EFFECT OF INORGANIC FERTILIZERS AND PLANTING DENSITY ON GROWTH AND YIELD OF SELECTED MAIZE VARIETIES IN EASTERN RWANDA

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DEPARTMENT OF PLANT SCIENCE AND CROP PROTECTION
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This is my original work and has not been presented for a degree in any other university.

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ABBREVIATION AND ACRONYMS

ANOVA	:	Analysis of Variance
ASI	:	Anthesis Silking Interval
Av. P :	:	Available Phosphorus
CIMMYT	:	Centro internacional de Mejoramiento de Maiz y Trigo (The international Maize and wheat improvement Center)
CIP	:	Crop Intensification program
CV	:	Coefficient of variation
ESA	:	Ethiopian Seed Association
FAO	:	Food and Agriculture Organization of the United Nations
FY	:	Farm Yield
IITA	:	International Institute of Tropical Agriculture
LSD	:	Least Significant Difference
LUC	:	Land Use Consolidation
MINAGRI	:	Ministry of agriculture, animal resources
NISR	:	National Institute of Statistics of Rwanda
NPK	:	Nitrogen, Phosphorus and Potassium
OPV	:	Open Pollinated Variety
pH	:	potential of Hydrogen
RAB	:	Rwanda Agriculture and Animal Resources Development Board
RCBD	:	Randomized Complete Block Design
RDB	:	Rwanda Development Board
TN	:	Total Nitrogen
UoN	:	University of Nairobi
V8	:	Vegetative growth 8th leaf collar visible
VT	:	Vegetative growth last branch of Tassel well visible
YP	:	Yield Potential

DEDICATION

To my wife Uwimana Jeanne d’Arc, my son Mugisha Basil and my daughter Irakoze Charité for their prayers, endurance and love during my study.

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ABSTRACT

Maize is a priority staple food crop in Rwanda and helps farmers to generate income through the surplus sales; despite its low yields of 2.2 t/ha compared to 5.5t/ha worldwide. With the aim to participate in maize grain yield increase, the specific objectives of this research were: (1) to determine the effect of varying N, P, and K fertilizer rate on growth and yield of selected maize varieties and (2) to determine the effect of varying plant density on growth and yield of selected maize varieties. The study was conducted in eastern Rwanda in Bugesera district in two different sites. Field layout was RCBD with 3 replications under 2 x 3 x 4 factorial arrangement. Plant material were RHM 104 hybrid (V1) and ZM 607 OPV (V2). The planting densities were 83,334 plants/ha (D1), 68,334 plants/ha (D2) and 53,334 plants/ha (D3: control recommended by breeders). The fertilizer rates per hectare were NPK 175-68-68 (R1), NPK 150-59.5-59.5 (R2), NPK 97-51-51 (R3) and the control without NPK application (R4). The crop was gown from October 2017 to March 2018. Planting was done in a plot of 5 m x 4.5 m with 2 seeds/hill which were later thinned to one plant/hill. The distance between rows was 0.75 m with 32 hills/row, 26 hills/row and 20 hills/row for D1, D2 and D3 respectively. The data were analyzed using genstat 15th edition and mean were separated using LSD. Significant difference was observed between sites on plant height, ear height, number of ear harvested, grain moisture at harvesting, and grain yield. Observed interactions were planting density x fertilizer rate on days to anthesis and silking; variety x planting density x fertilizer rate on ear height, site x variety x fertilizer rate on grain moisture at harvesting and variety x planting density on grain yield. RHM 104 hybrid variety tolerated higher plant population than ZM 607 OPV and gave the highest grain yield, above 10 t/ha, with planting density of 68,334 plants/ha. This research revealed the possibility to increase grain yield through increased planting density up to 68,334 plants/ha using RHM 104 hybrid variety. Further research is needed toward site specific fertilizer recommendation and crop management for maximum agronomic efficiency. It is necessary to undertake other researches on all varieties recently released by RAB to determine varieties which are most tolerant to high planting densities and therefore giving highest grain yields.

CHAPTER 1: INTRODUCTION

1.1. Background

Maize (*Zea mays*) is a major food security and income generating crop for small scale farmers in Rwanda. Although maize crop farming has not yet reached intended yield potential in the country, it ranks first among grain crops in annual production (RAB, 2013). Different government strategies especially Crop Intensification Program (CIP) and Land Use Consolidation (LUC) contributed remarkably in increasing maize production in Rwanda from 97,251 t in 2005 year to 668,000 t in 2013 (Context Network, 2016) and slightly reduced to 580,000 t in 2016 (Indexmundi, 2017). Maize cultivated area expanded from 102,000 ha in 2007 to 223,414 ha in 2011 (RDB, 2015) and its yield increased from 0.7 t/ha in 2007 to 2.2 t/ha in 2013 (Factfish, 2016).

Improved hybrid seeds are imported by regional seed companies such as Kenya Seed with hybrids H628, H629 and DH04, SeedCo with hybrids SC 719, SC 637, SC 513 and SC 403, finally PANNAR with hybrids PANNAR 691, PANNAR 4M21, PANNAR 53 and PANNAR 67 from Kenya, Zambia and South Africa respectively. In addition, scientists have bred local hybrid varieties to respond to Rwanda's government intention of promoting hybrid cultivation country wide at 100%. It was expected to put to the market first locally produced hybrids by 2019 (Context Network, 2016). In Rwanda, fertilizer recommendation in maize cultivation is 1 to 10 t/ha for organic manure and 250 to 300 kg of NPK 17.17.17 for mineral fertilizer, with a side dressing fertilizer of 100 kg/ha of urea (46% N) (Kelly and Murekezi, 2000). With these fertilizer amounts, mineral fertilizer application per hectare is equivalent to 97 kg of N, 51 kg of P_2O_5 and 51 kg of K_2O.

1.2. Problem statement

National level fertilizer use in Rwanda is low at 30 kg/ha instead of 50 kg/ha recommended for green revolution (MINAGRI, 2014). Maize yield gap is high (RAB, 2013) and is estimated to be more than 3 t/ha (Reddy, 2016; Niyitanga *et al*., 2015). Certain barriers make farm yield to be lower than the yield potential these include lack of access to sufficient intensive agriculture inputs such as improved hybrid seeds, fertilizers and pesticides (Fischer *et al*., 2014); declining of available land per person; degraded soils (Reddy, 2016) and lack of irrigation facilities (Aylward *et al*., 2015). Fortune of Africa (2016) identified Rwanda maize production constraints including limited investment in maize production, lack of sufficient well skilled agronomists to train farmers on improved maize production technologies and insufficient research on maize growing techniques. In addition, the World Bank (2014) identified specific constraints impeding maize production in Rwanda namely lack of hybrid seeds (hybrid seed were imported at 100%), low quality output processing technologies, high level of post-harvest losses, high transport cost on imported agricultural equipment and small size farms.

Maize hybrid varieties with high genetic yield potential respond well to optimum fertilizer input and plant population in favorable environmental conditions. Good response of maize to fertilizer, especially to nitrogen (N), both in biomass and grain yield, is well documented (Ali *et al*., 2002; Shapiro and Wortmann, 2006; Arif *et al*., 2010; Dawadi and Sah, 2012 and Khan *et al*., 2014). Most of these authors found the highest yield at N level of between 140 and 160 kg per hectare and planting density of between 60,000 and 80,000 plants per hectare compared to an average of 40,000 plants per hectare in farmers' fields. Currently, improvement of maize yields is being done considering maize limited genetic tillering capacity compared to other cereals. Consequently, increasing the number of ears/ha as a means of maize production improvement is not possible unless you increase plant population (Abuzar *et al*., 2011) and

(Fischer *et al.*, 2014). In their activities, breeders in Rwanda develop maize hybrids using a static planting density of 53,334 plants per hectare with a spacing of 0.75 m x 0.25 m which is not necessarily the optimum agronomic plant population for these hybrids. Fertilizer recommendation are blanket based on agro-ecological zones (Kelly and Murekezi, 2000). Maize yield potential, in tropical environment, under irrigation with high input level, range between 6 and 15.6 t/ha and 3.5 to 10.5 t/ha with intermediate input level (Jones, 2003). In Rwanda, maize expected yield potential in 2017, under Crop Intensification Program (CIP) conditions, was 6.5 t/ha (from a basic of 1.9 t/ha in 2010) if hybrid seeds would constitute 80% of planted maize in combination with other intensive agriculture inputs (Kathiresan, 2011). In contrast, maize high farm yield achieved in USA is as high as 11 t/ha (Fischer *et al.*, 2014).

1.3. Justification

Maize is a priority crop in Rwanda due to its potential in the economy of the country. A big part of maize production in Rwanda, up to 52%, is used for household consumption (Trócaire, 2014). Furthermore, maize has become one of the agricultural exchange products in Rwanda. In 2016, the country imported 125,000 MT of maize and exported 10,000 MT (mainly of maize flour) with a domestic consumption of 700,000 MT (Indexmundi, 2017).

The quantity of NPK fertilizer and planting density recommended in maize cultivation in Rwanda is insufficient for maximum yield potential farm yield. Scientific investigation is necessary to determine optimum NPK fertilizer and planting density to reach yield potential for new maize hybrids recently released by Rwanda Agriculture and animal resource development Board (RAB).

The government of Rwanda is focused on increasing maize yield to reduce maize grain and seed importation to ensure self-reliance and sustainable food security. As such, it is even possible to reach a yield higher than the target if maize is grown in more intensified conditions.

The interaction of increased planting density and mineral fertilizers with good genetic capacity hybrids resulted in increased yields in various parts of the world (Fischer *et al*., 2014). This need to be determined in Rwandan conditions for confirmation before being used by various stakeholders including farmers, policy makers and academicians.

1.4. General objective

The general objective of this research was to increase maize productivity through increased N, P and K fertilizers and increased planting density in eastern Rwanda, by evaluating recently released new maize hybrid.

1.5. Specific objectives

1. To determine the effect of varying N, P, and K fertilizers rate on growth and yield of selected maize varieties.
2. To determine the effect of varying plant density on growth and yield of selected maize varieties.

1.6. Hypotheses

From the objectives above, the following hypotheses were formulated:

1. Growth and yield of selected maize varieties do not increase with increasing fertilizer rates.
2. Growth and yield of selected maize varieties do not increase with increasing planting density.

CHAPTER 2: LITERATURE REVIEW

2.1. Ecology, biology and importance of maize

2.1.1. Ecology

Maize (*Zea mays* L.) can be grown in tropical and temperate climates from 45^0 S to 55^0 N latitude, (Chandrasekaran *et al*., 2010) with a favorable climate below 47^0 latitude (Jones, 2003). It grows at an altitude up to 2500 m (Chandrasekaran *et al*., 2010), in a temperature range not less than 10^0C, a minimum for germination (Plessis, 2003) and not higher than 35 ^{0}C, beyond which pollen germination declines. Temperatures below 15^0 C delay anthesis and silking (Chandrasekaran *et al*., 2010). The best growing temperatures are between 21 and 27 ^{0}C (Jones, 2003). At maturity, a single maize plant could have used around 250 L of water without moisture stress (Plessis, 2003). Maize rainfall requirements are 500 to 700 mm well distributed per season for optimum growing. Maize is very sensitive to water logging at the level of losing 40 - 45 % of its yield in three days of continuous inundation. Maize grows better in well-drained sandy loam to silt loam texture with a pH ranging from 5.5 to 7.5 (Chandrasekaran *et al*., 2010).

2.1.2. Biology

Maize (*Zea mays* L.) belongs to the family of poaceae. Based on archeological records discovered in Mexico, the known maize origin, it is accepted that maize is one of the first crops domesticated by humans since 7000 years ago (Bajaj, 1994) and (Ranum *et al*., 2014). The first grown ancestral crops are nowadays a wild grass known as teosinte (Abbassian, 2006). Maize has various growth stages (table 1) which are linked with specific requirements in nutrients application, water supply and many other crop management practices (ESA, 2014). The growth of maize is subdivided into 11 stages that can be put into 2 groups such as Vegetative growth (V) and Reproductive growth (R). They are named vegetative stage V1, V2, V3, … Vn, Vt with Vn standing for the last stage before Vt (tasseling stage) and R1, R2, …, R6 standing for reproductive stage 1 to 6.

Table 1: Growth stages of maize

No	Stage	Description
0	VE	Coleoptile emerges from the soil surface. Under warm, moist conditions maize emerges 6 to 10 days, but under cool or dry conditions it takes 2 weeks or longer
1	V1	1^{st} leaf collar visible
2	V2	Second leaf collar visible
3	Vn	n leaf collar visible. Usually n varies from 16 to 22. Around 10 leaves ear shoot develops at 6^{th} and 8^{th} nodes, around 12 leaves ear developing rapidly and ovule determined. Maize uses more than half of its N requirement from V8 to VT. It is about 30 days after planting depending on environmental conditions (temperature and moisture). The side dressing must be done taking into consideration these stages to maximize maize growth
4	VT	The last branch of tassel well visible (different from anthesis when the pollen is being shed), at around 14 leaves tassels are near full size, 1 or 2 ear develops quickly
5	R1	Silking takes place: 50% of plants have visible silks which continue to grow until fertilized, stem elongation stops
6	R2	Blister stage: Kernels have clear fluid, visible embryo, starch accumulation begins, cob and husk fully developed
7	R3	Milk stage: Kernels have a white, milky fluid.
8	R4	Dough stage: Kernels have a white paste of bread dough consistency. The embryo is wide almost half of kernel.
9	R5	Dent stage: The kernels upper parts filled with solid starch and, gains dented for dent type. A "milk line" visible in both flint and dent types.
10	R6	Physiological maturity: black layer visible at the base of the grain. Grain moisture is about 35%.

Source: Adapted from Jones (2003); Lafite, (1993); Plessis (2003) and Butzen (2016).

Each stage is determined based on the highest visible leaf collar and when 50% of all plants have reached the stage because all plants do not reach a phase at the same time (Darby and Lauer, 2013).

2.1.3. Importance

Maize is one of the most cultivated cereals crop in the world together with rice and wheat. Nowadays, the global maize production is higher than any other cultivated cereal. Its total world production is estimated at around 870 Mt (Fischer *et al*., 2014). A great part of this production is used for feeds: up to 65% and low portion up to 15% help for human food consumption especially in low income countries, and the remaining part of 20 % is used in different industrial applications (Abbassian, 2006). Maize is globally consumed by 200 million people directly as a staple food (Plessis, 2003). In high income countries, a great part of produced maize is used for biodiesel production as well as animal feed and other industrial uses. The United States of America (USA) is a major maize producer and contribute up to 40% of global maize production, used mainly for animal feed (Nafziger, 2017). The production of ethanol consumes 120 Mt, the amount equivalent to 15% of total world maize production (Fischer *et al*., 2014). Maize grain production must augment in order to satisfy its various and increasing demand. The projection of maize global production based on the demand is 1,051 million metric tons (FAO, 2017).

2.2. Maize yield potential

Yield potential (YP) is defined as yield of a crop when grown in an environment in which it is adapted without constraints of crop yield limiting factors like water, nutrients, air, temperature and solar radiation (Wolf, 1995) and (Jan *et al*., 2007) and pest and diseases well controlled (Evans and Fischer, 1999). Some authors interchange yield potential with potential yield giving both terms the same definition (Fischer *et al*., 2014). Maize YP is variable depending on the variety, agro-ecological zone and management practices such as planting density, fertilization and pest and disease control. The measurement of potential yields is done using plant growth models based on past weather data and determining appropriate management practices (adequate planting date, planting density, biological maturity, efficient soil moisture and supplementary irrigation) (Pasuquin and Witt, 2007). It is difficult for farmers to reach the potential yield due to lack of fulfillment of all requirements for a maximum plant growth. The difference between the YP and farm yield (FY) is called Yield Gap (YG). The YG is high in farmers of low income countries compared to farmers of high income countries. The average YG is 36% and 400% between farmers in high income countries and farmers in low income countries. A FY of 11.4 t/ha and a YP of 15 t/ha are reported in USA (Fischer *et al*., 2014) and a FY of 5.5 t/ha worldwide (VIB, 2017) while a FY of 1.5 t/ha and YP of 7.1 t/ha have been reported in Eastern Africa (Fischer *et al*., 2014).

2.3. Maize in Rwandan and East African economy

Agriculture is like a backbone in Rwandan economy where it can contribute up to 34 % in gross domestic product (GDP) (MINAGRI, 2014). Maize was listed in priority crops of government of Rwanda and strengthened through Crop Intensification Program (CIP) since 2007 (Broek and Byakweli, 2014). Recently, maize has become an income generating crop for small scale farmers in Rwanda (RAB, 2013). Maize has been categorized as priority crop due to its potential to reduce poverty, produce animal feed especially for poultry and fish, substitute food imports, fight hunger (easy storage) and increase food security (Context Network, 2016). A big part of maize production in Rwanda, up to 52%, is used for household consumption (Trócaire, 2014). Furthermore, maize has become one of agricultural exchange products in Rwanda. In 2016, the country imported 125,000 MT of maize and exported 10,000 MT (mainly maize flour) with a domestic consumption of 700,000 MT (Indexmundi, 2017). More than 300 million of Africans use maize as staple food and they grow it at approximately 24 % of crop land in Africa (VIB, 2017). In Eastern Africa, maize is the most important staple food where the annual total consumption range between 50 kg and 129 kg per person (Kornher, 2018).

2.4. Constraints to maize production

Maize production is globally handicapped by various constraints which reduce vegetative growth by decreasing leaf area hence reduced light interception and productivity. These constraints are low soil fertility and drought stress (Lafite, 1993 and Fischer *et al*., 2014), insufficient agricultural input, inadequate crop management (Reddy, 2016). Moreover, maize production is also challenged by pests and diseases and herbicide resistant weeds (Fischer *et al*., 2014). These constraints are specific in various locations all over the world. In United State of

America maize producers are facing weaknesses of lacking crop rotation (maize following maize), development of glyphosate resistant weeds, emergence of *Bacillus thuringiensis (Bt)* transgene resistant maize rootworm and moderate loss of nitrogen fertilizer in the environment (Fischer *et al*., 2014). Genetically modified organism (GMO) and *Bt* technologies contributed to yield improvement up to 916 kg in USA, where GM maize is being used and adopted at high extent with both *Bt* and herbicide resistance and / tolerance genes (Fernandez-cornejo *et al*., 2014). In Sub-Saharan Africa, major problems contributing to yield loss are soils fertility constraints up to 44 %, drought stress up to 18 %, weeds especially striga up to 19 % and post-harvest handling up to 17 % (Fischer *et al*., 2014). In western Kenya, the reported major constraints of farmers in maize seed production are late harvesting, *Striga helmonthica* weed infestation that may lead to complete yield loss and low soil fertility (Wambugu *et al*., 2012).

In Rwanda, maize production constraints for small scale farmers, are lack of access to modern agricultural inputs, degraded soils, lack of irrigation facilities (Aylward *et al*., 2015) and farmers limited technical skills. Fortune of Africa (2016) identified Rwanda maize production constraints namely insufficient investment in maize production, limited number of agronomist to assist farmers in maize production and insufficient research on maize crop. Furthermore, particular attention is needed to address lack of hybrid seed (100% of planted hybrids are imported), disease and pest (Maize lethal necrosis and fall army worm), less competitive processing technologies, high rate of post-harvest losses, high transport cost to and from the sea (agricultural mechanization machine and pesticide are imported overseas) and small size farm (World Bank, 2014).

Irrigation is a common constraints in maize production for small scale famers, due to its high cost and lack of accessibility to finance (Aylward *et al*., 2015). Maize use high amount of water to give higher yields. Its growers generally use full irrigation to obtain best yields (Plessis, 2003). It is reported that supplemental irrigation is needed even in moderate to high rainfall regions of Brazil and Argentina (Fischer *et al*., 2014). Maximum yield depends on use of adapted high yielding varieties, grown in the optimum environment (weather, soil and water quality) with crop management practices realized adequately (Payero, 2008). The grain yield of maize is highly sensitive to drought especially during flowering period (anthesis and silking) and may be significantly reduced if severe drought affect maize at reproductive stage one (Wolf, 1995).

2.5. Improvement of maize production

High maize farm yield is a result of various efforts used by commercial agricultural farms in different maize agro-ecological zones around the world. The major common points in those farms are the use of high yielding hybrid varieties, high planting density, adequate use of fertilizers, and efficient pests and diseases control. In certain parts where water supply to maize crop is not enough, irrigation is key to high maize yields.

2.5.1. Effect of improved maize hybrid varieties on maize yield

As quoted by Brewbaker (2003), “good seed doesn’t cost, it pays”. Maize hybrid varieties or cultivars have a great influence in yield obtained on the farm. The choice of cultivars should be done very carefully to use those which are well adapted with a high known yield potential (Plessis, 2003). In USA, as global first maize producer, farmers use single cross hybrids and annual maize (corn is the most used term in USA) contest is conducted with excellent hybrids as key component among others (Brewbaker, 2003). A high number of maize hybrids cultivated in United State of America, especially in Iowa where up to 90 % of all hybrid seeds are genetically modified organism with herbicide and insect resistant traits (*Bt* genes) (Fischer *et al*., 2014).

In sub-Saharan Africa (SSA), the effort for high maize yields seeds is oriented towards alleviation of specific constraints in maize production in the region. The focus is put on new improved varieties and hybrids with resistance and tolerance to drought, low soil fertility, heat, diseases such as Maize Lethal Necrosis (MLN) and pests affecting a large target of maize production areas (CIMMYT, 2016). Promising results are available in SSA where drought tolerant (DT) maize is able to provide extra income to small holder families in Zimbabwe, up to 240 US$ per hectare without additional cost (Johnson, 2017). Maize breeding work for hybrids seed production is young in Rwanda hence hybrids seeds were exclusively imported from regional countries including Kenya, Zambia and South Africa through Kenya seed, Seedco and PANNAR companies respectively. This is due to the fact that maize has not been a staple food crop in Rwanda up to 2007 when the government launched crop intensification program (CIP), considering maize as one of priority crops, based on its potential to enhance food security (Daly *et al*., 2016). Hybrid varieties developed in Rwanda were expected to gradually stop hybrid seed importation and first local hybrids to be put to the market for cultivation by 2019 (Context Network, 2016).

2.5.2. Effect of planting density on yield of maize

The planting density can be defined as the number of plants per unit area and is very important on the yield of maize. Within gramineae crops, maize has the characteristic of no or low tillering capacity hence the high sensitivity to planting density (Arif *et al*., 2010). The history of maize shows that the planting density has been increasing in time with the planting density of farmers lower than the recommended one. Four decades ago, most African farmers were growing less or equal to 30,000 maize plants/ha while the average recommendation was 45,000 to 50,000 plants/ha (Brady, 1982). Improved hybrids achieve higher yields at high plant population due to the genetic change that allow higher plant population pressure. Nowadays, the planting density is doubled in Iowa (USA) from 40,000 in 1960 to about 80,000 (Fischer *et al*., 2014).

High plant population is associated with narrow row spacing less than 76.2 cm with a top yield around 55.88 cm row (DuPont Pioneer, 2016). Shapiro and Wortmann, (2006) reported that maize yield increased up to 4% due to decreasing row spacing from 0.76 to 0.51 m. Higher plant density produces more biomass up to 38% and more grain yield up to 25 % compared to low plant density (Imran *et al*., 2015).

2.5.3. Effect of N, P, and K fertilizers on yield of maize

The adequate use of fertilizers consist of applying them in appropriate amount, place and time. Maize is a crop that respond well to fertilizer application especially to N (table 2). The increased plant density with narrow row spacing is known to require the increased quantity of N fertilizer (Shapiro and Wortmann, 2006).

Table 2: Major nutrients uptake in Kg/ha for two different yields of maize

Element	**Yield of 9.5 t/ha**		**Yield of 6.3 t/ha**	
	Grain	**Stover (Stalks)**	**Grain**	**Stover (Stalks)**
N	129	62	100	63
P (as phosphate)	71	18	40	23
K (as potash)	47	188	29	92
Ca (as oxide)	2.1	55	1.5	15
Mg (as oxide)	18	55	9.3	28
S	12	9	7.8	9

Source: Jones, 2003

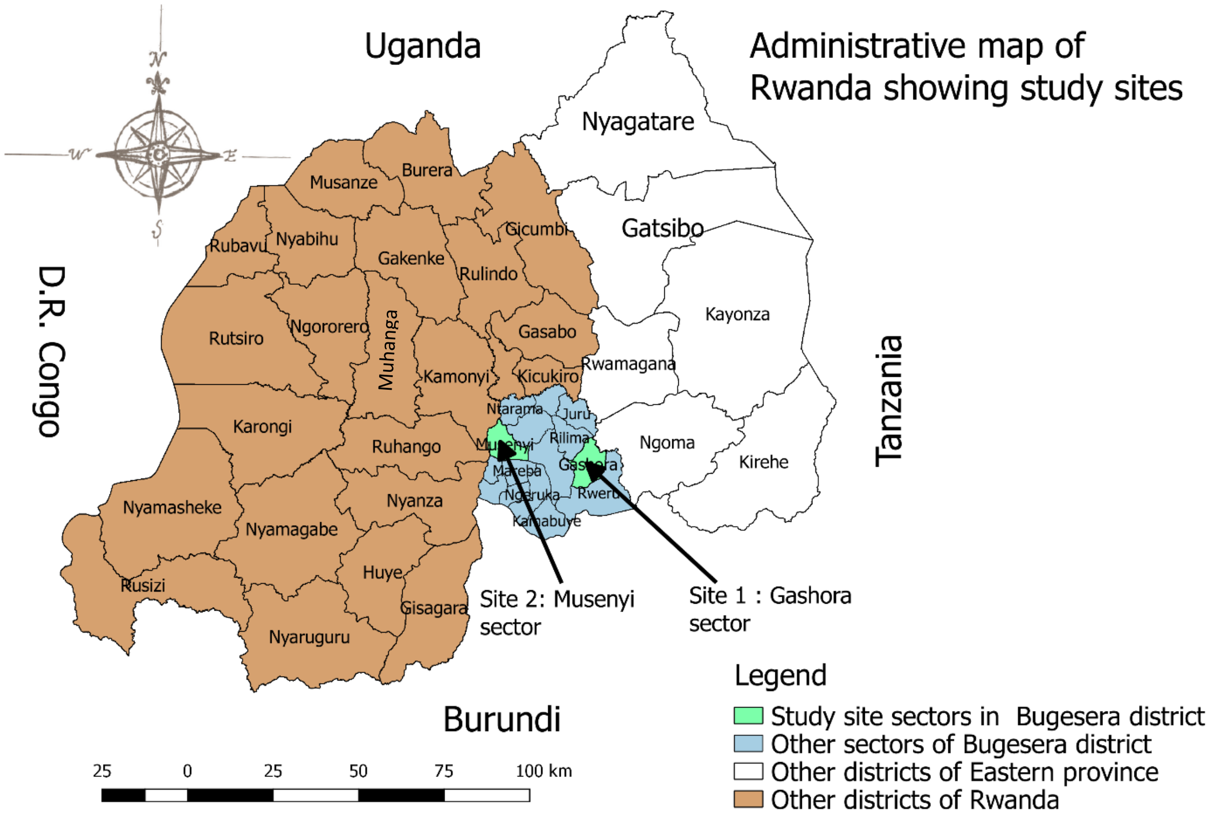
The grain yield depends on many factors including nutrient uptake by the plant, canopy light interception and genetic potential crop species among others. Maize stalk and grain yields are closely related to the amount of nutrient up taken. Fertilizer recommendations were varying considerably depending on the nutrients, soil conditions, genetic capacity of the variety and the intended yield (Brady, 1982) and (Shapiro *et al*., 2008). The range of N for maximum grain yield is between 140 and 160 kg/ha (Ali *et al*., 2002); (Arif *et al*., 2010); (Dawadi and Sah, 2012); (Khan *et al*., 2014); (Abuzar *et al*., 2011) and (Fischer *et al*., 2014).

CHAPTER 3: MATERIALS AND METHODS

3.1. Site description

This study was conducted in two sites. The first site was in Gashora sector with coordinates of 30.281 E and 2.252 S while the second site was in Musenyi sector with coordinates of 30.033 E and 2.172 S, both in Bugesera district (Figure 1). Soil analysis was done in both sites to determine the soil fertility status before planting, taking into account the field history including crop rotation. This study started in October 2017 and ended in March 2018.

Bugesera district is part of Eastern province of Rwanda. It has 15 sectors, 72 cells and 581 villages and covers an area of 1337 km^2 with 77.8% of its population depending on agriculture against 72% at the national level (Bugesera district, 2013). Rwanda's 4th Population and Housing Census estimated Bugesera population to 361,914 (NISR, 2012b). The borders of Bugesera district are Burundi country in South, Ngoma district in the East, Rwamagana, Kicukiro and Nyarugenge districts in the North, finally Kamonyi, Ruhango and Nyanza districts in the West. Bugesera district has medium altitude of between 1100 and 1780 m. This district has a wide range of water resources including 9 lakes and 3 rivers making it favorable for irrigation. Its climate is dry with annual temperature varying between 20 and 30 ^{0}C. Bugesera district has two rain seasons, the first starting in September and ending in February of the following year and the second starting in February and ending in June of the same year.



Source:(NISR, 2012a)

Figure 1: Study sites localization in Rwanda

3.2. Experimental design and treatments

A randomized complete block design (RCBD) under 2 x 3 x 4 factorial arrangement with 3 replications was used. The three factors were Variety (V), planting density (D) and N, P, and K fertilizers rates (R) which resulted in 24 treatments. The total number of experimental plots was 72 in one location and 144 experimental units for the whole study in both locations. One plot measured 5 m x 4.5 m with 6 rows/plot.

The varieties tested were 1 new maize hybrid (RHM 104) and one widely used open pollinated variety (ZM 607). These varieties are white in color and their seeds are distributed by Rwanda Agriculture and animal resource development Board.

The optimum growing region for RHM 104 is low and medium altitude. The necessary time for harvesting is around 125 days with drought tolerance traits and potential yield of 7.89 t/ha (The newtimes, 2017). Variety ZM 607 yields 6.5 t/ha and is grown in low and medium altitude regions (Gashamura, 2009). There were planting 3 densities including D1: 83,334 plants/ha, D2: 68,334 plants/ha and D3: 53,334 plants/ha (control used by breeders). According to Fischer *et al*. (2014) highest maize yields are achieved with increased planting density. Fertilizer rate (R) treatments were 4 (Table 3) including two increased rates (R1 and R2) and two controls: (1) recommended fertilizer rate on maize crop in Rwanda (R3) (Kelly and Murekezi, 2000), and (2) no fertilizer application.

Table 3: Fertilizer rates used and their respective sources

Fertilizer	N (Kg/ha)	P_2O_5 (Kg/ha)	K_2O (Kg/ha)	Source			
				Basal application		Side dressing	
Rates				Quantity (Kg/ha)	Type	Quantity (Kg/ha)	Type
R1	175	68	68	400	NPK 17.17.17	232.6	Urea 46 %
R2	150	59.5	59.5	350	NPK 17.17.17	196.7	Urea 46 %
R3	97	51	51	300	NPK 17.17.17	160.7	Urea 46 %
R4	0	0	0	-	-	-	-

3.3. Crop management

The crop management was done following the requirements of maize vegetative growth stages for maximum grain yield (Plessis, 2003). Apart from study factor variables, all other crop management techniques were administered equally to various experimental units. Soil cultivation was done twice before sowing to make the land suitable for maize easy germination. Planting was done on 11th October 2017 at Karama site and on 10th November 2017 at Musenyi site. Sowing depth was 5 cm with 2 seeds/hill and later thinned to 1plant/hill. Plant spacing was calculated to fit planned planting densities: 75 cm x 16.5 with 32 hills/row, 75 cm x 19.2 cm with 26 hills/row and 75 cm x 25 cm with 20 hills/row for the 1st, 2nd and 3rd planting density treatments, respectively.

Trenches of 20 cm deep and 30 cm in width were dug to stop fertilizer movement from one plot to another. NPK 17.17.17 fertilizer was applied at planting and side dressing with Urea fertilizer was done in the 6^{th} week after sowing. Weeding was done 3 times depending on the level of weed infestation. Ridging was realized during side dressing to optimize soil water. Supplementary irrigation was done to maintain adequate moisture in dry spells characterized by a rainfall less than 8.3 mm/five days period. Water was distributed at the rate of 700 - 800 m^3/ha to refill the soil to its field capacity (amount of moisture remaining after the soil has drained away excess of water and downward has become minimal) (Ngure, 2003). Stem borer was a widespread pest and was efficiently controlled with Roket 44 EC (active ingredients: Profenofos 40% + Cypermethrin 4%) insecticide to stop them making significant economic loss. Harvesting was done when the ears were mature enough with a black layer at the base of the grain (Puntel, 2012).

3.4. Data collection

Data was collected on growth and yield parameters of crop growth cycle. In addition, eventual data on pest and diseases were recorded. Soil sampling was done randomly before planting following zig-zag method using a diagonal path 4 times while crossing the field from one end to the other (Lafite, 1993).

3.4.1. Growth parameters

a) **Plant stand:** This was taken three weeks after planting at the stage of V2 to V3. I was preceded by thinning and then recording of number of all plants remaining in each plot.

b) **Plant height:** For 10 plants selected at random plant heights (cm) were recorded after complete anthesis up to tassel's lowermost branch insertion point (Abendroth *et al.*, 2011) using tape measure.

c) Ear height: For 10 plants selected at random, the distance (cm) from the soil (plant base) to the points of insertion of the highest ears were measured.

d) Anthesis and Silking: The time between sowing date and when 50 % of plants per plot shed pollen or showed silks. They were recorded chronologically then days after sowing calculated (Lafite, 1993).

3.4.2. Yield parameters

a) Plant aspect and ear aspect: Plant aspect data was recorded at the brown husk stage when plants were still green and the ears fully developed considering uniformity, vigor and the health of plants. Ear aspect data was recorded at harvesting, before sampling for moisture determination. Single plot ears pile were spread out and rated for disease, insect damage, size, grain filling, and uniformity. Score scale used was 1 to 5 with: (1): Very good, (2): Good, (3): Average, (4): Poor (5): Very poor (Birhanie, 2015).

b) Number of plants harvested: The number of plants to be harvested were counted by plot.

c) Number of ears harvested: The total number of ears harvested was counted in each plot and recorded. All plants without ears or that ears had no grains were not harvested.

d) Number of barren plants: After ear removal from mother plants, the total number of plants that failed to bear ears or that ears had no grains was counted and recorded per plot.

e) Field weight: all ears weight per plot (in kg) was measured immediately after harvesting.

f) Grain moisture at Harvesting: A sample of 5 ears from the harvested ear pile was randomly selected. Grains shelled from middle part of sampled were used for moisture determination (Lafite, 1993).

g) Grain weight or Grain yield: After shelling, individual plot grains were weighed, and extrapolated on hectare basis for grain yield (in kg/ha).

The following formula was used to calculate grain dry weight (GDW):

$$GDW\ (13.5\ \%) = \frac{Grain\ yield\ X\ (100-actual\ grain\ yield\ moisture\ \%)}{86.5}.$$

With 13.5% as the moisture content at which grains are stored (not constant, variable depending on country). This value is deducted from 100% to give the denominator of the formula (Badu-Apraku *et al*., 2012).

h) Weight of 100 grains: after shelling, 100 grains were sampled, for each plot and weighed.

3.4.3. Pest and Diseases

Pests and diseases were recorded following the methodology from Maroof *et al*. (1993) and Soonthornpoct *et al*. (2001). The recording of diseases was done in two ways. The first method is disease rating. This was done for the following important diseases: Turcicum Leaf blight (TLB), Grey Leaf Spot (GLS) and Rust (RUS). The rating scale was 1 to 5 where: 1 = Absence of visual symptoms; 2 = Low presence of symptoms from 1 to 25 %; 3 = Moderate symptoms from 26 to 50 %; 4 = Heavy symptoms, the whole plant bears the symptoms except the panicle from 51 to 75 % and 5 = the whole plant is heavily infested including panicle plants are almost dying, from 76 to 100 %. The second method is disease/or pest incidence by counting the number of plant infected and/or infested by pest and/or disease and calculating the percentage of the disease in relation to plant in each plot (Manandhar *et al*., 2016 and Gashaw, *et al*., 2014). Incidence method was used for Maize streak Virus (MSV), & Head smut diseases and stem borer pest.

3.5. Data analysis

Microsoft excel 2013 software was used for data entry. The data was analyzed using software GenStat 15th edition for analysis of variance (ANOVA). In case significant differences were observed, mean separation was done using the least significant difference (LSD) at 5 % level (Badu-Apraku, *et al*., 2012).

CHAPTER 4: RESULTS

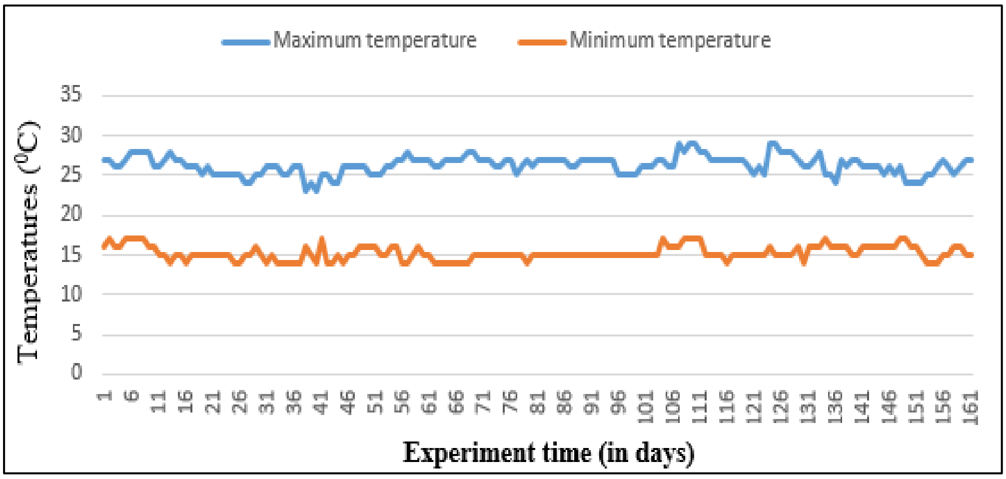
4.1. Soil analysis and weather data

Soil analysis revealed that pH varied from 6.3 to 7.5 with a mean of 7.08 at Karama site and from 5.1 to 5.9 with a mean of 5.4 at Musenyi site (Table 4). During research period, temperatures were favorable for maize growth as the mean varied from 15 ^{0}C to 26 ^{0}C compared to the accepted range of 15 ^{0}C to 35 ^{0}C for minimum and maximum temperatures respectively (Figure 2) (Chandrasekaran *et al.*, 2010). Total rainfall was 638.4 mm and was enough to support normal maize growth (Plessis, 2003). However, rainfall was not well distributed during research period. Low amount of rainfall, less than 8.3 mm/five days period, that required supplementary irrigation (Ngure, 2003), was observed in December 2017 in the second decade and the whole month of February 2018 (Figure 3).

Table 4: Results of soil chemical analysis before planting at Karama and Musenyi sites

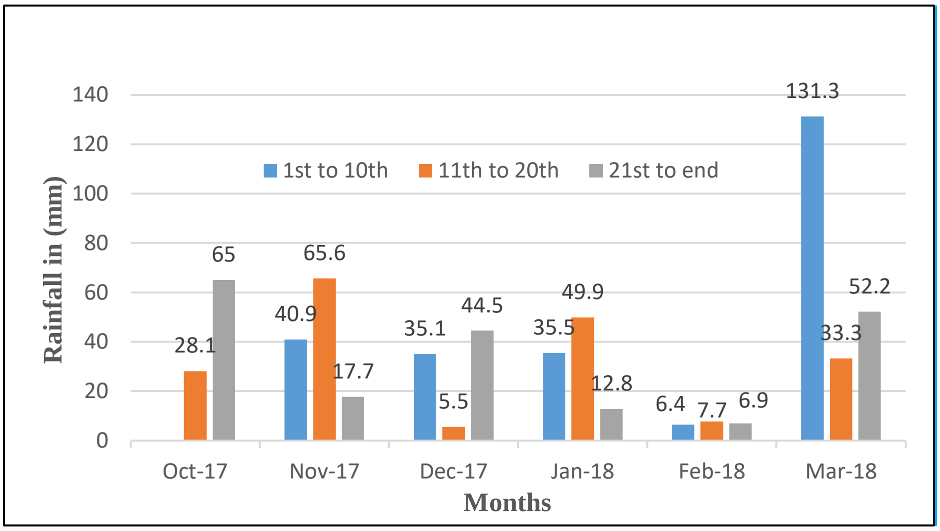
Sample ID	pH water	T N (%)	Av. P (ppm)	K (meq/100g)
Karama 1	7.5	0.17	26	2.2
Karama 2	7.2	0.18	30	1.8
Karama 3	7.1	0.22	27	1.5
Karama 4	6.3	0.21	24	2.3
Karama 5	7.3	0.22	28	2.5
Mean and appreciation	**7.08 accepted range for maize growing**	**0.20 Moderate**	**27.00 Very high**	**2.06 Very high**
Musenyi 1	5.9	0.09	7.6	0.09
Musenyi 2	5.1	0.12	10.7	0.09
Musenyi 3	5.2	0.11	8.8	0.09
Musenyi 4	5.4	0.13	5.7	0.09
Musenyi 5	5.4	0.13	14.9	0.09
Mean and appreciation	**5.4 below range for maize growing**	**0.1160 Low**	**9.5 Low**	**0.090 Low**

With TN: Total Nitrogen, Av P: Available Phosphorus, and K: Potassium. Appreciation for pH adapted from Lafite, (1993)*; TN and av. P from* SMART (2017) *and* Hazelton & Murphy (2007) *and K from* SMART (2017).



Source: Meteo Rwanda (2018) Temperature recorded on five days interval periodicity from the second week of October on the 11^th^, 2017 to March the 31^st^, 2018

Figure 2: Temperature variation during experiment period in study location of Bugesera district



Source: Meteo Rwanda (2018) Rainfall recorded on ten days interval periodicity from second week of October on the 11^th^, 2017 to March the 31^st^, 2018

Figure 3: Rainfall during experiment period in study location of Bugesera district

4.2. Vegetative growth

Maize growth from planting to harvesting was 133 days for Karama site and 138 days for Musenyi site putting 5 days difference between sites.

4.2.1. Plant height

Plant height (PH) was significantly different between sites with a P value < 0.001 (Appendix 3). Plants in field view analysis showed that heights were normally distributed (Figure 4) with median of 207.4 cm and mean of 207 cm for Karama site compared to 158.5 cm as median and 156 cm as mean for Musenyi site.

Maximum height of 233.2 cm was observed in Karama site and the minimum height of 120 cm was found in Musenyi site (Figure 5) with variation coefficient (C.V) of 16.09 %.

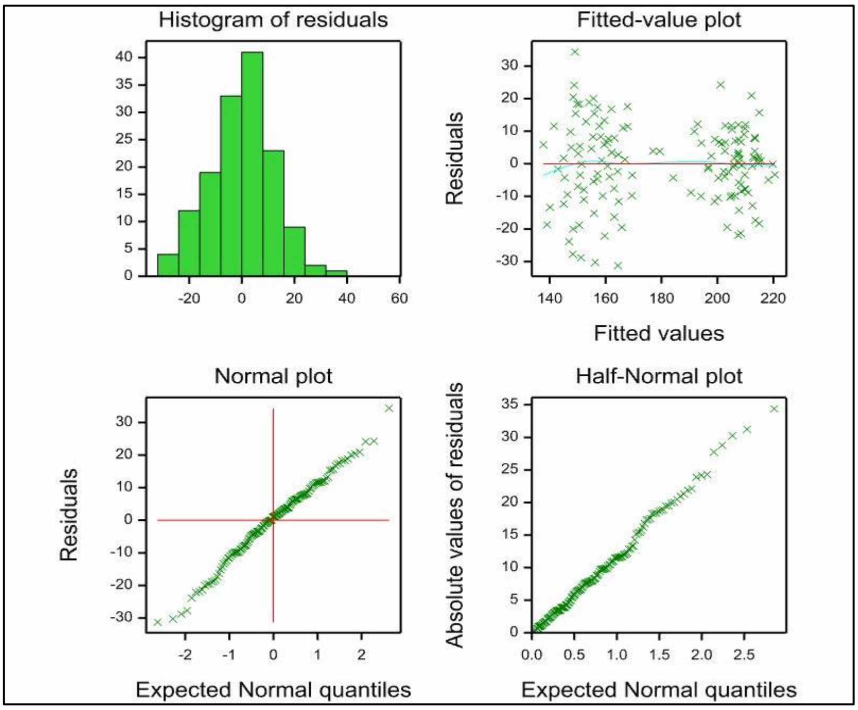


Figure 4: Residual plots from ANOVA of Plant height of Karama and Musenyi sites

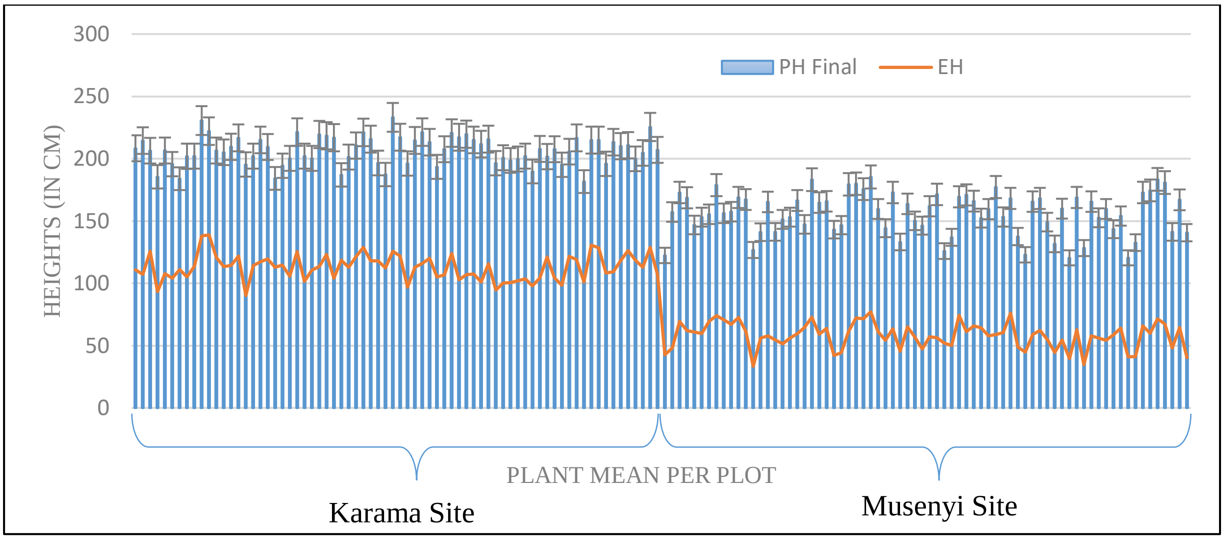


Figure 5: Field view of plant height (PH) and ear height insertion (EH) at Karama and Musenyi sites

There was no significant difference observed on plant height between varieties, planting densities and fertilizer rates. The interaction between these variables revealed no significant difference as well.

4.2.2. Days to flowering and maturity

Significant interaction was observed between planting densities and fertilizer rates for days to anthesis with a P value of 0.026 (Appendix 4). Planting density of 83,334 plants/ha, 68,334 plants/ha and 53, 334 plants/ha in interaction with fertilizer rate of NPK 150-59.5-59.5 and control (D1 x R2 and D2 x R4 interactions) delayed more than others to reach 50 % anthesis with mean of 70.17 and 70.33 days respectively (Table 5). Maximum time to anthesis was 74 days while minimum time was 65 days. According to days to silking, there was significant interaction between planting density and fertilizer rates with P value of 0.008 (Appendix 5). Planting density of 83,334 plants/ha and 68,334 plants/ha with fertilizer rates of NPK 150-59.5-59.5 and control (D1 x R2, D1 x R4 and D2 x R4) took more time than others to reach 50 % silking with mean of 72.25, 72.42 and 71.92 days, respectively. The maximum and minimum time registered were 76 and 67 days respectively.

Table 5: Effect of planting densities and fertilizer rates on days to anthesis and silking

	Anthesis					Silking				
Fertilizer rates (R) / Planting density (D)	**R1**	**R2**	**R3**	**R4**	**Mean**	**R1**	**R2**	**R3**	**R4**	**Mean**
D1	69.7ab	70.17a	69.42ab	68bc	**69.32**	71.58abc	72.25a	71.42abc	72.42a	**71.91**
D2	69.25abc	67.33c	69.08abc	70.33a	**68.89**	71.75ab	69.25d	71.08abcd	71.92a	**71.00**
D3	69.33ab	69.08abc	68bc	69.92ab	**69.08**	71.08abcd	71.17abcd	69.67cd	69.83bcd	**70.43**
Mean	**69.44**	**68.86**	**68.83**	**69.41**	**69.09**	**71.47**	**71.89**	**70.72**	**71.39**	**71.11**
Fpr (D)	**0.524 ns**					**0.733ns**				
Fpr (R)	**0.575 ns**					**0.519 ns**				
Fpr (D x R)	**0.026***					**0.008 ***				
LSD (0.05%) (D)	**1**					**1.02**				
LSD (0.05%) (R)	**1.16**					**1.18**				
LSD (0.05%) (D x R)	**2**					**2.05**				
CV %	**3.6**					**3.6**				

*With D1: 83,334 plants/ha, D2: 68,334 plants/ha, D3: 53,334 plants/ha; R1: NPK 175-68-68, R2: NPK 150-59.5-59.5, R3: NPK 97-51-51, R4: Control (no fertilizer applied). Means with the same letter(s) are not statistically different using LSD of D x R interaction, *: statistically significant, ns: statistically not significant.*

The total time from planting to harvesting was 123 days for early maturity plots to 133 days for late maturity plots in Karama site. This time was 117 days for early maturity plots to 138 days for late maturity plots in Musenyi site. The difference between early maturity and late maturity plots was 10 days for Karama site compared to 21 days for Musenyi site.

4.2.3. Ear height

Ear height showed significant difference between sites, with P value of < 0.001 (Appendix 6). Karama site had greatest ear height (113 cm) than Musenyi site (58 cm). Ear height also showed significant difference between rates of fertilizers, with P value of 0.042. Within the 4 fertilizer rates, the highest ears (90 cm) were observed with the rate of NPK 97-51-51. Ear height revealed significant interaction between varieties, planting densities and rates of fertilizers with P value of 0.022. Highest ears were observed in interaction of V1 x D2 x R2, V2 x D3 x R3 with a mean of 95 cm and the shortest ears were seen in V1 x D1 x R2 a mean of 77 cm (Table 6).

There was no significant difference observed for ear height due to variety and planting density. No significant difference detected for ear height due to interaction between site and variety (S x V), site and planting density (S x D), site and fertilizers rates (S x R), variety and planting density (V x D), variety and fertilizer rates (V x R), planting density and fertilizer rates (D x R), site, variety & fertilizer rates (S x V x R) and site, variety & planting density (S x V x D).

Table 6: Effect of varieties x planting densities x rates of fertilizers on ear height for Karama and Musenyi sites

Variety	Planting density(D) \ Fertilizer Rates(R)	R1	R2	R3	R4	Mean
V1	D1	94 ab	77 d	88 abcd	83 bcd	**85.5**
	D2	80 cd	95 a	90 abcd	83 bcd	**87.0**
	D3	88 abcd	84 abcd	85 abcd	80 cd	**84.2**
V2	D1	82 cd	89 abc	87 abcd	88 abcd	**86.5**
	D2	83 bcd	81 cd	92 abc	83 bcd	**84.7**
	D3	83 bcd	80 cd	95 a	83 bcd	**85.2**
Mean		**85.0**	**84.3**	**89.5**	**84.3**	
Fpr (V)		**0.947ns**				
Fpr (D)		**0.848ns**				
Fpr (R)		**0.042***				
Fpr (V x D x R)		**0.022***				
LSD (0.05%) (V)		**3.2**				
LSD (0.05%) (D)		**3.9**				
LSD (0.05%) (R)		**4.6**				
LSD (0.05%) (V x D x R)		**11.2**				
CV %		**11.4**				

*With: Units in cm; V1: RHM 104 hybrid, V2: ZM 607 OPV; D1: 83,334 plants/ha, D2: 68,334 plants/ha, D3: 53,334 plants/ha; R1: NPK 175-68-68, R2: NPK 150-59.5-59.5, R3: NPK 97-51-51, R4: Control (no fertilizer applied); Means with the same leter(s) are not significantly different using LSD V x D x R interaction, *: statistically significant, ns: statistically not significant.*

4.3. Yield components

4.3.1. Number of plants harvested, ears harvested and barren plants

Significant differences were revealed between sites in number of ears harvested with P value < 0.001 (Table 11). Number of ears harvested mean was 139 ears per plot for Karama site and 113 ears for Musenyi site. The highest number of ears was 185 ears per plot and was observed at Karama site while the lowest number was 45 ears observed at Musenyi site. There was no significant difference revealed in number of plant harvested between sites. Considering, plots which had up to 20 % of barrenness (plants failure to produce ears /or seeds) where yields were low to very low (Figure 6 and Table 17), planting density of 83,334 plants/ha (D1) had maximum percentage of barren plants per plots up to 77 % compared to the maximum of 51 % and 59 % for 68,334 plants/ha and 53,334 plants/ha respectively. There was significant relationship (regression analysis) between the number of barren plants and grain yield with P value < 0.001. Grain yield increased with decreasing barrenness percentage with correlation /coefficient of – 0.675 (Figure 7).

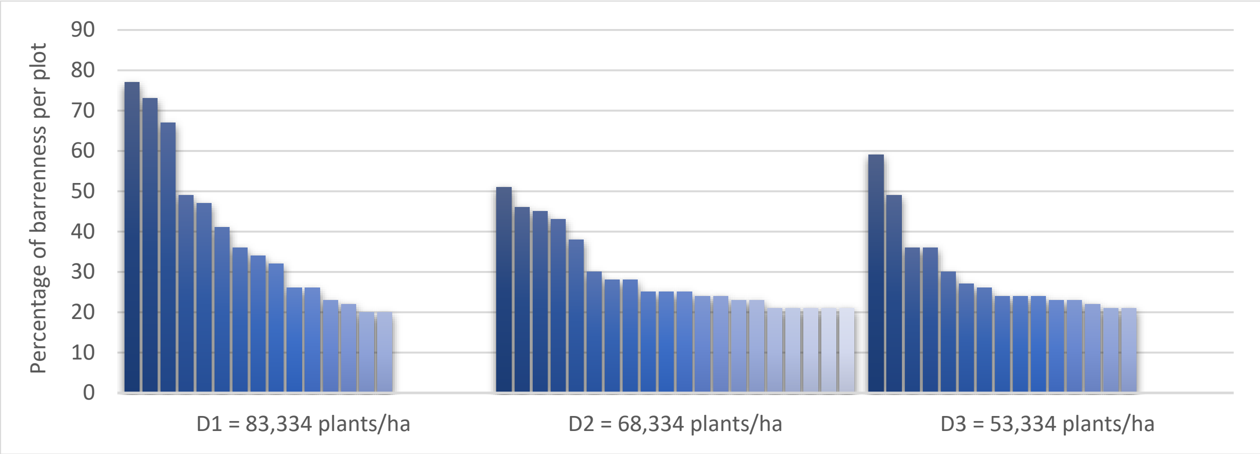


Figure 6: Comparison between planting densities for plots which got up to 20 % of barren plants at Karama and Musenyi sites

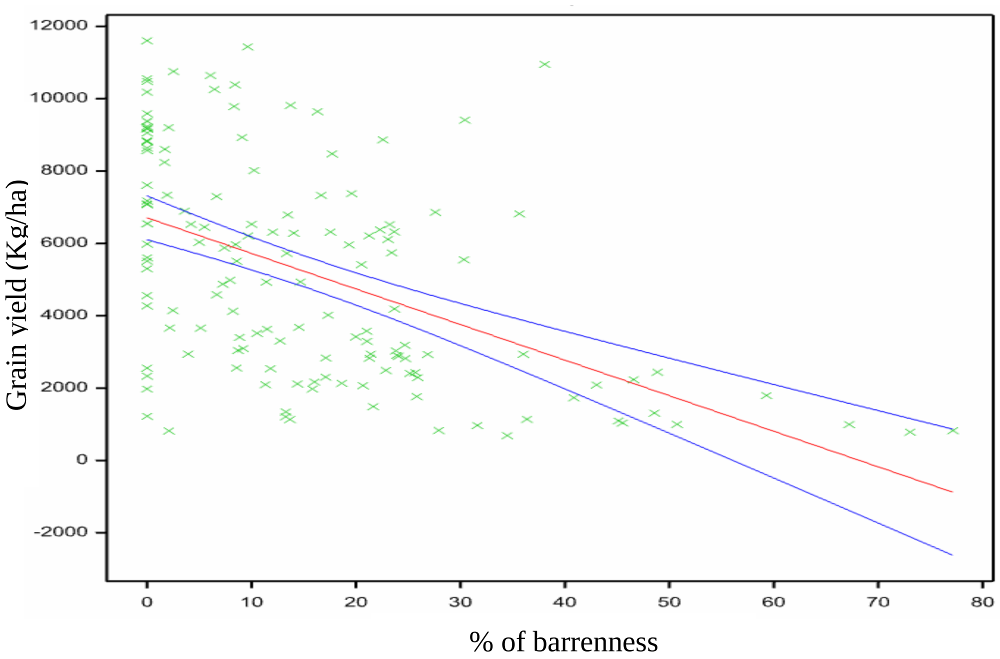


Figure 7: Relationship between grain yield and barrenness percentage at 95 % confidence limits

4.3.2. Grain moisture at harvesting

Grain moisture at harvesting showed significant differences between sites with P value < 0.001 (Appendix 8). Grain moisture during harvesting was higher at Musenyi site with a mean of 30.32 % compared to 22.42 % at Karama site.

4.3.3. Hundred grains weight

A hundred grains weight (GW 100) was significantly different between sites with P value < 0.001 (Appendix 9). The maximum weight of 100 grains observed was 60 g and was found in Karama site with a median of 50 g. Grains were heavier at Karama site than at Musenyi site: up to 45.8 % had 50 g, 31.9 % had 40 g, 12.5 % had 30 g and 9.7 % had 60 g in Karama site while 45.8% had 30 g, 43 % had 40 g, 9 % had 50 g, and 1.3 % had 20 g in Musenyi site. Significant interaction was observed between site, variety and fertilizer rate with P value of 0.034. Heavier grains were identified in interaction of S1 x V1 x R3 with the mean of 50 g/100 grains. Hundred grains weight revealed no significant difference between variety, planting density and fertilizer rate. No significant interaction was seen between site x variety, site x planting density, site x fertilizer rates, variety x planting density, variety x fertilizer rates, planting density x fertilizer rate, site x variety x planting density, site x planting density x fertilizer rate, and variety x planting density x fertilizer rate.

Table 7: Effect of sites x varieties x rates of fertilizers on weight of 100 grains

Site(S)	Fertilizer rates(R) / Variety (V)	R1	R2	R3	R4	Mean
S1	**V1**	43.33 abcd	46.67 abc	50.00 a	42.22 bcde	**45.55**
S1	**V2**	42.22 bcde	46.67 abc	43.33 abcd	47.78 ab	**45.00**
S2	**V1**	35.56 efg	32.22 g	34.44 fg	40.00 cdef	**35.55**
S2	**V2**	37.78 defg	37.78 defg	36.67 defg	34.44 fg	**36.66**
Mean		**39.72**	**40.83**	**41.11**	**41.11**	
Fpr (S)		**<0.001 ****				
Fpr (V)		**0.827 ns**				
Fpr (R)		**0.846 ns**				
Fpr (S x V x R)		**0.034 ***				
LSD (5%) (S)		**2.522**				
LSD (5%) (V)		**2.522**				
LSD (5%) (R)		**3.566**				
LSD (5%) (S x V x R)		**7.132**				
C.V %		**18.7**				

*With V1: RHM 104 hybrid, V2: ZM 607 OPV; S1: Karama site, S2: Musenyi site; R1: NPK 175-68-68, R2: NPK 150-59.5-59.5, R3: NPK 97-51-51, R4: Control (no fertilizer applied) **: statistically highly significant, *: statistically significant, ns: statistically not significant, means with the same letter(s) are not significantly different using using, LSD: S x V x R interaction.*

4.3.4. Grain yield of Karama and Musenyi study sites

Analysis of variance of grain yield dried up to 13.5 % showed highly significant differences between sites with P value < 0.001 (Appendix 10). Highest yields above 10 t/ha were obtained considering grain yield in relation to plant aspect, ear aspect and level of barrenness (Table 9). Interaction between variety and planting density revealed significant differences with P value of 0.003 (Appendix 10). Highest mean (5975 Kg/ha) was seen from interaction of RHM 104 hybrid variety and planting density and 68,334 plants/ha (Table 8).

Table 8: Effect of varieties x planting densities on grain yield at Karama and Musenyi sites

Planting densities / Varieties	D1	D2	D3	Mean
V1	4649 b	5975 a	5070 b	**5231**
V2	5434 ab	4600 b	5315 ab	**5116**
Mean	**5041**	**5287**	**5192**	
Fpr (V)	**0.663 ns**			
Fpr (D)	**0.742 ns**			
Fpr (V x D)	**0.003 ***			
LSD (5%) (V)	**519.6**			
LSD (5%) (D)	**636.4**			
LSD (5%) (V x D)	**900.1**			
C.V %	**30.4**			

*With: Units in Kg/ha; V1: RHM 104 hybrid, V2: ZM 607 OPV; D1: 83,334 plants/ha, D2: 68,334 plants/ha, D3: 53,334 plants/ha; Means with the same letter(s) are not significantly different, *: statistically significant, ns: statistically not significant.*

Table 9: Different grain yield in relation to plant aspect, ear aspect and barrenness at Karama and Musenyi sites

ON	PA	EA	% of barre-nness	Grain yield							
				Range (in t/ha)	Mean (Kg/ha)	Karama site		Musenyi site		Total	
						NPR	%	NPR	%	NPR	%
1	1.9	1.2	7	Up to 10	10725	10	13.9	-	-	10	6.9
2	1.7	1.3	6	9 to 9.9	9403	12	16.7	-	-	12	8.3
3	1.8	1.5	6	8 to 8.9	8599	10	13.9	-	-	10	6.9
4	2.4	1.9	6	7 to 7.9	7289	8	11.1	-	-	8	5.6
5	2.7	2.4	14	6 to 6.9	6458	18	25	1	1.4	19	13.2
6	2.8	2.6	16	5 to 5.9	5681	11	15.3	1	1.4	12	8.3
7	3.1	2.9	9	4 to 4.9	4513	3	4.2	8	11.1	11	7.6
8	3.4	3	14	3 to 3.9	3395	-	-	14	19.4	14	9.7
9	3.7	3.3	21	2 to 2.9	2513	-	-	26	36.1	26	18.1
10	4.1	3.8	29	1 to 1.9	1418	-	-	15	20.8	15	10.4
11	4.5	4.3	45	Below 1	846	-	-	7	9.7	7	4.9
Total	**3**	**2.7**	**16**	**5 to 5.9**	**5174**	**72**	**100**	**72**	**100**	**144**	**100**

With ON: Ordinal numbering, PA: Plant aspect, EA: Ear aspect in ordinal ranking good ears with small numbers (see 3.4.2 for description), NPR: Number of plots per grain yield range.

4.3.5. Grain yield for Karama sites

There was significant interaction between variety and planting density for Karama site with P value of 0.032 (Appendix 11). The highest grain yield was observed from the interaction of V1 x D2 with a mean of 8679 kg/ha (Table 10). The highest yield of 11606 Kg/ha achieved in this study was obtained from interaction of V1 x D2 at Karama site.

Table 10: Effect of Varieties x planting densities for Karama site

Planting density (D) / Variety (V)	D1	D2	D3	Mean
V1	7110 b	8679 a	7493 ab	**7760**
V2	8308 ab	7077 b	7676 ab	**7687**
Mean	**7709**	**7878**	**7584**	
Fpr (V)	**0.863 ns**			
Fpr (D)	**0.852 ns**			
Fpr (V x D)	**0.032***			
LSD (5%) (V)	**854**			
LSD (5%) (D)	**1045**			
LSD (5%) (V x D)	**1479**			
C.V %	**23.3**			

*With: Units in Kg/ha; V1: RHM 104 hybrid, V2: ZM 607 OPV; D1: 83,334 plants/ha, D2: 68,334 plants/ha, D3: 53,334 plants/ha; Means with the same letter(s) are not significantly different using LSD V x D interaction, *: statistically significant, ns: statistically not significant.*

There was no significant difference observed between single factor variables and their interaction at Musenyi site.

4.4. Pest and diseases

Diseases which were recorded using rating method (see 3.4.3 for description) developed moderate to heavy lesions in both sites (Table 11) with slight increase of turcicum leaf blight at Karama site (2.6) compared to Musenyi site (2.2). There was no apparent purple color symptoms at Karama site compared to 2.1 at Musenyi site.

Table 11: Rating of turcicum leaf blight, rust, grey leaf spot and purple color diseases/ deficiency symptoms

Disease Rating scale \ Number of plot/ rating	Turcicum leaf blight		Rust		Grey leaf spot		Purple color	
	Karama site	Musenyi site	Karama site	Musenyi site	Karama site	Musenyi site	Karama site	Musenyi site
5 (76 to 100 %)	0	0	0	0	0	0	0	0
4 (51 to 75 %)	0	0	0	0	0	0	0	5
3 (26 to 51 %)	36	11	0	0	0	0	0	12
2 (1 to 25 %)	36	43	19	0	1	23	0	29
1 (no visual symptoms)	0	18	53	72	71	49	72	26
Mean rating	**2.6**	**2.2**	**1.4**	**1**	**1.5**	**1.4**	**1**	**2.1**

Diseases and/or pest which were recorded using incidence method (see 3.4.3 for description) had slightly higher percentage at Musenyi site compared to Karama site (Figure 8, 9, and 10) with a maximum of 13.1 % for head smut at Musenyi site compared to 0.7 % at Karama site.

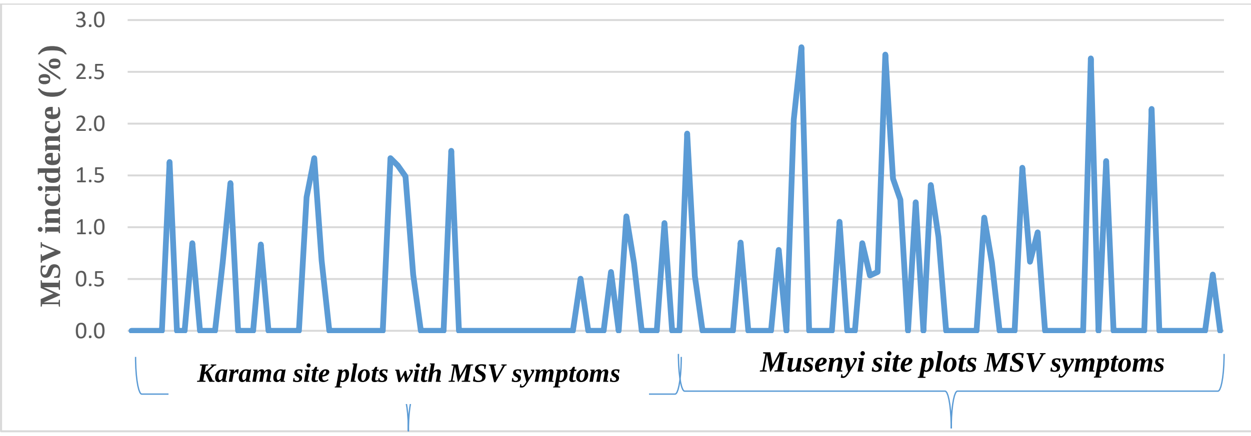


Figure 8: Incidence of maize streak virus disease at Karama and Musenyi site

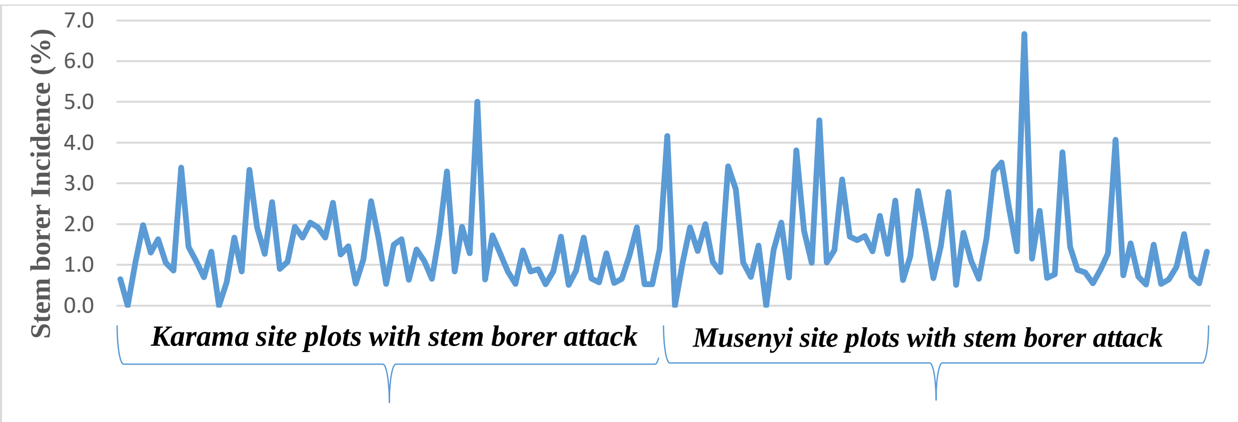


Figure 9: Incidence of Stem borer pest at Karama and Musenyi sites

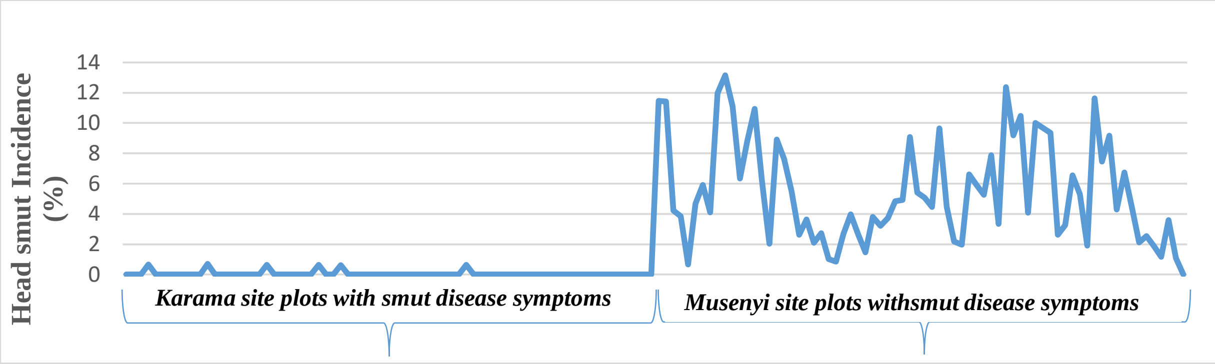


Figure 10: Incidence of head smut disease at Karama and Musenyi sites

CHAPTER 5: DISCUSSION

5.1. Baseline soil fertility of study sites

Observed conditions of soil in study sites were crucial considering pH range required for appropriate growth and yield of maize. The first site (Karama) had pH levels suitable for maize production (mean pH 7.08). This may have positively affected growth and yield of maize due to effect of pH on availability of crop nutrients present in the soil. Musenyi site pH range was strongly acid, (mean pH 5.4) based on categorization of Jones, (2003). According to Lafite (1993) maize crop adequate pH range is between 5.5 and 7.8. Beyond this range, pH affects availability, toxicity or deficiency of crop nutrient. Moderate to high phosphorus deficiency was observed in Musenyi site through purple color symptom (mean rating of 2.18 on the score range of 1 to 5: 1 as apparent symptoms and 5 severe symptoms) (Maroof *et al*., 1993). Below 5.5 pH level, phosphorus and magnesium become deficient and aluminum & manganese become toxic (Lafite, 1993). Nitrogen content in soil was moderate at Karama site and low at Musenyi site (see Table 4). Phosphorus was very high (27 ppm) in Karama site and low in Musenyi site (9.5 ppm) in conformity with SMART (2017) and Hazelton & Murphy, (2007). Potassium was very high in Karama site (2.06 meq/100g) and low in Musenyi site (0.090 meq/100g) in accordance to SMART (2017).

5.2. Effect of sites on growth and yield of selected maize varieties

Highly significant differences ($P < 0.001$) were observed between sites in plant height, ear height, number of ears harvested, weight of 100 grains and grain yield. This may be attributed to the influence of soil pH and initial soil fertility conditions during the research period. Soil pH may be the reason why plant and ear were highest in Karama site (207 cm) where soil pH was favorable for maize growth (7.08) and shortest in Musenyi site (156 cm) where soil pH (5.4) was unfavorable for maize growth.

In addition, best plant and ear height observed at Karama site, may be attributed to availability of crop nutrients and absence of Al toxicity possible in soils with good pH levels for maize growth. Poor plant and ear height seen at Musenyi site may be explained by low pH level of soil that reduced nitrogen, phosphorus and potassium major nutrients availability. These major nutrients deficiency, especially potassium, may be the reason for higher level of diseases observed at Musenyi site compared to Karama site in accordance with Jones (2012). Low pH decreases fertilizer use efficiency and crop performance as reported by Nduwumuremyi, (2013). Moreover, low soil pH had negatively affected the number of ears harvested, weight of 100 grains and grain yield at Musenyi site. According to Krstic *et al*., (2012) crop performance decreases in poor soil pH conditions due to Al toxicity that injures maize roots causing poor iron and water uptake. Significant difference in grain moisture at harvesting between sites may be attributed to heavy rains observed in the month of March 2018 hence five days to maturity delay observed between Musenyi and Karama sites. The difference between early maturity and late maturity plots may be attributed to nitrogen deficiency at Musenyi site (21 days) that lead to quick maturity in more stressed plots compared to Karama site (10 days) where nitrogen was enough for normal physiological maturity of maize. Plants with nitrogen deficiency grow slowly, become stunted and mature earlier (Jones, 2003).

5.3. Effect of N, P and K fertilizers on growth and yield of selected maize varieties

5.3.1. Effect of NPK fertilizers on maize growth

The interaction of fertilizer levels and varieties on ear height was detected in combination with planting density levels (Variety x planting density x fertilizer rates, $P = 0.022$). Considering fertilizer rates and variety levels interaction, (see 5.4. for planting density), RHM 104 new hybrid had highest ears with increased fertilizer levels of NPK 175-68-68 and NPK 150-59.5-59.5 while ZM 607 open pollinated variety had the same highest ears with fertilizer rate of NPK 97-51-51. Highest ears observed on RMH 104 hybrid variety may be attributed to its improved genetic potential to utilize available nutrients for best vegetative growth. Ability of ZM 607 OPV to have highest ears with the lowest rate of fertilizer applied (NPK 97-51-51) may be attributed to its genetic capacity to use low amount of fertilizer for a maximum growth. Varieties' genetic make-up may affect their nutrients take up and utilization (Jones, 2003); therefore the difference in growth and development.

Fertilizer rate NPK 150-59.5-59.5 and the control in interaction with planting density increased days to anthesis and silking. Considering fertilizer levels (see 5.4 for planting density), the increased time to reach anthesis observed in interaction of 83,334 plants/ha x control may be attributed to high demand of nutrients required 30 days after planting from V8 to VT stages when the last branch of tassel is visible. Nitrogen was becoming limiting in control and may be the cause of retarded growth at that period. Delayed anthesis observed in interaction of 68,334 plants/ha x NPK 150-59.5-59.5 may be due to high amount of nitrogen from NPK 150-59.5-59.5 fertilizer that was available for 68,334 plants and caused reduced growth speed. Excessive amount of nitrogen may cause deficiency of other nutrients and carbohydrate depletion therefore growth reduction (Jones, 2003) and delayed anthesis. These findings are in line with Arif *et al*. (2010) and Imran *et al*. (2015) who reported that increased nitrogen extended days to anthesis. According to days to silking, control plots delayed than others to reach 50 % silking stage. Nitrogen content in control plots was not enough to support sufficiently plant growth and caused delay in silking. In case of low nitrogen levels, there is delayed anthesis and silking due to slow growth and stunting during vegetative stage (Molla *et al*., 2014). Nitrogen is implicated in many physiological processes, especially protein synthesis, that are imbalanced when it is not enough (Jones, 2012).

5.3.2. Effect of NPK fertilizers on maize yield components

Significant response of selected maize varieties to NPK fertilizer rates applied was seen in interaction with site on weight of 100 grains. Heavier grains observed in interaction of Karama site x RHM 104 hybrid x NPK 97-51-51 indicated that fertilizer rate NPK 97-51-51 produced heavier grains on RHM 104 hybrid variety in Karama site. Soil pH at Karama site was favorable for maize growth and allowed RHM 104 hybrid variety to utilize NPK 97-51-51 nutrients efficiently for maximum 100 grains weight. Other fertilizer rates were too high (NPK 175-68-68 and NPK 150-59.5-59.5) or too low (Control) hence reduced grains weight. In both cases, there may be deficiency due to inhibition by the excessive elements of the deficient nutrients or due to low level of nutrients present in soil solution (Jones, 2012). Nutrients were deficient due to high acidity and resulted in small grains at Musenyi site compared to Karama site.

There was significant effect of NPK fertilizers rates applied on grain yield of cultivated varieties. Our result is different from many other findings on fertilizers research that confirm a positive response of crops, especially maize, on N, P and K fertilizers, including, among others Bakht *et al*. (2006), Dawadi & Sah (2012), Khan *et al*. (2014), Adeniyan (2014) and Dibaba *et al*. (2014). Two reasons may explain the cause of unresponsiveness of our maize varieties towards fertilizer rates applied. The first reason may be soil fertility of the field where maize was grown. When a field is fertile enough to support maize nutrient demand, or when the field is highly degraded due to inappropriate pH that renders some nutrients unavailable, the response to fertilizer application may be poor to none. According to Kihara, Huising *et al*. (2016) response to fertilizer may be poor to none if control yields are more than 6 t/ha. Control yield mean was 8,215 Kg/ha for Karama site thus classifying this site in category of non-responsive fertile fields. This good control yield may be attributed to accepted range of pH in Karama site that allowed maize to utilize appropriately available moderate content of soil nitrogen and very high amount of phosphorus and potassium (Table 4). Musenyi site may be classified as poor non-responsive fields due to its acidic degraded soils (pH = 5.4) and phosphorus deficiency symptoms observed. Musenyi site soil acidity is a common crop production constraint in tropical regions where it affects more than 40 % of arable lands and associated with twin problems of aluminum toxicity and phosphorus deficiency (New Agriculturist, 2011). In acidic soils, aluminum toxicity is the most problematic as it reduces availability of crop nutrients, limits root growth hence decreased nutrients uptake (Vanlauwe *et al*., 2015). The second reason may be genetic capacity of cultivated varieties. Maize varieties respond differently to NPK fertilization. Some varieties give very high yields with increasing NPK levels up to optimum rate while others increase yields slightly with increasing NPK levels (Hallof, 2008).

According to Pepó and Karancsi (2014), there are 4 groups of maize varieties in relation to their response to NPK fertilization namely: (i) varieties with high natural capacity of utilization of nutrients and give high yields response to fertilizer application, (ii) varieties with moderate natural capacity of utilization of nutrients and give high yields response to fertilizer application, (iii) varieties with high natural capacity of utilization of nutrients and give moderate yields response to fertilization and (iv) varieties with moderate natural capacity of nutrients utilization and give moderate yields response to fertilizer application. Cultivated varieties of RHM 104 hybrids and ZM 607 OPV may be classified in group 3 and 4 giving moderate to poor response to fertilizer applied. Adequate technology for site specific fertilizer recommendation should be developed to apply fertilizers where they are needed, and in required amount. Fertile non-responsive field (Karama site in our case) would receive low amounts of fertilizers for maintenance purpose and degraded non-responsive soils need amendments before being responsive to any fertilizer application in accordance with Vanlauwe *et al*. (2015) and Kihara, Nziguheba *et al*. (2016). Fertile fields needs hybrids with best natural capacity of utilization of nutrients with poor response to fertilizer therefore giving best yields with maintenance fertilizer application. Hybrid RHM 104 (V1) and open pollinated variety ZM 607 (V2) can give good yields in fertile soils with low amount of fertilizer application. This is due to best yields (7,761 Kg/ha and 7,687 Kg/ha respectively) observed at Karama site and their poor to none response to fertilizer rates applied in line with Kihara, Huising, *et al*. (2016). However, there is a need of further studies to determine which low amount of fertilizer is the most agronomically efficient rate for best yield in fertile fields like Karama site. Degraded fields like Musenyi site need determination of types of degradation to be addressed before being responsive to fertilizers application.

5.4. Effect of planting densities on growth and yield of selected maize varieties

5.4.1. Effect of planting densities on flowering

The effect of planting density levels on growth of selected maize varieties was revealed in interaction with fertilizer rates on days to anthesis and days to silking with P value of 0.026 and 0.008 respectively. Considering planting densities, (see hereinbefore point 5.3 for fertilizer rates) the density of 83,334 plants/ha and 68,334 plants/ha delayed to reach 50 % anthesis compared to the density of 53,334 plants/ha. According to days to silking, the density of 83,334 plants/ha took longer time to reach 50 % silking stage. This significant interaction may be attributed to higher plant density that increased interplant competition for growth resources such as water, nutrient (Arif *et al*., 2010) and light. According to Mandić *et al*. (2016) high plant population increases intraspecific competition and reduces the amount of resources available per individual plant. Reduction of growth resources per individual plant resulted in slowed growth and increased time to reach 50 % anthesis and silking periods. Our finding is in conformity with Amanullah *et al*. (2009) and Imran *et al*. (2015) who reported that tasseling and silking were delayed at higher planting density.

5.4.2. Effect of planting densities on ear height

Ear height of used maize varieties was affected by plant density in combination with fertilizer rates. Our results reflect the effect of higher plant densities on maize growth by influencing internode elongation due to interplant competition for light that stimulate apical dominance (Mandić *et al*., 2016). Considering variety and plant density (see point 5.3 for variety and fertilizer rates), highest ears were observed in higher planting densities of 83,334 plants/ha and 68,334 plants/ha for RHM104 hybrid variety. The open pollinated variety (OPV) ZM 607 was in the first group of highest ears as the hybrid RHM 104 but with lower plant density of 53,334 plants/ha. Consequently, hybrid variety RHM 104 tolerated higher plant population than ZM 607 OPV. Our finding is in accordance with Jeschke, *et al*., (2018) who reported that ear height increased with plant density up to optimum of 36,000 plants/acre (~ 90,000 plants/ha) and stayed constant with slight increase at extremely high plant population beyond 45000 plants/acre (~111, 600 plants/ha). Furthermore, improved maize hybrids varieties have tolerance to stresses including higher plant population hence higher yields (Ipsilandis and Vafias, 2005).

5.4.3. Effect of planting densities on the level of barrenness

Response of studied maize varieties to plant densities was revealed through the number of barren plants. The negative correlation (see point 4.3.4 hereinbefore) observed between grain yield and number of barren plants explains how the increase in barrenness resulted in decrease of grain yield and vice versa. The increase of barrenness probably was caused by high resource competition that took place in higher plant population. When maize growth factors such as nutrients, light and water become insufficient, tassel development dominate over ear development creating imbalance in flowering. Ears develop slowly and silking take place later compared to tasseling in normal conditions hence increased anthesis-silking interval (ASI) in conformity with (Mandić *et al*., 2016). Maximum ASI interval varied between 2 to 4 days consequently, late silks were poorly or not pollinated resulting in poor kernel set and increased barrenness. Percentage of barrenness related to plant density was 22 %, 21 % and 18 % for 83,334, 68,334 and 53334 plants/ha respectively. Although our barrenness percentages are closer due to the tightness of used range between low and high plant density, the trend remain the same with Helland (2012) who reported the same ASI with an average of 10 % of barren plants for low plant density (45,000 plants/ha) compared to almost 25 % for high plant density (155,000).

5.4.4. Effect of planting densities on grain yield

Variety and density positive interaction may be attributed to genetic capacity of varieties and effect of higher plant population on maize grain yield. The best yield was obtained from hybrid variety RHM 104 in the density of 68,334 plants/ha. This interaction may be caused by the positive response of the hybrid to increased plant population compared to 53,334 plants/ha. The increase in yield resulted from increase of ear per unit area up to optimum number of plants & ears harvested, satisfactory plant and ear quality (aspect), optimum weight of 100 grains and limited number of barren plants. Maize has a low tillering capacity hence to increase the number of ear per unit area imply to increase the number of plants per unit area. Hybrid variety RHM 104 tolerated competition between plants created by high plant population in density of 68,334 plants/ha. Optimum mean number of plant and ear harvested for yields above 10 t/ha was 67,334 plants/ha and 64,288 ear/ha respectively with 1.9 for plant aspect and 1.2 for ear aspect, 7 % of barren plants (Table 9) and 52 g for weight of 100 grains. Below this plant density, plant and ear aspect were better, 100 grains were heavier and barrenness was lower (figure 6) but the number of ears was not enough to give the highest yields. At the density of 83,334 plants/ha; ear and plant aspect were worse (thin plants, small size ears and/or incomplete kernel set), 100 grains were light and barrenness was higher (figure 6) reducing the number of ears per unit area and grain yield. The best planting density was 68,334 plants with the RHM 104 hybrid variety.

This hybrid variety was able to produce sufficient number of ears/ha with optimum plant aspect, ear aspect, 100 grain weight and barrenness to produce obtained maximum grain yields.

Our results are in accordance with Mandić *et al*., (2016) who reported that maximum yield components (ear length, number of rows/ear, number of grains/row, number of grains/ear, grain weight/ear, cob weight and weight of 100 grains) were recorded in the lowest crop density. Negative correlation revealed between grain yield and weight of 100 grains; indicates that heavy and big grains were seen on ears from low planting density which had low competition for growing factors. Arif *et al*., (2010) explained that grain yield increased with increasing plant density which produced high number of ears per unit area thus high grain yield. Abuzar *et al*. (2011) and Mahdi & Ismail (2015) emphasized that grain yield increased with plant density. Yields increase were related to greater number of ears per unit area at optimum level. Above optimum level, the number of ears is no longer able to compensate for yield decline caused by ear size decreasing with increasing plant density (Jeschke *et al*., 2018; and Amiri *et al*., 2014). Best maize hybrid may have genetic capacity to tolerate highest planting density and therefore giving high grain yield.

CHAPTER 6: CONCLUSION AND RECOMMENDATION

6.1. Conclusion

This study revealed the possibility to increase maize grain yield in eastern Rwanda by increasing planting densities. The effect of varying planting density on growth and yield of selected maize varieties was detected on flowering, ear height, level of barrenness and gain yield. It is very important to cultivate maize varieties which tolerate high planting density due to positive effect of increased plant population found by this research. There is no way of increasing maize grain yield based on plant population other than increasing the number of plants per unit area which increase the number of ears per unit area due to natural low tillering capacity of maize compared to other cereals. Hybrid RHM 104 variety was seen to be tolerant to high plant population in comparison to OPV ZM 607. Variety ZM 607 performed well at low plant population but the number of ears was not enough to give highest yield reached in this research. The density of 83,334 plants/ha was not the best on grain yield because of increased delay in anthesis and silking hence increased level of barrenness and significant reduction of grain yield. The density of 53,334 plants/ha produced low number of ear/ha to support highest grain yield. Best varieties may have optimum high plant density capacity that allows to increase the number of ears per unit area. Highest grain yield of 11606 Kg/ha, was achieved with RHM 104 hybrid variety at density of 68,334 plants/ha. Research sites revealed poor to none response to fertilizer rates applied on growth and yield of cultivated maize varieties due to high fertility of the field for Karama site and high degradation of soil for Musenyi site. Common mineral fertilization practices to farmers in Rwanda are mainly blanket recommendations based on agro-ecological zones and type of crop. However, our findings revealed a need to shift from such recommendations to site specific fertilizer application that take into consideration heterogeneity of soil fertility.

6.2. Recommendation

Grain yield achieved in this study exceeded Rwandan government yield expectation of 6.5t/ha in 2017 year (see 1.2) giving possibility of higher than planned yields if the following recommendation are applied:

- Agronomic research is needed on all new varieties recently released in Rwanda in order to determine hybrids which are the most tolerant to higher planting density and therefore giving the highest grain yields. Breeders in Rwanda may continue to select maize hybrid varieties that are more tolerant to high plant population and consequently producing best grain yields.

- Pioneer farmers in Rwanda with best management practices may start to use increased planting density up to 68,334 plants/ha with RHM 104 hybrid variety due to their observed interaction for higher maize grain yields.

- Research institutions in Rwanda may undertake further studies to determine site specific fertilizer recommendations that take into consideration soil fertility heterogeneity in order to apply fertilizer in appropriate amount and responsive fields to improve grain yield and agronomic efficiency. The later reduces in fertile and highly degraded fields which are non-responsive to fertilizer application. Emphasis should be put in soil acidity correction by liming to increase pH at accepted range for degraded fields to be responsive to fertilizer application. In addition, more agronomic efficiency can be achieved by introducing precision agriculture in research agenda in Rwanda that may lead to site specific crop management.

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APPENDICES

Appendix 1: Data of temperatures during research period (in ^{0} C)

Dates	Oct-17		Nov-17		Dec-17		Jan-18		Feb-18		Mar-18	
	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min
1			25	15			26	15	26	16	26	16
2			25	15	24	14	27	15	26	16	27	16
3			25	15	24	15	27	15	29	16	28	16
4			25	14	26	14	25	15	26	16	25	17
5	Research was not yet started		25	14	26	15	26	15	29	16	25	16
6			24	15	26	15	27	14	28	17	24	16
7			24	15	26	16	26	15	29	17	27	16
8			25	16	25	16	27	15	29	17	26	16
9			25	15	25	16	27	15	28	17	27	15
10			26	14	25	15	27	15	28	15	27	15
11	27	16	26	15	26	15	27	15	27	15	26	16
12	27	17	26	14	26	16	27	15	27	15	26	16
13	26	16	25	14	27	16	27	15	27	15	26	16
14	26	16	25	14	27	14	26	15	27	14	26	16
15	27	17	26	14	28	14	26	15	27	15	25	16
16	28	17	26	14	27	15	27	15	27	15	26	16
17	28	17	26	14	27	16	27	15	27	15	25	16
18	28	17	27	14	27	15	27	15	26	15	26	17
19	28	16	26	14	27	15	27	15	25	15	24	17
20	26	16	26	14	26	14	27	15	26	15	24	16
21	26	15	23	16	26	14	27	15	25	15	24	16
22	27	15	24	15	27	14	27	15	29	16	24	15
23	28	14	23	14	27	14	25	15	29	15	25	14
24	27	15	25	17	27	14	25	15	28	15	25	14
25	27	15	25	14	27	14	25	15	28	15	26	14
26	26	14	25	14	28	14	25	15	28	15	27	15
27	26	15	25	17	28	15	26	15	27	16	26	15
28	26	15	24	14	27	15	26	15	26	14	25	16
29	25	15	NA	NA	27	15	26	15	NA	NA	26	16
30	26	15	NA	NA	27	15	27	15	NA	NA	27	15
31	25	15	NA	NA	26	15	27	17	NA	NA	27	15

With NA: non applicable

Appendix 2: Data of rainfall during research period (in mm)

Month Decade	Oct-17	Nov-17	Dec-17	Jan-18	Feb-18	Mar-18
1	Research was not yet started	40.9	35.1	35.5	6.4	131.3
2	28.1	65.6	5.5	49.9	7.7	33.3
3	65	17.7	44.5	12.8	6.9	52.2

Appendix 3: Difference between variables on plant height for Karama and Musenyi sites

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Sites (S)	1	92259.9	92259.9	445.52	<0.001**
Varieties (V)	1	364	364	1.76	0.188ns
Planting Densities (D)	2	10.7	5.4	0.03	0.974ns
Fertilizer Rates (R)	3	1155.2	385.1	1.86	0.141ns
Sites x Varieties (S x V)	1	62.8	62.8	0.3	0.583ns
Sites x Planting Densities (S x D)	2	562.1	281.1	1.36	0.262ns
Varieties x Planting Densities (V x D)	2	451.8	225.9	1.09	0.34ns
Sites x Fertilizer Rates (S x R)	3	541	180.3	0.87	0.459ns
Varieties x Fertilizer Rates (V x R)	3	123.7	41.2	0.2	0.897ns
Planting Densities x Fertilizer Rates (D x R)	6	715.1	119.2	0.58	0.749ns
Sites x Varieties x Planting Densities (S x V x D)	2	597.8	298.9	1.44	0.241ns
Sites x Varieties x Fertilizer Rates (S x V x R)	3	789.1	263	1.27	0.289ns
Sites x Planting Densities x Fertilizer Rates (S x D x R)	6	1314.9	219.1	1.06	0.393ns
Varieties x Planting Densities x Fertilizer Rates (V x D x R)	6	1098.1	183	0.88	0.51ns

*With **: statistically highly significant, ns: statistically not significant*

Appendix 4: Difference between variables on days to anthesis for Karama and Musenyi sites

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Sites (S)	1	1.361	1.361	0.22	0.639ns
Varieties (V)	1	4.694	4.694	0.76	0.384ns
Planting Densities (D)	2	8.014	4.007	0.65	0.524ns
Fertilizer Rates (R)	3	12.278	4.093	0.67	0.575ns
Sites x Varieties (S x V)	1	7.111	7.111	1.16	0.285ns
Sites x Planting Densities (S x D)	2	7.764	3.882	0.63	0.534ns
Varieties x Planting Densities (V x D)	2	7.931	3.965	0.64	0.527ns
Sites x Fertilizer Rates (S x R)	3	19.806	6.602	1.07	0.364ns
Varieties x Fertilizer Rates (V x R)	3	9.139	3.046	0.5	0.686ns
Planting Densities x Fertilizer Rates (D x R)	6	93.097	15.516	2.52	0.026*
Sites x Varieties x Planting Densities (S x V x D)	2	6.681	3.34	0.54	0.583ns
Sites x Varieties x Fertilizer Rates (S x V x R)	3	7.5	2.5	0.41	0.749ns
Sites x Planting Densities x Fertilizer Rates (S x D x R)	6	12.236	2.039	0.33	0.919ns
Varieties x Planting Densities x Fertilizer Rates (V x D x R)	6	47.069	7.845	1.28	0.276ns

*With *: statistically significant, ns: statistically not significant*

Appendix 5: Difference between variables on days to silking for Karama and Musenyi sites

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Sites (S)	1	1.562	1.562	0.24	0.624ns
Varieties (V)	1	6.674	6.674	1.04	0.311ns
Planting Densities (D)	2	4.014	2.007	0.31	0.733ns
Fertilizer Rates (R)	3	14.688	4.896	0.76	0.519ns
Sites x Varieties (S x V)	1	4.34	4.34	0.67	0.414ns
Sites x Planting Densities (S x D)	2	13.875	6.938	1.08	0.345ns
Varieties x Planting Densities (V x D)	2	6.431	3.215	0.5	0.609ns
Sites x Fertilizer Rates (S x R)	3	18.465	6.155	0.95	0.417ns
Varieties x Fertilizer Rates (V x R)	3	6.688	2.229	0.35	0.792ns
Planting Densities x Fertilizer Rates (D x R)	6	120.042	20.007	3.1	0.008*
Sites x Varieties x Planting Densities (S x V x D)	2	9.847	4.924	0.76	0.469ns
Sites x Varieties x Fertilizer Rates (S x V x R)	3	2.354	0.785	0.12	0.947ns
Sites x Planting Densities x Fertilizer Rates (S x D x R)	6	28.847	4.808	0.75	0.614ns
Varieties x Planting Densities x Fertilizer Rates (V x D x R)	6	56.292	9.382	1.46	0.201ns

*With *: statistically significant, ns: statistically not significant*

Appendix 6: Difference between variables on ear height for Karama and Musenyi sites

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Sites (S)	1	108246.7	108246.7	1140.42	<0.001**
Varieties (V)	1	0.42	0.42	0	0.947ns
Planting Densities (D)	2	31.4	15.7	0.17	0.848ns
Fertilizer Rates (R)	3	807.03	269.01	2.83	0.042*
Sites x Varieties (S x V)	1	103.11	103.11	1.09	0.3ns
Sites x Planting Densities (S x D)	2	143.43	71.72	0.76	0.472ns
Varieties x Planting Densities (V x D)	2	71.66	35.83	0.38	0.687ns
Sites x Fertilizer Rates (S x R)	3	164.43	54.81	0.58	0.631ns
Varieties x Fertilizer Rates (V x R)	3	454.12	151.37	1.59	0.195ns
Planting Densities x Fertilizer Rates (D x R)	6	634.86	105.81	1.11	0.359ns
Sites x Varieties x Planting Densities (S x V x D)	2	132.14	66.07	0.7	0.501ns
Sites x Varieties x Fertilizer Rates (S x V x R)	3	311.47	103.82	1.09	0.355ns
Sites x Planting Densities x Fertilizer Rates (S x D x R)	6	763.97	127.33	1.34	0.246ns
Varieties x Planting Densities x Fertilizer Rates (V x D x R)	6	1483.94	247.32	2.61	0.022*

*With **: statistically highly significant, *: statistically significant, ns: statistically not significant.*

Appendix 7: Difference between variables on number of ears harvested at Karama and Musenyi sites

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Sites (S)	1	24937.7	24937.7	34.89	<0.001**
Varieties (V)	1	11.7	11.7	0.02	0.899ns
Planting Densities (D)	2	2364	1182	1.65	0.196ns
Fertilizer Rates (R)	3	682.1	227.4	0.32	0.812ns
Sites x Varieties (S x V)	1	0.6	0.6	0	0.978ns
Sites x Planting Densities (S x D)	2	2654.4	1327.2	1.86	0.161ns
Varieties x Planting Densities (V x D)	2	3968.2	1984.1	2.78	0.067ns
Sites x Fertilizer Rates (S x R)	3	1192.1	397.4	0.56	0.645ns
Varieties x Fertilizer Rates (V x R)	3	3453.4	1151.1	1.61	0.192ns
Planting Densities x Fertilizer Rates (D x R)	6	6733.6	1122.3	1.57	0.164ns
Sites x Varieties x Planting Densities (S x V x D)	2	459.9	229.9	0.32	0.726ns
Sites x Varieties x Fertilizer Rates (S x V x R)	3	1344.4	448.1	0.63	0.599ns
Sites x Planting Densities x Fertilizer Rates (S x D x R)	6	5000.1	833.3	1.17	0.331ns
Varieties x Planting Densities x Fertilizer Rates (V x D x R)	6	7703.3	1283.9	1.8	0.107ns

*With **: statistically highly significant, ns: statistically not significant.*

Appendix 8: Difference between variables on grain moisture at harvesting sites at Karama and Musenyi

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Sites (S)	1	2243.6	2243.6	81.32	<0.001**
Varieties (V)	1	17.64	17.64	0.64	0.426ns
Planting Densities (D)	2	66.1	33.05	1.2	0.306ns
Fertilizer Rates (R)	3	49.61	16.54	0.6	0.617ns
Sites x Varieties (S x V)	1	6.76	6.76	0.25	0.622ns
Sites x Planting Densities (S x D)	2	12.97	6.49	0.24	0.791ns
Varieties x Planting Densities (V x D)	2	117.38	58.69	2.13	0.125ns
Sites x Fertilizer Rates (S x R)	3	52.45	17.48	0.63	0.595ns
Varieties x Fertilizer Rates (V x R)	3	180.75	60.25	2.18	0.095ns
Planting Densities x Fertilizer Rates (D x R)	6	146.57	24.43	0.89	0.509ns
Sites x Varieties x Planting Densities (S x V x D)	2	149.86	74.93	2.72	0.071ns
Sites x Varieties x Fertilizer Rates (S x V x R)	3	32.19	10.73	0.39	0.761ns
Sites x Planting Densities x Fertilizer Rates (S x D x R)	6	185.59	30.93	1.12	0.356ns
Varieties x Planting Densities x Fertilizer Rates (V x D x R)	6	100.23	16.71	0.61	0.725ns

*With **: statistically highly significant, ns: statistically not significant.*

Appendix 9: Difference between variables on 100 grains weight at Karama and Musenyi sites

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Sites (S)	1	3025	3025	52.02	<0.001**
Varieties (V)	1	2.78	2.78	0.05	0.827ns
Planting Densities (D)	2	193.06	96.53	1.66	0.195ns
Fertilizer Rates (R)	3	47.22	15.74	0.27	0.846ns
Sites x Varieties (S x V)	1	25	25	0.43	0.514ns
Sites x Planting Densities (S x D)	2	37.5	18.75	0.32	0.725ns
Varieties x Planting Densities (V x D)	2	168.06	84.03	1.44	0.241ns
Sites x Fertilizer Rates (S x R)	3	191.67	63.89	1.1	0.353ns
Varieties x Fertilizer Rates (V x R)	3	113.89	37.96	0.65	0.583ns
Planting Densities x Fertilizer Rates (D x R)	6	540.28	90.05	1.55	0.17ns
Sites x Varieties x Planting Densities (S x V x D)	2	79.17	39.58	0.68	0.509ns
Sites x Varieties x Fertilizer Rates (S x V x R)	3	525	175	3.01	0.034*
Sites x Planting Densities x Fertilizer Rates (S x D x R)	6	295.83	49.31	0.85	0.536ns
Varieties x Planting Densities x Fertilizer Rates (V x D x R)	6	165.28	27.55	0.47	0.826ns

*With **: statistically highly significant, *: statistically significant, ns: statistically not significant.*

Appendix 10: Difference between variables on grain yield for Karama and Musenyi sites

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Sites (S)	1	9.37E+08	9.37E+08	379.18	<0.001**
Varieties (V)	1	4.73E+05	4.73E+05	0.19	0.663ns
Planting Densities (D)	2	1.48E+06	7.40E+05	0.3	0.742ns
Fertilizer Rates (R)	3	8.53E+06	2.84E+06	1.15	0.332ns
Sites x Varieties (S x V)	1	6.05E+04	6.05E+04	0.02	0.876ns
Sites x Planting Densities (S x D)	2	1.95E+06	9.73E+05	0.39	0.676ns
Varieties x Planting Densities (V x D)	2	3.03E+07	1.52E+07	6.14	0.003*
Sites x Fertilizer Rates (S x R)	3	2.67E+06	8.91E+05	0.36	0.782ns
Varieties x Fertilizer Rates (V x R)	3	1.09E+07	3.64E+06	1.47	0.226ns
Planting Densities x Fertilizer Rates (D x R)	6	2.71E+07	4.51E+06	1.83	0.102ns
Sites x Varieties x Planting Densities (S x V x D)	2	2.66E+06	1.33E+06	0.54	0.585ns
Sites x Varieties x Fertilizer Rates (S x V x R)	3	3.62E+06	1.21E+06	0.49	0.691ns
Sites x Planting Densities x Fertilizer Rates (S x D x R)	6	1.71E+07	2.85E+06	1.15	0.338ns
Varieties x Planting Densities x Fertilizer Rates (V x D x R)	6	5.80E+06	9.66E+05	0.39	0.883ns

*With **: statistically highly significant, *: statistically significant, ns: statistically not significant.*

Appendix 11: Difference between variables on grain yield for Karama site

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Varieties (V)	1	97395	97395	0.03	0.863ns
Planting Densities (D)	2	1044334	522167	0.16	0.852ns
Fertilizer Rates (R)	3	7252544	2417515	0.75	0.53ns
Varieties x Planting Densities (V x D)	2	24125649	12062824	3.72	0.032*
Varieties x Fertilizer Rates (V x R)	3	11242721	3747574	1.16	0.336ns
Planting Densities x Fertilizer Rates (D x R)	6	38212157	6368693	1.97	0.09ns
Varieties x Planting Densities x Fertilizer Rates (V x D x R)	6	10256323	1709387	0.53	0.784ns

*With *: statistically significant, ns: statistically not significant.*