recovered after the cereal (sorghum) was harvested and produced seed yields equivalent to 70% of the sole crop. Other workers such as Tarhalkar and Rao (1981), Ali (1990), Egbo, and Ngumalen (2010) also reported that intercropping cereals with early-maturing pigeonpea often leads to drastic reduction in pigeonpea yield. From the foregoing, it is apparent that intercropping maize with the long duration pigeonpea variety gives both higher maize and pigeonpea yields as opposed to the short and medium duration varieties which only guarantee higher maize yields at the expense of pigeonpea yields. Long duration pigeonpea is able to mobilize nutrients and water from deeper soil horizons due to its strong and deep tap root system and massive litterfall and is therefore the best variety for incorporation into maize-based cropping systems in marginal areas such as semi-arid eastern Kenya.

5.4. Conclusion

Ordinarily, because of pigeonpea's strong deep root system and massive litterfall, one would expect that intercropping it with maize would improve soil physical properties and crop yields. However, it is apparent from this study that intercropping maize with the three pigeonpea varieties used in this study does not improve soil physical properties. Instead, it increases soil bulk density beyond the prescribed range for non-restricted plant growth which may impair root growth and curtail soil aeration through reduced porosity and lead to reduction in yields. It also reduces aggregate stability due to low organic matter accumulation thereby exposing land to severe degradation. Nonetheless, it had no effect on soil texture.

Intercropping maize with the three pigeonpea varieties, especially the long duration variety (Mbaazi II), requires more water compared to maize and pigeonpea sole crops. However, this can be addressed by conserving sufficient water in the profile by ploughing back crop residues instead of feeding all of them to livestock. Finally, intercropping long duration pigeonpea with maize offers the best option for farmers in marginal areas similar to Katumani since it significantly increases maize and pigeonpea grain yields and produces sufficient maize stover and pigeonpea stalks to plough back and minimise soil degradation and feed livestock.

CHAPTER SIX

6.0. IMPACT OF CLIMATE CHANGE ON MAIZE AND PIGEONPEA YIELDS IN SEMI-ARID KENYA

Abstract

There is scarcity of detailed information on the impact of climate change on pigeonpea-maize intercropping systems in semi-arid areas to guide in formulating appropriate adaptation measures to ensure food security in the future. The objective of this study was to assess the potential impact of climate change under a range of scenarios on intercrops of maize and improved pigeonpea varieties developed and released in Kenya in recent times. Future climate data for Katumani was downscaled from the National Meteorological Research Centre (CNRM) and Commonwealth Scientific and Industrial Research Organization (CSIRO) climate models using the Statistical Downscaling Model (SDSM) version 4.2. Both models, predicted that Katumani would be warmer by 2°C and wetter by 11% by 2100. Agricultural Production Systems Simulator (APSIM) model version 7.3 was used to assess the impact of both increase in temperature and rainfall on maize and pigeonpea yield in Katumani. Simulations showed that maize yields from sole maize crop would increase by 141-150% and 10-23% in 2050 and 2100, respectively. Data indicate that intercropping maize with pigeonpea will give mixed maize yield results. Pigeonpea yields will decline by 10-20 and 4-9% by 2100 under CSIRO and CNRM models, respectively, due to the projected 2°C and 11% increase in temperature and precipitation, respectively. Intercropping short and medium duration pigeonpea varieties with maize will reduce pigeonpea yields by 60-80 and 70-90 % in the same period under the CSIRO and CNRM model, respectively. There is need to develop heat and waterlogging-tolerant pigeonpea varieties to help farmers adapt to climate change and to protect the huge pigeonpea export market currently enjoyed by Kenya.

Key words: climate change impacts, semi-arid, adaptation, maize yields, pigeonpea varieties

6.1. Introduction

Kenya is the world's fourth largest producer of pigeonpea after India, Myanmar and Malawi, of which 99% is produced in semi-arid eastern Kenya, especially Machakos, Kitui, Makueni, Meru, Lower Embu, and Tharaka-Nithi Counties. It is also grown in the drier parts of Kirinyaga, Murang'a, and Kiambu Counties in Central Kenya; and some parts of Lamu, Kilifi, Kwale, Tana River, and Taita-Taveta Counties at the Coast; mainly by small-scale resource-poor farmers (HØgh-Jensen *et al*., 2007; Audi *et al*., 2008; Nagarajan *et al*., 2008; Shiferaw *et al*., 2008; USAID, 2010; Gwata and Shimelis, 2013). Most farmers intercrop pigeonpea with maize or sorghum on the same land, either in alternate or in multiple rows, as a form of security against total crop failure (Recha *et al*., 2012).

Pigeonpea provides multiple benefits to the rural poor. Firstly, its protein-rich grain can be consumed both fresh and dry and provides a cheap source of protein for the poor farmers in the drylands. Secondly, its leaves and hulls are used as livestock feeds and the stem as fuelwood. Thirdly, it has the ability to enrich the soil through di-nitrogen fixation (Kumar *et al*., 2011), litter fall and being a deep-rooted crop, to mobilize nutrients, particularly phosphorus, from the deep soil horizons (Adu-Gyamfi *et al*., 2007; Myaka *et al*., 2006; Snapp and Silim, 2002). Fourthly, intercropping pigeonpea with cereals enhances soil coverage, reduces soil erosion and boosts cereal yields (Adu-Gyamfi *et al*., 2008; Myaka *et al*., 2006). Finally, the crop provides an assured source of income for farm families and foreign exchange for Kenya. About 7000ton of dhal (dehulled pigeonpea) and 15,000 ton of whole grain are exported annually to Europe, North America, the Middle East, and India, but this figure represents just 30% of Kenya's export potential (Audi *et al*., 2008; Nagarajan *et al*., 2008; Shiferaw *et al*., 2008; Simtowe *et al*., 2008; USAID, 2010). Thus, pigeonpea has immense untapped potential which if fully exploited could transform the lives of many communities and economies of many countries in the East African region. Maize on the other hand is the staple food for over 90% of Kenya's population and accounts for 56% of cultivated land in Kenya (Kirimi *et al*., 2011).

Despite the importance of maize-pigeonpea intercropping system in semi-arid Kenya and elsewhere in the region, their productivity has continued to decline. Maize and pigeonpea yields on farmers' fields are low, averaging 300-500 kg ha^{-1} against a yield potential of 2.5 t ha^{-1}, mainly due to non-use of improved varieties and poor farming practices, low soil fertility and climate variability (USAID, 2010; Ngome *et al.*, 2011; Gwata and Shimelis, 2013). The situation is bound to worsen in future with the expected change in climate. Temperatures and rainfall in Kenya and the rest of East Africa are expected to increase by about 2°C and 11%, respectively, by 2050 due to climate change (Thornton *et al*., 2009; Christensen *et al*., 2007; Cooper *et al*., 2008; Doherty *et al*., 2009). However, the rise in temperature may cause a substantial increase in evaporation rates, which are likely to balance and exceed any benefit from the predicted increase in precipitation (Osbahr and Viner, 2006). Thus, if not checked, climate change will undermine agricultural productivity and expose millions of people to hunger and poverty, especially in semi-arid areas where temperatures are already high and rainfall low and unreliable, agriculture is predominantly rain-fed and adoption of modern technologies is low (Herrero *et al*., 2010; Ochieng *et al*., 2016).

A lot of work has been done to quantify some of the agricultural impacts associated with projected changes in future climate using a variety of simulation models, but most of it has been carried out at global, regional and country levels hence not applicable to community-based adaptation planning (Parr *et al*., 2004; Cline, 2007; Lobell *et al*., 2008; Herrero *et al*., 2010). Similarly, despite the importance of pigeonpea in Kenya and elsewhere in the region, few studies have assessed the impact of climate change on its performance. Most studies have focused on staple and commercial crops such as maize, tea, wheat, rice, beans and groundnuts (Jones and Thornton, 2003; Kabubo-Mariara and Karanja, 2007; Herrero *et al*., 2010; FAO, 2014; Ochieng *et al*., 2016) and tomatoes (Karuku *et al*., 2014). There is a need for more detailed information on the impacts of climate change on pigeonpea-maize intercropping systems to guide in formulating appropriate adaptation measures that will increase their productivity, ensure food security in future and safeguard pigeonpea's niche markets. Therefore, the objective of this study was to assess the impact of climate change under a range of scenarios on intercrops of maize and improved pigeonpea varieties developed and released in Kenya in recent times.

6.2. Materials and methods

6.2.1. Study area

The study was conducted at the Kenya Agricultural and Livestock Research Organization (KALRO) Katumani Research Centre in Machakos County, 80 km south-east of Nairobi (37˚14´E and 1˚35´S). Katumani has bimodal rainfall pattern and receives an average of 711mm annually. The long rains (LR) occur from March to May and the short rains (SR) from October to December with peaks in April and November, respectively (Recha *et al*., 2012; Jaetzold *et al*., 2006). Inter-seasonal rainfall variation is large with coefficient of variation ranging between 45 and 58% (Keating *et al*., 1992). Temperatures range between 17 and 24^{o}C with February and September being the hottest months. The mean annual temperature is 20^{o}C. Evaporation rates are high and exceed the amount of rainfall, most of the year, except in the month of November. The mean potential evaporation is in the range of 1820 to 1840 mm per year whilst evapotranspiration is estimated at 1239 mm (Gicheru, 1996) giving an r/ETo ratio of 0.57. Katumani is 1600 m asl and the terrain ranges from flat to hilly with slopes varying from 2-20% (Gicheru and Ita, 1987). It falls under agro-climatic zone IV which has a low potential for rain-fed agriculture (Jaetzold *et al*., 2006). The dominant soils are chromic Luvisols (FAO/UNESCO, 1997; WRB, 2006), which are low in organic C, highly deficient in N and P and to some extent Zinc and generally have poor structure (NAAIAP, 2014).

Mixed farming systems involving food crops and livestock are characteristic of the region. Crops grown are predominantly drought-escaping or early maturing varieties of pigeonpea, maize, beans, sorghum and millet (Jaetzold *et al*., 2006). Due to the erratic nature of rainfall, most farmers around Katumani and the larger semi-arid Eastern Kenya prefer to intercrop maize with at least a legume (pigeonpea, beans or cowpeas) on the same land. This is often done either in alternate or in multiple rows, and is seen by many farmers as a form of security against total crop failure (Recha *et al*., 2012). Long duration pigeonpea is normally planted during SR in October-November and harvested in August-September the following year. Medium and short duration varieties can be planted and harvested in one season (Audi *et al*., 2008; Nagarajan *et al*., 2008; Shiferaw *et al*., 2008; USAID, 2010). Crop combinations, planting patterns and plant populations of pigeonpea and other crops vary considerably, depending on the soil type, climate and farmer’s preferences. However, dominant pigeonpea cropping systems practiced in the region include: pigeonpea intercropped with maize, sorghum, millets, cowpea and green gram; pigeonpea and cowpea intercrops; and maize/bean/pigeonpea intercrops (Audi *et al*., 2008; Nagarajan *et al*., 2008; Shiferaw *et al*., 2008; USAID, 2010).

6.2.2. Long-term simulation

Agricultural Production Systems Simulator (APSIM) version 7.3 was used to predict the impact of climate change on maize and pigeonpea yields in Katumani and similar areas in eastern Kenya. APSIM was preferred due to its user-friendliness, widespread application in the region and ability to make highly precise simulations/predictions once properly initialized (Dixit *et al*., 2011; Coopers *et al*., 2009, 2008; Challinor *et al*., 2007; Dimes, 2005; Micheni *et al*., 2004). The APSIM has the capacity to predict the outcome of diverse range of farming systems and management practices under variable climatic conditions, both short and long term (Keating *et al*., 2003; Dimes, 2005; Whitbread *et al*., 2010; Holzworth *et al*., 2014). It also simulates growth and yield of a range of crops in response to a variety of management practices, crop mixtures and rotation sequences, including pastures and livestock (Keating *et al*., 2003; Dimes, 2005; Whitbread *et al*., 2010; Holzworth *et al*., 2014). The model runs with a daily time step and has four key components: (1) a set of biophysical modules that simulate biological and physical processes in farming systems, (2) a set of management modules that allow the user to specify the intended management rules that characterize the scenario being simulated and controls the conduct of the simulation, (3) various modules that facilitate data input and output to and from the simulation, and (4) a simulation engine that drives the simulation process and controls all messages passing between the independent modules (Wang *et al*., 2007; Keating *et al*., 2003). It has a user interface which allows selection of input data (climate, soil, crop, management), output data from modules of interest (e.g. water balance, carbon, nitrogen and phosphorus balances, crop growth and yield) management of simulation scenarios (saving, running, retrieving, deleting), error checking (summary of scenario set-up inputs and run time operations) and output analysis via software links for viewing output data in text file, Excel or graphs (Keating *et al*., 2003; Dimes, 2005; Whitbread *et al*., 2010; Holzworth *et al*., 2014).

APSIM requires site-specific data on latitude and longitude, soil texture and depth (m), slope (%) and slope length (m); climate (daily maximum and minimum temperature (^{o}C), daily solar radiation (MJ/m^2) and daily rainfall (mm); crop growth and phenology (crop type and cultivar name, maturity type, date of 50% flowering and total number of leaves, total biomass at harvest (kg ha^{-1}), grain yield (kg ha^{-1}), final plant population (plts m^{-2}), N and P contents of plant parts, biomass at anthesis (kg ha^{-1}), population at thinning (plts m^{-2}), date of physiological maturity (black layer) and maximum leaf area index (LAI); soil water, nitrogen and phosphorus; residues and manure (crop and manure type, dry weight (kg ha^{-1}), N, C and P content (%), ash content, and ground cover (%); and management (date of all operations e.g. sowing, harvest, thinning, weeding, tillage and fertilizer applications, sowing depth and plant population, type, rate and depth of fertilizer application, and type (hoe, disc, harrow etc.) and depth of tillage) to run. These data can be obtained from field trials or secondary sources. However, this study used the APSIM that had been calibrated and validated for Katumani semi-arid area by Okwach and Simiyu (1999) and Okwach (2002).

Daily minimum and maximum temperature, solar radiation and rainfall data for Katumani for the near (2050) and far (2100) future scenarios were downscaled from the National Meteorological Research Centre (CNRM) and Commonwealth Scientific and Industrial Research Organization (CSIRO) climate models using the Statistical Downscaling Model (SDSM) version 4.2 (Wilby and Dawson, 2007) and uploaded in APSIM. Both models, CNRM and CSIRO, have predicted a 1-2.5°C and 10% increase in temperature and rainfall, respectively, by the end of the century (2100) which is consistent with the Intergovernmental Panel on Climate Change (IPCC)'s prediction of 3.2°C and 11% rise in temperature and rainfall, respectively, for Kenya and the rest of East Africa by 2100. SDSM is a decision support tool for assessing local climate change impacts using a robust statistical downscaling technique. It is a hybrid of a stochastic weather generator and regression-based downscaling methods and facilitates the rapid development of multiple, low-cost, single-site scenarios of daily surface weather variables under current and future climate (Wilby *et al*., 2002). The tool has been used extensively with remarkable success (Wilby *et al*., 2002; Goldstein *et al*., 2004; Nguyen *et al*., 2006; Dibike *et al*., 2007; Nguyen *et al*., 2007; Rakhshandehroo *et al*., 2015).

The following eight cropping systems were simulated using the downscaled climate data: (1) Sole short duration maize crop, (2) Sole short duration pigeonpea crop, (3) Sole medium duration pigeonpea crop, (4) Sole long duration pigeonpea crop, (5) Short duration pigeonpea-maize intercrop, (6) medium duration pigeonpea-maize intercrop and (8) long duration pigeonpea-maize intercrop. The model was run to simulate 50 and 100 years under these cropping systems. The growing season was defined to start after five consecutive days with volumetric soil water content in the top 100 cm above 70%. The end of the season was deemed to occur when soil water content fell below 50% for eight consecutive days. KDVI maize variety was used to represent all early maturing (120 -150 days to mature) and high yielding maize varieties recommended for semi-arid conditions. Similarly Mbaazi I, Kat 60/8 and Mbaazi II pigeonpea varieties were used to represent short (100 days to mature), medium (150 days to mature) and long (180-220 days to mature) duration pigeonpea varieties, respectively. Pigeonpea was planted at spacings of 90 cm x 60 cm, 75 cm x 30 cm and 50cm x 25cm for the long, medium and short duration varieties, respectively, whilst maize was planted with Triple Super Phosphate (TSP) fertilizer at the recommended rate of 40 kg P_2O_5 ha^{-1} at spacing of 90 cm x 30 cm. Other agronomic practices were adopted as currently practiced by farmers such as early planting, timely weeding and thinning.

6.3. Results and discussion

6.3.1. Maize yields

Long-term yields of maize under variable and changing climate in Katumani are presented in Figure 3. Prospects for increased maize production under sole maize crop in Katumani (Machakos County) are high, both in the near (by 2050) and far (2100) future scenarios under the two climate models, CNRM and CSIRO models. Relative to baseline yield of 500kg ha^{-1}, maize yields are expected to increase by 141 and 10% in 2050 and 2100, respectively, under the CSIRO model. The CNRM model was more optimistic and predicted maize yield increases of 150 and 23% in 2050 and 2100, respectively, under maize sole crop. The increase in yield could be attributed to the projected increase in rainfall of 20-40 mm per year by 2100. The predictions corroborate reports by Waithaka *et al*. (2013) that Kenya's breadbasket could shift from the Rift Valley to semi-arid eastern and northeastern Kenya by 2050. Intercropping maize with pigeonpea will give mixed results. According to the CSIRO model, maize yield will increase by 18 and 15% under maize/Mbaazi I and maize/Mbaazi II intercrops, respectively, in 2050. However, yields under maize/Kat 60/8 intercrop will decline by 4% in the same period. A similar trend will be observed in 2100 where intercropping maize with pigeonpea will reduce maize yields by 10-20% under the CSIRO model. The projected decline in maize yield could be attributed to high evapotranspiration due to anticipated rise in temperature. According to Thornton *et al*. (2009), high evapotranspiration is bound to cause water scarcity which will adversely affect maize growth. These results agree with Herrero *et al*. (2011) who predicted maize yield losses of upto 50% in the ASALs due to climate change, albeit under the Hadley model. Thornton *et al*.(2009), Jones and Thornton (2003) and Downing (1992) have also predicted a significant decline in yields of maize and other food crops in the East African region due to the same phenomenon. However, encouraging farmers to adopt irrigation, conservation agriculture, seed priming and in-situ water harvesting among other adaptation measures (GoK, 2013) could arrest the decline in maize yield.

Conversely, according to the CNRM model, intercropping will increase maize yields by 28 and 11% under maize/short duration pigeonpea and maize/medium duration pigeonpea intercrops, respectively, by 2050. Maize yields under maize/long duration pigeonpea intercrop will declined by 16%. However, maize yields will increase by 18, 13 and 4% under maize/short duration pigeonpea, maize/medium duration pigeonpea and maize/long duration pigeonpea intercrops, respectively, in the far future (2100). Because of these conflicting results, it is difficult to generalize the impacts of climate change on maize yields from maize/pigeonpea intercrops in Katumani and similar areas in the country. Further simulations involving many GCM model X scenario combinations are therefore required to establish the correct direction of change in maize yields under these systems, whether they will increase or decrease. Meanwhile, the results corroborate observation by Herrero *et al*. (2011) that climate change impacts on maize yields depend on the emission scenario, crop model and the Global Climate Change Model (GCM) used.

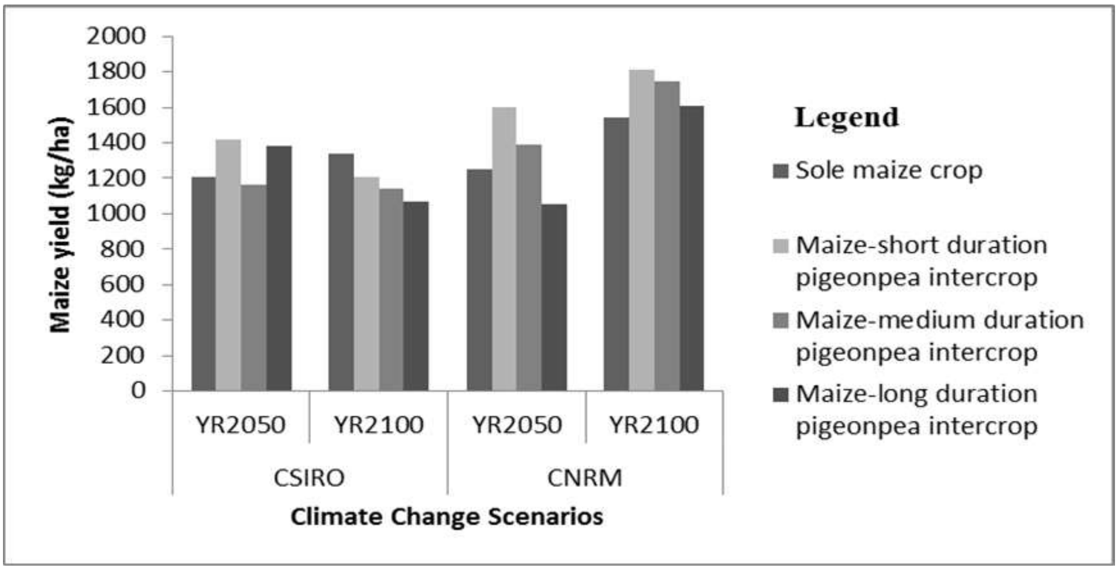

Fig.3. Long term effect of pigeonpea on maize yield in Katumani under variable and changing climate

6.3.2. Pigeonpea yields

Long-term yields of pigeonpea under variable and changing climate in Katumani are presented in Figure 4. Unlike maize, both CSIRO and CNRM models predicted decreased pigeonpea yields in Katumani in the near and far future. Yields from sole pigeonpea crop will decline by 10-20% and 4-9% under CSIRO and CNRM models, respectively, by 2100. Intercropping short and medium duration pigeonpea varieties with maize will reduce pigeonpea yields by 60-80% and 70-90% under the CSIRO and CNRM model, respectively. However, long duration varieties will yield highest under the two Global Climate Change Models (GCMs) irrespective of the cropping system, but the yields will be much lower than the potential yield of over 2tha^{-1} obtained from research experiments and large-scale commercial farms in the region. The decline in pigeonpea yields could be attributed to the projected 2°C and 11% increase in temperature and rainfall, respectively. Pigeonpea is a Carbon-3 (C3) plant and is highly sensitive to waterlogging, therefore, existing pigeonpea varieties may not thrive in the predicted hotter and wetter conditions (Chauhan *et al*., 1997; Perera *et al*., 2001). High temperatures reduce the rate of photosynthesis in legumes due to their C3 photosynthesis cycle leading to low yields (Black and Ong, 2000; Lindquist *et al*., 2005). Waterlogging blocks oxygen supply to roots which hamper permeability (Else *et al*., 1995), delays flowering and reduces vegetative growth, photosynthetic rate, biomass and grain yield in pigeonpea (Sarode *et al*., 2007; Takele and Mcdavid, 1995). Short duration pigeonpea varieties like Mbaazi I are more prone to the risk of yield reduction due to waterlogging compared to the medium and long duration varieties such as Kat 60/8 and Mbaazi II, respectively (Matsunaga *et al*.,1991). Therefore, farmers in Katumani and similar areas in the country may have to rethink their dependence on pigeonpea going into the future. Scientists also need to start breeding for more heat and waterlogging-tolerant varieties to save the livelihoods of thousands of resource-poor households in ASALs and safeguard the huge pigeonpea export market that Kenya currently commands.

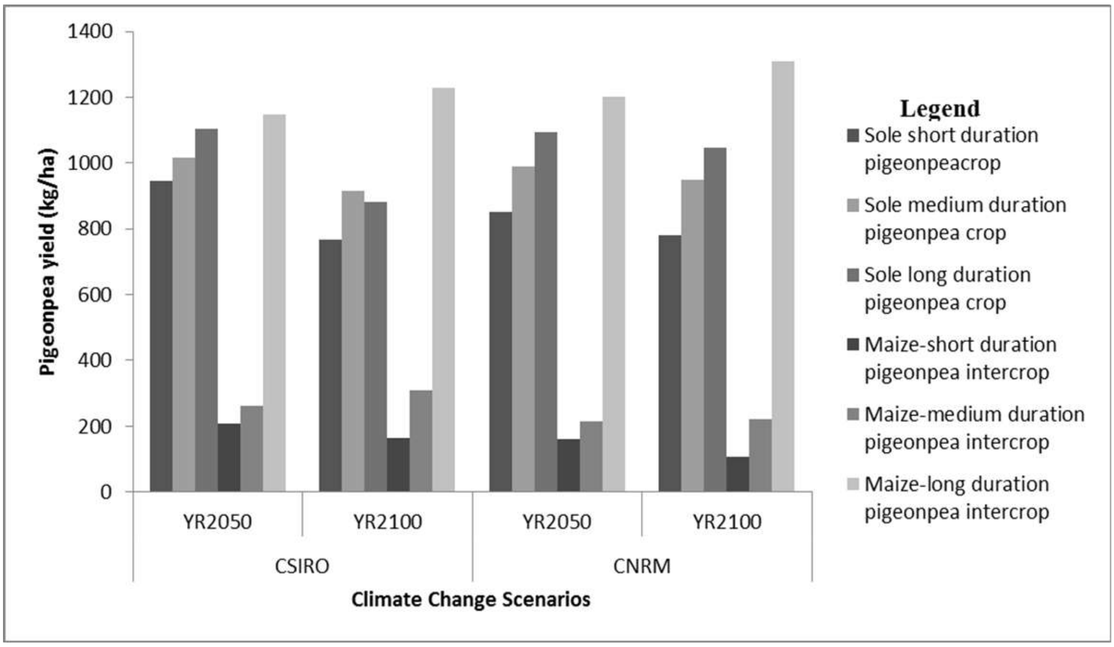

Fig.4. Projected pigeonpea yields for Katumani in the near and far future

6.4. Conclusion

Prospects for growing maize in Katumani are high both in the near (2050) and far (2100) future. However, pigeonpea production will be negatively affected by climate change going forward due to pigeonpea's susceptibility to high temperatures and waterlogging. Therefore, farmers in the ASALs need to rethink their dependence on pigeonpea whilst national plant breeding programs need start developing heat and waterlogging-tolerant varieties to help thousands of resource-poor households in ASALs to adapt to climate change and protect the huge pigeonpea export market that Kenya currently enjoys.

CHAPTER SEVEN

7.0. GENERAL DISCUSSION, CONCLUSIONS AND RECOMMENDATIONS

7.1. General discussion and conclusions

Most small-scale farmers in Kenya grow the traditional, tall, long-duration landraces and use inadequate amounts of organic manure and virtually no inorganic fertilizers because they not only believe that legumes do not respond to inorganic fertilizers under poor rainfall and soil moisture conditions in the growing areas, but also lack capital to purchase these inputs. As a result, they obtain very low yields (<0.5 t ha^{-1}). However, it is apparent from this study that growing improved pigeonpea varieties such as Mbaazi I, Kat 60/8 and Mbaazi II, can increase pigeonpea yields several-folds without any nutrient input, provided farmers use certified seeds, plant early, at correct spacing, weed adequately, and spray against pests and diseases.

Similarly, because of the erratic nature of rainfall in pigeonpea-growing areas, most farmers routinely intercrop pigeonpea with a cereal (maize, sorghum or millet). This is often done either in alternate or in multiple rows, and is seen by many farmers as a form of security against total crop failure in case of poor rainfall. However, this study has demonstrated that intercropping short and medium duration pigeonpea varieties with maize in a water-deficit environment like Katumani is not feasible. It depresses pigeonpea grain and biomass yield and can only work for the long duration pigeonpea varieties because of their phenological complementarity with maize.

Like the rest of sub-Saharan Africa where intercropping is widely practiced, pigeonpea farmers in Kenya harvest not only the grain but the entire aboveground biomass of both the cereal and pigeonpea and export them to homesteads for multiple uses such as livestock feed, thatch and fuelwood. This practice mines the soil. Results from this study indicate that ploughing back crop residues improves soil aggregation and water retention and increases maize and pigeonpea yields significantly. Intercropping maize with long duration pigeonpea and ploughing back 4 t ha^{-1} of crop residues offers the best option since it gave higher maize (1.9 t ha^{-1}) and pigeonpea (1.4t ha^{-1}) grain yields per season and over 4 t ha^{-1} of crop residues. Farmers are therefore encouraged to adopt it and balance between competing uses for the crop residues to increase crop yields.

As indicated in Chapter One, crop production in Kenya is seriously undermined by low nitrogen (N) in most soils across the country. For instance, in the densely populated and heavily cropped County of Kisii in southwestern Kenya, aggregate N losses are estimated at 112 kg N ha^{-1} yr^{-1} whilst in central Kenya highlands, annual net N depletion rate exceeds 30 kg N ha^{-1}. The situation is worse in semi-arid lands. All the three pigeonpea varieties tested in this study (i.e. Mbaazi I, Kat 60/8 and Mbaazi II) are good N fixers and do not require *Rhizobia* inoculation. Farmers are therefore encouraged to adopt them to supply N and increase cereal yields.

Finally, maize yields in Katumani are likely to increase both in the near (2050) and far (2100) future due to climate change. Katumani will register yields of over 1.2 t ha^{-1} compared to baseline yields of 0.5 t ha^{-1} provided farmers use certified seeds and plant early among other sound agronomic practices. The highest maize yield will be realized by intercropping maize with either Mbaazi I or Kat 60/8. However, pigeonpea yields will be affected negatively by climate change both in the near and far future. Yields will decline by over 60% by 2050 due to pigeonpea's sensitivity to high temperatures and waterlogging.

7.2. Recommendations

Firstly, given that Kenya is the fourth largest producer of pigeonpea in the world after India, Myanmar and Malawi and most of it is produced by smallholder farmers who consume it and export the surplus to India and the Middle East, national plant breeding programs need to start developing heat and waterlogging-tolerant pigeonpea varieties to help farmers to adapt to climate change and to protect these export markets. Secondly, apart from the three pigeonpea varieties (i.e. Mbaazi I, Kat 60/8 and Mbaazi II) investigated in this study, efforts must be made to evaluate many other newly developed pigeonpea varieties for their nitrogen fixation under field conditions inorder to optimize their contribution to soil fertility improvement. Lastly, the newly developed pigeonpea varieties need to be evaluated for their compatibility with sorghum and finger millet among other cereals in order to increase food security and help thousands of vulnerable households in ASALs to diversify crop production and adapt to climate change.

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9.0. APPENDIX: LIST OF JOURNAL MANUSCRIPTS IN DIFFERENT STAGES OF PUBLICATION IN INTERNATIONAL PEER-REVIEWED JOURNALS

1. Kwena, K., Karuku, G.N., Ayuke, F.O. and Esilaba, A.O. (2017). The menace of nitrogen deficiency in semi-arid Kenya: can pigeonpea fix it? *East African Agricultural and Forestry Journal* (Under review, submitted on 25.05.2017).
2. Kwena, K., Ayuke, F.O., Karuku, G.N. and Esilaba, A.O. (2017). The curse of low soil fertility and diminishing maize yields in semi-arid Kenya: can pigeonpea play savior? *Tropical and Subtropical Agroecosystems*, 20 (2017):263-278.
3. Kwena, K., Ayuke, F.O., Karuku, G.N. and Esilaba, A.O. (2018). No rain but bumper harvest: the magic of pigeonpea in semi-arid Kenya. *International Journal of Agricultural Resources, Governance and Ecology, 14(2):181-203.*
4. Kwena, K., Karuku, G.N., Ayuke, F.O. and Esilaba, A.O. (2018). Impact of climate change on maize and pigeonpea yields in semi-arid area of Katumani-Kenya*.* *Climatic Change* (Under review, submitted on 25.04.2018).