EVALUATION OF SOIL PROPERTIES AND RESPONSE OF MAIZE (*Zea mays* L.) TO BIOSLURRY AND MINERAL FERTILIZERS IN TERRACED ACRISOLS AND LIXISOLS OF RWANDA

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DECLARATION AND RECOMMENDATION

Declaration

I declare that this thesis is my original work and has not been previously published or presented for the award of a degree in any University**.**

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DEDICATION

This thesis is dedicated to the memory of my parents and my brother Dr. Anastase Kagenza who believed in my education. It is also dedicated to my brothers and sisters. Special dedication is given to my wife Mrs. Sarah Mukarukaka and my sons Alain Fashaho Hirwa, Eloi Ineza and Benis Ishimwe.

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ABSTRACT

Land terracing is promoted as a management practice for effective soil conservation in hilly areas of Rwanda. However, terraced lands are likely to have low crop productivity where management practices, especially fertilizer application, do not consider the changes in the soil properties following terracing. Fertilizer recommendations currently in use are based on studies done in non-terraced land. The objectives of this study were therefore to determine the changes in soil properties following bench terracing and the effects of nitrogen and phosphorus, and bioslurry application on soil properties and maize growth, N uptake and yields in terraced lands. Trials were conducted at medium and high altitudes sites in Rwamagana and Gicumbi Districts of Rwanda. In the first trial, a Randomized Complete Block Design with factorial arrangement was used. Factors comprised terracing (terraced and non-terraced lands), slope positions (top, middle and bottom) and soil depths. The physical, chemical and biological properties of soil were determined. The second and third field trials were conducted using a Randomized Complete Block Design in factorial arrangement replicated three times. The second trial had two factors; nitrogen fertilizer at four levels (0, 60, 120 and 180 kg N ha^{-1}) and phosphorus fertilizer at four level (0, 40, 80 and 120 kg P_2O_5 ha^{-1}). Data on maize growth and yields were collected. The third trial comprised four levels of mineral nitrogen (0, 30, 60 and 90 kg N ha^{-1}) and four levels of bioslurry (0, 6, 12 and 18 t ha^{-1} in the medium altitude site and 0, 5, 10 and 15 t ha^{-1} in the high altitude site). Maize growth, N uptake and yields were measured, and the residual effect of treatments on soil properties was evaluated. Results showed significant ($P < 0.05$) changes in certain soil properties after terracing. Terraced lands had higher levels of silt, hydraulic conductivity and populations of bacteria and fungi. Non-terraced lands had higher clay content, water retention capacity and organic carbon. On maize performance, nitrogen fertilizer rates of 120 and 180 kg N ha^{-1} combined with phosphorus rates of 80 and 120 kg P_2O_5 ha^{-1} resulted in significantly ($P < 0.05$) higher grain yields of 6.4 – 6.5 t ha^{-1} in the medium altitude site and 6.0 – 6.1 t ha^{-1} in the high altitude site. A higher agronomic nitrogen use efficiency was obtained with application of 60 and 120 kg N ha^{-1}. Soil organic carbon, total nitrogen and populations of bacteria and fungi increased with increase in bioslurry rates. Bioslurry rates of 12 and 18 t ha^{-1} in medium altitude site and 10 and 15 t ha^{-1} in high altitude site combined with 60 and 90 kg mineral N ha^{-1} resulted in significantly ($P < 0.05$) higher grain yields of 7.8 - 8.0 t ha^{-1} and 6.9 -7.3 t ha^{-1} in medium and high altitudes sites, respectively. The study shows that bioslurry and inorganic fertilizer application in terraced lands need to be adjusted from current recommendations for enhanced maize yields.

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ABBREVIATIONS AND ACRONYMS

AEZ	Agro Ecological Zone
ANOVA	Analysis of Variance
a.s.l.	Above sea level
ATP	Adenosine Triphosphate
CABI	Centre for Agriculture and Bioscience International
CEC	Cation Exchange Capacity
CIP	Crop Intensification Program
CFU	Colony Forming Unit
DAP	Diammonium Phosphate
DMRT	Duncan’s Multiple Range Test
ECEC	Effective Cation Exchange Capacity
DAS	Days after Sowing
FAO	Food and Agriculture Organization
FYM	Farm Yard Manure
GDP	Gross Domestic Product
GPS	Global Position System
GTA	Graduate Teaching Assistantship
LWH	Land and Water Husbandry
MINAGRI	Ministry of Agriculture and Animal Resources (Rwanda)
MINALOC	Ministry of Local Government (Rwanda)
MINECOFIN	Ministry of Finance and Economic Planning (Rwanda)
MININFRA	Ministry of Infrastructure (Rwanda)
MT	Metric Tonnes
NDBP	National Domestic Biogas Programme
NISR	National Institute of Statistics of Rwanda
NPK	Nitrogen Phosphorus Potassium
NSW	New South Wales
PCA	Plate Count Agar
PDA	Potato Dextrose Agar
RAB	Rwanda Agriculture Board
RADA	Rwanda Agriculture Development Authority
RCBD	Randomized Complete Block Design

SAS	Statistical Analysis System
SCAPE	Soil Conservation and Protection for Europe
SNV	Netherlands Development Organization
SOC	Soil Organic Carbon
SOM	Soil Organic Matter
TAWC	Total Available Water Content
TSP	Triple Super Phosphate
WOCAT	World Overview of Conservation Approaches and Technologies

CHAPTER ONE
INTRODUCTION

1.1 Background information

Agriculture accounts for 33% of Rwanda's gross domestic product (GDP) and 70% of employment (FAO, 2019). Land degradation and erosion are among the main challenges facing the sector. The country's relief is hilly and mountainous with altitudes ranging from 900 to 4507 m above sea level (a.s.l.) (Habiyakare and Zhou, 2015; Twagiramungu, 2006). It is estimated that 90% of arable land is on slopes ranging from 5% to 55% (FAO, 2019) with consequent effects of erosion, soil loss and decrease of fertility.

Land terracing is an important measure to prevent soil erosion and preserve soil fertility and raise crop yields on sloppy lands (Amare *et al.,* 2013; Widomski, 2011; Posthumus and Stroosnijder, 2010; Wheaton and Monke, 2001). The common types of terraces in Rwanda are bench or radical terraces and progressive terraces (Ruganzu *et al.*, 2015). Bench terraces are a series of level or almost level strips running across the slope at vertical intervals, supported by steep banks or risers (Mesfin, 2016). In Rwanda, bench terracing has been widely adopted by farmers. The method involves isolation of top soil, and sub soil is reworked to create the required reverse-slope bench after which the top soil is spread over the surface. The terrace riser is planted with short runner grass for stabilization. Bench terraces are created principally to reduce soil losses through enhanced retention and infiltration of runoff (Kagabo, 2014; FAO, 2000), promote permanent agriculture on steep slopes and promote land consolidation and intensive land use (Kagabo, 2014).

Terracing work, however, perturbs soil horizons and consequently leads to changes in soil physical, chemical and biological properties. These include: changes in distribution of organic matter and chemical nutrients, changes in particle size distribution of fine fraction, hydraulic conductivity, water retention capacity and aggregate stability (Ramos *et al.*, 2007). Microbiological properties are sensitive and rapid indicators of perturbations and land use changes (García-Orenes *et al.*, 2013; Zornoza *et al.*, 2009). The major soil types in medium and high altitudes of eastern and north eastern Rwanda are Ferralsols, Lixisols and Acrisols (Verdoodt and Van Ranst, 2003). These soils have well developed horizons (AEBtC) and are susceptible to land transformation (Driessen *et al.*, 2001).

The properties of terrace soils in Rwanda are not documented. Therefore, fertilizer recommendations for maize production in Rwanda are still based on studies done before construction of terraces (MINAGRI, 2009; Kelly and Murekezi, 2000). The subsequent insufficient fertilizer use in these terraced land has lowered production (NISR, 2016; Chianu *et al.*, 2012). For example, the average maize grain yield of 1.74 t ha^{-1} is obtained at farm level (NISR, 2016) which is low compared to a potential yield of 6 to 10 t ha^{-1} and a world average productivity of 5.52 t ha^{-1} (Yadav *et al.*, 2016).

Integrated nutrient management has been advocated as a sound management principle for smallholder farming in the tropics (Vanlauwe and Zingore, 2011). Yield improvement is usually greater when organic inputs and inorganic fertilizers are applied together (Mugwe *et. al.*, 2019; Fairhurst, 2012). They can substantially improve agronomic efficiency of the nutrients (Vanlauwe *et al.*, 2001) without affecting soil fertility (Islam *et al.*, 2013). Combining bioslurry and nitrogen fertilizer can improve nitrogen management and consequently enhance maize yields in terraced lands. Bioslurry is an anaerobic digested organic material released as a by-product from the biogas plant after production of combustible methane gas. It is a nitrogen-rich source and a good soil amendment that can improve physical and biological qualities of soils (Karki, 2006). In Rwanda, bioslurry is largely produced through domestic biogas plants disseminated by the National Domestic Biogas Programme (NDBP) with 12,500 units (MININFRA, 2014). Studying response of maize to application of bioslurry and mineral nitrogen rates, and resulting changes in soil properties will contribute to sustainable management of terraced Lixisols and Acrisols of medium and high altitude regions.

1.2 Statement of the problem

Terracing is a soil conservation practice commonly used in hilly regions of Rwanda. It reduces soil loss by enhancing water retention and infiltration of runoff. Perturbation of soil horizons, however, occurs during construction of terraces and subsequently soil properties change. The layers of soils are mixed, and the distribution of organic matter, chemical nutrients, physical and biological properties change. These changes, depending on their magnitude, could have a significant effect on land use. For example, efficient irrigation practices and fertilizer applications are usually based on specific soil characteristics. Properties for terraced lands in many ecological zones of Rwanda are not yet studied and documented. Terraced lands are likely to have low productivity due to the management practices (especially fertilizer application) that do not consider the changes in the soil properties that result after terracing. Low production in terraced lands may be attributed to inappropriate and insufficient use of fertilizers with recommendations established before terracing. Nitrogen and phosphorus requirements for use in terraced soils in Rwanda have not been determined and are therefore not known. Bioslurry is a quality organic fertilizer that can be used to improve soil fertility and crop yields, and is environmentally friendly (Warnars and Oppenoorth, 2014; Tuyishime 2012; Islam *et al.*, 2010). It is largely produced in domestic biogas plants in Rwanda. Application rates of bioslurry in combination with mineral nitrogen that can optimize maize yield have not yet been investigated on perturbed soils of terraced lands. They are provided by this study.

1.3 Objectives

1.3.1 Broad objective

The broad objective of the study was to contribute to improved food security in Rwanda through increasing maize yields by application of bioslurry, nitrogen and phosphorus fertilizers in terraced lands.

1.3.2 Specific objectives

The specific objectives of the study were:

i) To evaluate the effect of land terracing on soil physical, chemical and biological properties across slope positions and soil depths.
ii) To determine effect of nitrogen and phosphorus inorganic fertilizer rates on maize growth and yields in terrace soils.
iii) To evaluate the effect of bioslurry and mineral nitrogen application rates on physical, chemical and biological properties of terrace soils.
iv) To determine effect of bioslurry and mineral nitrogen application rates on maize growth, nitrogen uptake and yields in terrace soils.

1.4 Hypotheses

The hypotheses postulated for the study were:

i) Land terracing has no significant effect on soil physical, chemical and biological properties across slope positions and soil depths.
ii) Nitrogen and phosphorus fertilizer rates have no significant effect on growth and yield of maize in terrace soils.
iii) Bioslurry and mineral nitrogen application rates have no significant effect on physical, chemical and biological properties of terrace soils.
iv) Bioslurry and mineral nitrogen application rates have no significant effect on maize growth, nitrogen uptake and yields in terrace soils.

1.5 Justification

Land terracing is promoted as a management practice for effective soil conservation in hilly areas; however, construction of terraces causes changes in soil properties. Hence, there was a need to characterize soil properties of terraced lands. Attention was made on the sustainable management of soil fertility of terraced Lixisols and Acrisols to enhance crop yields. Maize is one of the priority crops that can contribute to improvement of food security and poverty reduction in Rwanda. It has become a major income generating crop for small scale farmers and ranks first among pulse and grain crops in annual production. It is promoted on terraced lands in Rwanda, but its yields are low. One way yields can be improved is by use of organic and inorganic fertilizers. However, maize fertilizer recommendations in the terraced lands have so far been based on extrapolation of rates resulting from studies conducted before terracing. Fertilizer use should be based on recommendations established with consideration of the new properties of terraced lands. Bioslurry which has been demonstrated in different studies to be a good organic source for improving soil fertility, by nutrient supply and physical and biological quality improvement, needed investigations on terraced soils.

1.6 Scope and limitations

This research was conducted on terraced lands of medium and high altitudes of Eastern and North-eastern Rwanda in Mwurire and Kageyo Sectors of Rwamagana and Gicumbi Districts, respectively. The study was conducted from February 2017 to August 2018. It focused on selected soil physical, chemical and biological properties and fertility of terraced lands. The study was done on four-year old terraces. It was not able to provide data on short-term and long-term changes caused by land terracing, i.e., could not provide data on development of changes from new to old terraces. The test crop was maize (*Zea mays* L.). The fertilizer trials were limited to tests of macronutrients (nitrogen and phosphorus inorganic fertilizers), bioslurry and mineral N rates, and did not include micronutrients.

CHAPTER TWO
LITERATURE REVIEW

2.1 Land terracing

2.1.1 Introduction

Soil conservation in hilly and mountainous regions of many countries in Europe, North and South America, Asia, and Africa (e.g. Ethiopia, Rwanda and Tanzania) is done through construction of terraces (Widomski, 2011; Zuazo *et al.*, 2005). Terracing refers to building a mechanical structure of a channel and a bank or a single terrace wall, such as an earthen ridge or a stone wall (Morgan, 2009; Dorren and Rey, 2004). Terraces are created principally to reduce soil losses through enhanced retention and infiltration of runoff (Kagabo, 2014; FAO, 2000), and promote permanent agriculture on steep slopes, land consolidation and intensive land use (Kagabo, 2014). They prevent damage done by surface runoff (Widomski, 2011) and improve soil qualities and increase crop yields (Amare *et al.*, 2013).

2.1.2 Types of terraces in Rwanda

The common types of terraces in Rwanda are bench or radical terraces and progressive terraces (Ruganzu *et al.*, 2015). Bench terraces are a series of level or almost level strips running across the slope at vertical intervals, supported by steep banks or risers. The excavated bench terraces are carried out through the cut and fill process and sometime are known as "radical terraces" (Mesfin, 2016). Bench terraces were introduced in Rwanda in 1973 at Kisaro hill of the mountainous region of Buberuka agro-ecological zone (AEZ) as an effective way of controlling soil erosion and maintaining or progressively improving soil fertility (Rushemuka *et al.*, 2014). They are constructed on terrain with steeper slopes of up to 55% (Widomski, 2011). During construction of radical terraces, farmers carefully isolate the topsoil and rework the subsoil to create the required 1% reverse-slope bench after which the topsoil is spread over the surface. The riser is planted with short runner grass for stabilization (Mesfin, 2016; Kagabo, 2014). Land terracing has recently increased in Rwanda as the best practice for soil conservation in sloppy cropland. About 90% of the cropland is located on slopes of 5 – 55% (Karamage *et al.*, 2016). The country mean soil erosion rate is 250 t $ha^{-1}yr^{-1}$ with an annual soil loss of 594.5 million tonnes (Karamage *et al*, 2016). The area covered by bench terraces is 102,339 hectares out of 1,502,727 hectares of arable land (RAB, 2016).

Progressive terraces are formed by establishing contour bunds with soil or stones in combination with ditches and vegetation as in the *Fanya Juu* terraces of Kenya (Widomski, 2011). The progressive terraces are formed in time by the natural processes of erosion, cultivation operation, and deposition or sedimentation (Mesfin, 2016). They reduce the land slope and allow runoff from the upper side of the terrace to go into a lower portion where it spreads out and infiltrates. The terrace edge is planted with trees and grass to stabilize it and trap sediments (Ruganzu *et al.*, 2015).

Figure 2.1 Bench terraces illustration
Source: Ruganzu *et al.* (2015).

2.1.3 Land terracing and changes in soil properties

Perturbation of soil layers occurs during construction of terraces and this causes changes in soil physical and chemical properties. These include; changes in distribution of organic matter and chemical nutrients, changes in particle size distribution of fine fraction, hydraulic conductivity, water retention capacity and aggregate stability (Ramos *et al.*, 2007). Land terracing contributes to increasing the soil moisture content through improved infiltration

(Dorren and Rey, 2004), but depending on soil types and terracing techniques, water retention capacity and organic matter content may decrease up to 45% and 50%, respectively (Ramos *et al.*, 2007). Furthermore, microbiological properties are sensitive and rapid indicators of perturbations and land use changes in the surrounding soil (Morugán-Coronado *et al.*, 2015; García-Orenes *et al*., 2013; Zornoza *et al.*, 2009). They include bacteria and fungi which are the dominant decomposers in soil (Lelei and Onwonga, 2014; Waring *et al.*, 2013; Beauregard *et al.*, 2010). Changes depend on natural characteristics of soils.

The major soil types in medium and high altitudes of eastern and north eastern Rwanda are Ferralsols, Lixisols and Acrisols (Verdoodt and Van Ranst, 2003). They have high development of layers (AEBtC horizons) which are mostly susceptible to land transformation (Driessen *et al.*, 2001). Ferralsols are deep and intensely weathered soils. They are characterized by; (1) a deep solum with diffuse or gradual horizon boundaries, (2) a ferralic subsurface horizon, reddish or yellowish in colour, with weak macro-structure and strong microstructure, and (3) deep internal drainage (Driessen *et al.*, 2001). Lixisols are strongly weathered soils. They have a thin, brown, surface horizon over a brown or reddish brown argic Bt-horizon that often clear evidence of clay illuviation. Lixisols have higher base saturation and moisture holding properties slightly better than Ferralsols and Acrisols with the same contents in clay and organic matter (Driessen *et al.*, 2001). Acrisols are acidic soils with a layer of clay accumulation and a low cation exchange capacity. They have low availability of nutrients and its topsoil organic matter is easily lost. They also have a weak physical structure; i.e. weak microstructure and massive macrostructure, especially in the surface and subsurface soil (Driessen *et al.*, 2001).

Other soil types in the medium and high altitude areas include Cambisols and Regosols/ Leptosols. Cambisols are soils with slight profile development. They occur predominantly in hilly and mountain regions. They comprise of soils that range from shallow to moderately shallow and contain at least some weatherable minerals in the silt and sand fractions. Regosols and Leptosols are shallow in depth and with weak profile development (Verdoodt and Van Ranst, 2003; Driessen *et al*., 2001).

2.2 Maize production

2.2.1 Importance of maize production in food security

Maize is an important staple and food security crop in Rwanda. It has become a major income generating crop for small scale farmers and ranks first among pulse and grain crops in annual production (RAB, 2013). It is grown on a surface area covering 12.4% of agricultural land after cassava (21.5%) and bush beans (2.9%) (NISR, 2016). It was cultivated on 210,609 and 218,179 ha with total productions of 324,368 and 332,670 MT in cropping seasons A 2017 and A 2018, respectively (NISR, 2018). Its productivity on farm level was 1.74 t ha^{-1} in season A 2015 (NISR, 2016) and decreased to 1.5 and 1.6 t ha^{-1} in seasons A 2018 and A 2019, respectively (NISR, 2019). Worldwide, maize is grown in 184 M ha across 165 countries with total production of 1,016 MMT and average productivity of 5.52 t ha^{-1} (Yadav *et al.*, 2016).

2.2.2 Maize production on terraced land

Maize production has been promoted on terraced land in Rwanda. Terraces are created to promote permanent agriculture on steep slopes, land consolidation and intensive land use (Kagabo, 2014). Maize is one of the six priority crops in crop intensification program (CIP); i.e. maize, wheat, rice, Irish potatoes, beans and cassava (Rwibasira, 2016). Maize yields are likely greater in terraced lands than on sloppy areas. For example, bench terraces in the Andes resulted in 20% higher maize yields (Posthumus and Stroosnijder, 2010).

2.2.3 Climate and soil requirements in maize production

Maize is a warm weather crop. Although the minimum temperature for germination is 10ºC, it is faster and less variable at soil temperatures of 16 to 18ºC (Jéan du Plessis, 2003). Maize needs 450 to 600 mm of water per season, which is mainly acquired from the soil moisture reserves. Maize plant can be successfully grown on soils with pH ranging from 5 to 8, but the optimum level ranges from 6 to 7 (Mallarino *et al.*, 2011). Although large-scale maize production takes place on soils with a clay content of less than 10% (sandy soils) or in excess of 30% (clay and clay loam soils), the textural classes between 10 and 30% of clay have air and moisture regimes that are optimum for healthy maize production (Jéan du Plessis, 2003).

2.2.4 Nitrogen requirements in maize production

Nitrogen is an important element for maize, and the one that most often limits yield (Davis *et al.*, 2010; Belfield and Brown, 2008). Nitrogen increases vegetative growth and determines number of leaves and number of seeds per cob. It is an integral part of proteins, the building blocks of plant, and helps in maintaining higher auxin level (Reddy *et al.*, 2018). It increases the photosynthetic capacity, rapidly converts the synthesized carbohydrates to proteins and protoplasm, and this extra protein allows the plant to grow faster (Om *et al.*, 2014).

Under good growing conditions, a yield response of 30 kg grain per kg N can be obtained (Roy *et al.,* 2006). Nitrogen requirements for maize plant growth are high compared to those of other cereals; the rate of up to 150 kg N ha^{-1} is recommended (Getnet and Dugasa, 2019; Reddy *et al.,* 2018; Jassal *et al.,* 2017; Kaur, 2016; Taye *et al.,* 2015; Om *et al.,* 2014; Dawadi and Sah, 2012; Onasanya *et al.,* 2009; Belfield and Brown, 2008 and Zebarth *et al.,* 2006).

Maize plant absorbs small amounts of nitrogen at the start of the growing period. During vegetative growth maize can accumulate luxury N in excess of what is required for biomass accumulation (Nasielski *et al.*, 2019). The maximum N content in maize crop coincides with the greatest period of dry matter accumulation during its vegetative growth. This is the period from V10 (tenth leaf) to V14 (fourteenth leaf) of maize vegetative growth stages. Maize requires the availability of 7.8 lb (3.5 kg) N day^{-1} (Bender *et al*, 2013). At the flowering time, the plant can accumulate more than 40% of the total N required during the early growing period (Belfield and Brown, 2008). The N content decreases in the course of the plant maturity until at the harvest period, and about two-thirds of the N absorbed by the plant ends up in the kernels at maturity (Belfield and Brown, 2008). The potential uptake of 250 - 300 kg N ha^{-1} where grain yields of 12 t ha^{-1} or more can be expected (Roy *et al.,* 2006). Crop N uptake depends on soil mineral N availability and distribution, and it is dominantly up taken in the forms of NO_3^{2-} and NH_4^+ (Gastal and Lemaire, 2002). Soil organic N can also be up taken by crop and may represent a significant proportion of total N absorption under particular ecological situations like acidic soils and low temperature environments (Gastal and Lemaire, 2002). In an optimum N supply, N uptake depends on root system distribution, and in field conditions where N supply is limited, plants can increase their root size to assimilate more soluble N from the soil (Wang *et al.*, 2008).

For the methods and timing of N applications, Davis *et al.(*2010) reported that nitrogen may be applied to soil by various methods. The most efficient use is applying N just prior to the rapid growth period, i.e. 30 to 40 days after planting, when plants have about six leaves. However, it is good to apply all of the fertilizer before tasseling stage to maximize N use efficiency.

2.2.5 Phosphorus requirements in maize production

Phosphorus is the second most crop-limiting nutrient, after nitrogen, in most of soils. Phosphorus improves photosynthesis, utilization of sugar and starch, nucleus formation and cell division (Masood *et al.,* 2011; Roy *et al.,* 2006). It is a constituent of nucleic acids, phospholipids, coenzymes and most importantly adenosine triphosphate (ATP). It activates coenzymes for amino acid production used in protein synthesis (Reddy *et al.*, 2018). Energy from photosynthesis and the metabolism of carbohydrates is stored in phosphate compounds for later use in growth and reproduction (Masood *et al.*, 2011). Grain yield is also directly related to complex phenomenon of phosphorus utilization in plant metabolism (Reddy *et al.*, 2018). Phosphorus deficiency in many of the soils is largely due to low occurrence of P-containing minerals and P-fixation and continuous cropping without commensurate nutrient replenishment (Wasonga *et al.*, 2008; Bunemann, 2003). Rates of phosphorus application should be varied according to soil test for available P and in relation to yield potential. These should be in the range of 30 - 100 kg P_2O_5 ha^{-1} (Roy *et al.*, 2006).

2.2.6 Fertilizer use in maize production in Rwanda

Maize fertilization in Rwanda is done by applying farm yard manure (FYM) at the rate of 10 t ha^{-1} at time of the second ploughing and mineral fertilizers: 250 kg ha^{-1} of NPK17.17.17 or 100 kg ha^{-1} of DAP at time of sowing and 50 to 100 kg ha^{-1} of urea at 45 days after sowing (MINAGRI, 2009; Kelly and Murekezi, 2000). These rates are equivalent to 10 t FYM ha^{-1}, 41 -88.5 kg N ha^{-1} and 42.5 - 46 kg P_2O_5 ha^{-1}. On acid soils, 2.5 to 5 t ha^{-1} of lime is recommended and its effects last for two years (MINAGRI, 2009). These fertilizer recommendations were established before terraces construction. Inorganic fertilizers are insufficiently used. A country average of 48.6% large scale farmers used inorganic fertilizers on maize crop in season A 2015 (NISR, 2016).

2.3 Bioslurry use for improved soil properties and maize yields

2.3.1 Composition of bioslurry and forms of utilization

Bioslurry is an anaerobic digested organic material released as a by-product from a biogas plant after production of combustible methane gas. With the right amounts of materials, bioslurry consists of mainly 93% water, 7% dry matter of which 4.5% is organic and 2.5% is inorganic matter (Warnars and Oppenoorth, 2014; Karki, 2006). A well-digested bioslurry contains 1.4 -1.8% N, 1.0 - 2.0% P_2O_5, 0.8 - 1.2% K_2O and 25 - 40% organic carbon (Warnars and Oppenoorth, 2014). Nitrogen is the main nutrient in bioslurry. Factors influencing N availability from bioslurry are its inorganic N content, digestion process (aerobic or anaerobic), C: N ratio, pH, the method and timing of application, and physical and chemical properties of the soil (Shahbaz *et al.*, 2014; Islam *et al.*, 2010; Warman and Termeer, 2005). There are three forms of utilization while applying bioslurry to soils (Warnars and Oppenoorth, 2014; Karki, 2006). (i) Liquid form: the digested slurry can be applied directly in the field using a bucket or it can directly be discharged through an irrigation canal. (ii) Dried form: as the transportation of the liquid slurry is difficult, most of the farmers prefer to dry the slurry before transporting it to the field. (iii) Composted form: the best way to overcome the above mentioned drawbacks is to utilize the slurry by making compost.

Figure 2.2 Illustration of bioslurry liquid form

The availability of bioslurry depends on the unit quantities, size and management of installed biogas plants. In Rwanda, the National Domestic Biogas Programme (NDBP) targeted 12,500 units by 2016 (Rakotojaona, 2013). A total of 3,365 biogas digesters have been disseminated in households (domestic biogas plants) by 2013. They are different sizes: 4, 6, and 10 m^3 (MININFRA, 2014).

2.3.2 Bioslurry compared to Farm Yard Manure (FYM) and soil quality improvement

Bioslurry has proved to be a high quality organic manure compared to FYM and compost. Digested slurry has (slightly) more nutrients because in FYM the nutrients are lost to some extent by volatilization (nitrogen) due to exposure to sun (heat) as well as by leaching (Lam and Heegde, 2011). Respective average contents in N, P_2O_5 and K_2O are: 0.8, 0.7 and 0.7% for FYM, 1.0, 0.6 and 1.2% for compost, and 1.6, 1.55 and 1.00% for bioslurry (Karki, 2006).

Bioslurry may be considered as quality 100% organic fertilizer. It is environmental-friendly, renewable source of nutrients for plants, and has no toxic or harmful effects *(*Islam *et al.*, 2010; Islam, 2006). Bioslurry plays a vital role in restoring soil fertility; it has the potential to reduce dependency on expensive chemical fertilizers and increases yields (Shahbaz *et al.*, 2014). The use of bioslurry from the biogas plants can reduce the application of chemical fertilizers by 40 - 50% (Islam, 2006). In addition to nutrient supply, bio-slurries in their different forms improve the physical and biological quality of soil. Application of bioslurry improves soil structure and aeration, increases water-holding capacity, and diversifies nutrients for sustainable crop productivity (Shahbaz *et al.*, 2014; Zhu and Chen, 2002).

2.3.3 Effects of bioslurry on maize production

Bioslurry is suitable for field crops such as maize. Different studies have demonstrated that bioslurry-based organic fertilizers increased yields of crops including maize (Warnars and Oppenoorth, 2014; Karki, 2006). In Nepal, the application of slurry compost at 10 t ha^{-1} resulted in maize yield increment of 23% over control, and the application of the same rate of bioslurry (liquid form) increased yield by 10% over control, while the application of full dose of chemical fertilizers (120: 60: 40 as N: P_2O_5: K_2O kg ha^{-1}) yielded 8% more than the control (Karki, 2006). Islam *et al.* (2010) reported that maize plant height and stem circumference were significantly influenced by increasing rates of bioslurry (0, 60, 70 and 82 kg N ha^{-1}). Increases were observed with increase in bioslurry N rates up to 70 kg N ha^{-1} while decreases occurred with excessive application of 82 kg N ha^{-1}, at all evaluated dates (14, 28, 42, and 56 days after sowing).

2.4 Combined application of bioslurry and mineral inputs

Organic inputs contain nutrients that are released at a rate determined in part by their chemical characteristics or organic resource quality (Vanlauwe and Zingore, 2011). However, organic inputs applied at low rates, commonly used by smallholder farmers in Africa, seldom release sufficient nutrients for optimum crop yield. Combining organic and mineral inputs has been advocated as a sound management principle for smallholder farming in the tropics because neither of the two inputs is usually available in sufficient quantities and both are needed in the long-term to sustain soil fertility and crop production (Vanlauwe and Zingore, 2011). A combination of mineral and organic sources results in a general improvement in soil fertility status. Yield improvement is usually greater when organic inputs and fertilizers are applied together (Mugwe *et. al.*, 2019; Fairhurst, 2012). It results in improvement of agronomic efficiency of the nutrients compared to the same amount of nutrients applied through either source alone (Vanlauwe *et al.*, 2001). Thus, it is necessary to use fertilizer and manure in an integrated way in order to obtain sustainable crop yield without affecting soil fertility (Islam *et al.*, 2013). The combination of urea and bioslurry improves soil properties and enhances maize yields than their isolated application at the same rates (Tuyishime, 2012).

2.5 Models for estimating optimum fertilizer rates

Models are used in estimating optimum fertilizer rate and predict maximum crop yield. The quadratic regression analysis is described as a quadratic function (Cassman and Plant, 1992). Experimental factors (fertilizer rates) are predictors or explanatories and crop yield is predicted. The optimum is determined by calculating the first derivative of the derived crop yield response curve to the fertilizer application rate; i.e. projecting crop yield as a function of increasing rates of fertilizer. The full quadratic equation as a response model incorporates:

- Linear terms in each of the variables ($x_1, x_2, \dots, x_n$).
- Squared terms in each of the variables ($x_1^2, x_2^2, \dots, x_n^2$).
- The coefficients of the response model ($\beta_1, \beta_2, \dots, \beta_n$).
- The intercept coefficient (β_0).

The general model of the response depicted by a quadratic equation is:

$$Y = \beta_0 + \beta_1 x + \beta_2 x^2$$

Where: y is the predicted response (crop yield), β_1 the linear terms, β_2 the squared terms, x represents independent variable (fertilizer rates) and β_0 is the intercept coefficient.

Considering nitrogen fertilizer rates as independent variable (N), the formula depicting the response (quadratic) equation and agronomic optimum rate (N_{agr}) is presented below (Wang et al., 2014):

$$YN = Y - Y0 = \beta_1 N + \beta_2 N^2$$

$$N_{agr} = -\beta_1 / 2\beta_2$$

Where Y is crop yield (total) response with the application of a given N fertilizer rate, YN is the increase in crop yield response with the addition of N fertilizer application (i.e. N-derived yield), Y and Y_0 are the crop yields with and without applied N, respectively; N is the nitrogen fertilizer application rate (kg N ha^{-1}), β_1 and and β_2 are regression coefficients.

The quadratic regression analysis was used in this study to determine optimal fertilizer rates for maximum maize yield.

2.6 Gaps in literature

Soils of Rwanda in different AEZ were characterized and documented in soil maps before the recent explosive promotion of land terracing practice for soil conservation. Thus data on new characteristics of the perturbed soils of terraced lands are lacking. In addition different studies have been conducted and demonstrated the benefit of combining organic and inorganic fertilizers in soil fertility replenishment, but fertilizer recommendation for terraced lands is lacking. The use of bioslurry as organic fertilizer has been demonstrated to increase crop yields and its integration effect with nitrogen fertilizer to enhance maize yields. However, application rates of bioslurry in combination with mineral N that optimize maize yields in terraced lands are lacking.

CHAPTER THREE
MATERIALS AND METHODS

3.1 Experimental sites

The study was done in Rwamagana and Gicumbi districts located in the medium- and high-altitude regions of eastern and north eastern Rwanda, respectively (Figure 3.1), from February 2017 to August 2018. The medium altitude site (1502 – 1647 m a.s.l.) is situated in the plateaux of Eastern Province agro-ecological zone (AEZ). Soils are mainly Ferralsols/ Lixisols (Verdoodt and Van Ranst, 2003). Mean annual rainfall received is 950 - 1000 mm and average annual temperature range is 19 - 30°C (Rwamagana District, 2013). The high altitude site (1881 – 2130 m a.s.l.) is located in the Buberuka highlands AEZ. The predominant soils are Alisols / Acrisols (Verdoodt and Van Ranst, 2003). Mean annual rainfall received is 1200 - 1500 mm and average annual temperature range is 13.2 - 20.8°C (Gicumbi District, 2013). Crops grown in the previous cropping season were beans in medium altitude site and peas in high altitude. Soil fertilization practice was application of Farm Yard Manure (FYM) in both areas. The coordinates and specific soil types across the top, medium and bottom slopes of the study sites are presented in Table 3.1. The trial for objectives three and four was set up at middle slope of terraced land adjacent to the trial for objective two in the same study area. There was one site per altitude.

3.2 Trial one: effect of terracing on soil physical, chemical and biological properties across slope positions and profile depths

3.2.1 Soil sampling

Soil samples for analysis of chemical, physical and biological properties were collected from the top, middle and bottom slopes of four year old terraced and adjacent non - terraced lands, in both Rwagamana and Gicumbi districts. For determination of soil chemical properties and texture, composite samples were collected in a zig zag pattern using a soil auger from each slope position and site at three soil depths (0 - 30, 30 – 60 and 60 - 90 cm), in triplicates. A total of 108 samples, composed of 6 samples taken at each of the three soil depths in the three slope positions of the two sites, were collected. The collected soil samples were placed in labelled bags, sealed and transported to the laboratory. The samples were air-dried for a week and sieved through a 2-mm sieve.

Table 3.1 Coordinates and soil types across slope positions in the study areas

Site	Slope position	Slope average (%)	Altitude (m)	Coordinates		Soil types
				Latitude	Longitude	
Medium altitude	Top	28	1647	1˚ 56' 26" S	30˚ 19' 33" E	Dystric Regosols/ dystric Leptosols
	Middle	21	1565	1˚ 56' 42" S	30˚ 19' 38" E	Haplic (humic) Ferralsols/ haplic Lixisols
	Bottom	21	1502	1˚ 56' 55" S	30˚ 19' 42" E	Haplic (humic) Ferralsols/ haplic Lixisols
High altitude	Top	22	2130	1˚37' 52" S	30˚ 05' 01" E	Humic Alisols/ humic Acrisols
	Middle	32	2061	1˚ 37' 56" S	30˚ 04' 31" E	Humic Alisols/ humic Acrisols
	Bottom	22	1881	1˚ 37' 35" S	30˚ 04' 39" E	Humic Acrisols/ humic (ferralic) Cambisols

Source: GPS Garmin data processed with ArcGIS 10.2 and GIS soil map of Rwanda (Verdoodt and Van Ranst, 2003)

For bulk density determination, four undisturbed soil samples were collected in duplicates using 5 x 5 cm core rings at each of the four soil depths (0 – 20, 20 – 40, 40 – 60 and 60 – 80 cm) in the three slope positions of the two sites to give a total of 96 samples (Figure 3.2). For water holding capacity and hydraulic conductivity determinations, four undisturbed 5 x 5 cm core samples were collected in duplicates from 0 – 30 and 30 - 60 cm depths in each of the 3 slope positions in the two sites giving a total of 48 samples (Figure 3.2). The collected soil cores were trimmed, labelled, and the top and bottom were secured with plastic caps and sealed in bags. The soil cores were transported to the laboratory. For biological analysis, composite samples were collected, in triplicate, from surface soil (0 – 30 cm depth) at each slope position and site, giving a total of 36 samples for analysis. The collected samples were placed in labelled bags, sealed and transported to the laboratory in portable cooled boxes. They were frozen at 4^oC for a maximum of 48 hours before analysis.

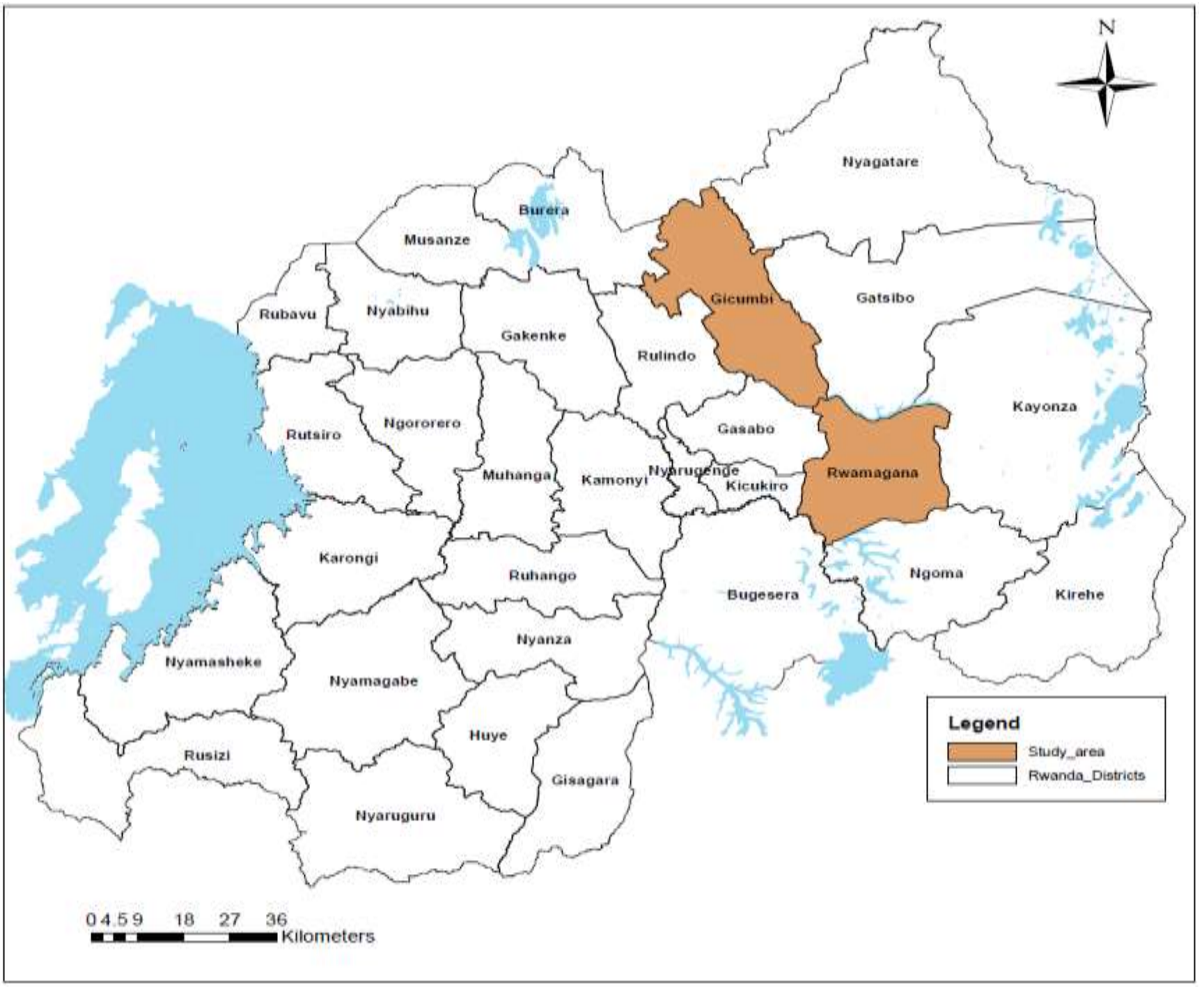


Figure 3.1 Study area processed with administrative shapefiles of Rwanda and GPS data

Figure 3.2 A typical soil profile pit in the high altitude site and taking undisturbed core soil sample

Texture, bulk density and chemical and biological properties of soils were measured at the soil science laboratory of the College of Agriculture, Animal Sciences and Veterinary Medicine, University of Rwanda. Soil water holding capacity and hydraulic conductivity were measured at the laboratory of Kenya Agriculture and Livestock Research Organization (KALRO - Kabete).

3.2.2 Analysis of soil physical properties: texture, bulk density, water holding capacity and hydraulic conductivity

Soil texture: texture was determined using the hydrometer method (Pal, 2013; Kroetsch and Wang, 2006; Okalebo *et al.*, 2002). Fifty grams of air dried soil (< 2mm) was weighed, moistened with distilled water and 10% hydrogen peroxide added in aliquots of 10 ml in a fume chamber. Hydrogen peroxide oxidizes any organic matter present in the soil. The sample was allowed to stand for 12 hours for the reaction to take place and thereafter 50 ml of calgon solution (10% sodium hexametaphosphate) was added to separate the particles of sand, silt and clay. The sample was stirred to disperse the particles. The mixture was then transferred into a 1000 ml sedimentation cylinder and topped up with distilled water to make 1000 ml. The cylinder was covered with tight-fitting rubber bund and the suspension mixed by inverting the cylinder carefully ten times. Two drops of amyl alcohol were quickly added to remove froth and after 20 seconds, a hydrometer was gently placed in the column. After 40 seconds, the first hydrometer reading was taken and temperature of suspension measured. The soil suspension was again mixed ten times. The cylinder was allowed to stand undisturbed for 2 hours. Then the second hydrometer and temperature readings were taken. Temperature records were used to correct hydrometer readings (Table 3.2) because hydrometer had been calibrated at 20°C (Okalebo *et al.*, 2002).

The first reading corresponds to the concentration of clay and slit, the second to the concentration of clay alone. Percentages of sand (2 - 0.05 mm), silt (0.05 - 0.002 mm) and clay (< 0.002 mm) were calculated using the hydrometer readings. A textural triangle (appendix 21) was then used to assign the soil into its textural class.

% Sand : [(W – (H1 + hc))/W]*100 …………………….………………………....…. (1)

% Clay : [(H2 + hc)/W]*100 …………………………………………………..……. (2)

% Silt : 100 - (% Sand + % Clay) ………………………......………...…………. (3)

Where: H1 is the first reading with hydrometer (i.e. clay + silt), H2 is the second reading with hydrometer (i.e. clay), hc is the hydrometer reading correction factor and W is the weight of sample (i.e. 50 g).

Table 3.2 Temperature correction for hydrometer readings of soil texture

Temperature (°C)	Hydrometer correction (hc) (g per litre)
15	- 2
16	-1.5
17	-1.0
18	-1.0
19	-0.5
20	Nil
21	+0.5
22	+1.0
23	+1.0
24	+1.5
25	+2.0

Source: Okalebo *et al.* (2002)

Bulk density: soil bulk density was determined on undisturbed soil core samples oven-dried to constant weight at 105ºC for 48 hours. Bulk density was calculated by dividing the dry weight of each core sample by volume of the core ring (Pal, 2013; Kroetsch and Wang, 2006; Okalebo *et al.*, 2002).

Bulk density (g cm^{-3}) = (W2 g – W1 g) / V cm^3 …………………………….…… (4)

Where: W1 is the weight of core ring, W2 is the weight of dry sample with core ring, and V is the volume of the core ring.

Soil water holding capacity: soil retention capacity was determined by the pressure-plate method (Jury *et al.*, 1991). It consists of an air-tight chamber enclosing a water-saturated, porous ceramic plate connected on its underside to a tube that extends through the chamber to the open air. Water retained by the soil at various pressures was measured, from which the respective soil moisture characteristic curves were obtained. These were then used to obtain the total available water content (TAWC) as the difference between moisture at field capacity, pF2.0 (i.e. 0.1 bar suction), and permanent wilting point, pF4.2 (i.e.15 bar suction). The TAWC was expressed in percentage on a volume rather than dry-weight basis (Banami and Ofen, 1984). The percent on volume basis was obtained by multiplying percentage on weight basis by relative bulk density (i.e. soil bulk density divided by density of water). One percent of water content in the soil is equivalent to 1 cm (or 10 mm) of water per meter depth of soil. Assuming a homogeneous soil profile, (i.e. by using average values for a profile), the TAWC was calculated using Equation below:

TAWC = [FC (%wt) – PWP (%wt)] * RBD * 10 * Root zone depth (m)……............. (5)

Where: TAWC (mm m^{-1} soil depth) is the total available water content, FC (%wt) is the percentage of water content at field capacity, PWP (%wt) is the percentage of water content at permanent wilting point, and RBD is the relative bulk density.

Hydraulic conductivity: soil permeability, which is equivalent to saturated hydraulic conductivity, Ks, was determined from soil core samples obtained from profile pits in the field. The constant head method was used, whereby one-dimensional vertical flow of water was imposed upon a core sample by confining it, except for the ends, in an impermeable casing (Klute and Dirksen, 1986). A steady flow rate of water, at a constant head, h, was then passed continuously through the core sample of length, L. The water was then collected at its lower end and its volume recorded in a given time period. The saturated hydraulic conductivity, Ks (cm hr^{-1}), was then given by Equation below:

Ks = (Q/A)*(L/h) ……………………………………………………..………. (6)

Where: Q (cm^3 hr^{-1}) is the steady flow rate of water through the sample (i.e. volume / time), A (cm^2) is the cross-sectional area of the sample, L (cm) is length of the soil core sample, and h (cm) is the hydraulic constant head between the two ends, which is a constant in this case.

3.2.3 Analysis of soil chemical properties: pH, exchangeable acidity, organic carbon, total Nitrogen, available phosphorus, CEC and exchangeable bases

Soil pH: the $pH_{(water)}$ in a 1: 2.5 soil - water solution and $pH_{(KCl)}$ in a 1: 2.5 soil - KCl 1N solution was determined using the glass electrode method (Pal, 2013; Okalebo *et al.*, 2002). Ten grams of air-dried samples passed through a 2 mm sieve was put in two sets of clean plastic bottles. To each set, 25 ml of distilled water or KCl 1N solution was added. The samples were shaken for 30 minutes in a reciprocating mechanical shaker, allowed to stand for 30 minutes and the readings on a pH meter recorded.

Exchangeable acidity: the total exchangeable acidity ($H^+ + Al^{3+}$) and exchangeable Al^{3+} were analyzed using titration method (Okalebo *et al.*, 2002). Five grams of air-dried soil (2 mm) was put into 50 ml centrifuge tube, and 30 ml of KCl 1N solution was added to it. The mixture was shaken for 1 hour using a reciprocal mechanical-electric shaker. The contents were centrifuged at 2000 rotations per minute for 15 minutes. The clean supernatant liquid was carefully decanted off into a 100 ml clean volumetric flask. Thirty ml of KCl 1N was added to the same soil sample and shaken for 30 minutes, then centrifuged for 15 minutes and the clear supernatant was transferred into the same volumetric flask. The step was repeated for the third time and the clear supernatant was combined again into the same volumetric flask. The volume was made up to 100 ml mark with KCl 1N solution. The blank was also made. Twenty five ml of the above KCl 1N extract was put in an Erlenmeyer measuring cylinder of 100 ml. Five drops of phenolphthalein indicator added to it, and titrated with NaOH 0.05 N to a persistent pink end point. The amount of base used is equivalent to the total amount of acidity ($H^+ + Al^{3+}$) in the aliquot taken. To the same conical flask, 1 drop of HCl 0.05 N was added to bring the solution back to the colourless state and 10 ml of 4% NaF solution added. Then the solution was titrated with HCl 0.05 N until the colour disappeared and did not return within 2 minutes. The millequivalents of acid used are equal to the amount of exchangeable Al^{3+}. The blank was also made. The exchangeable acidity were calculated using the formula below:

Exchangeable acidity ($cmol_{(+)}\ kg^{-1}$) = (T – bl) * N * (100/w)*(100/v)…..…………….(7)

Exchangeable Al^{3+} ($cmol_{(+)}\ kg^{-1}$) = (T-bl)*N*(100/w)*(100/v)……………………..(8)

Where: T is titre of the sample, bl is titre of the blank, N is normality of NaOH used in titration for exchangeable acidity (i.e. 0.05) and normality of HCl used in titration for exchangeable Al^{3+} (i.e. 0.05), w is the weight of the sample (i.e. 5 g) and v is the volume of KCl extract titrated (i.e. 25 ml).

Organic carbon: soil organic carbon (SOC) was determined using the Walkley Black method (Pal, 2013; Okalebo *et al.*, 2002). This method involves complete oxidation of soil organic carbon using concentrated H_2SO_4 and potassium dichromate. One gram of air-dried soil (0.5 mm) was weighed into block digester tubes, and 5 ml of $K_2Cr_2O_7$ 1 N solution and 7.5

ml of concentrated H_2SO_4 were added. The tubes were placed in a pre-heated block at 145 - 155^oC for 30 minutes, then removed and allowed to cool. Quantitatively the digest was transferred in a 100 ml conical flack. The indicator solution was added (0.3 ml) and mixed using magnetic stirrer. The digest was thereafter titrated with ammonium ferrous sulphate 0.2 N solution; the endpoint was reached with a color change from greenish to brown. The organic carbon in percentage was calculated using the formula below.

Organic carbon (%) = (T – bl) * N * 0.03 /w ……………. ……………………… (9)

Where: T is titre of the sample, bl is title of the blank, N normality of ammonium ferrous used in titration (i.e. 0.2 N), 0.03 is ammonium ferrous correction factor, and w is weight of the sample (i.e. 1 g).

Total nitrogen: the total nitrogen was determined using the Kjeldahl method (Pal, 2013; Okalebo *et al.*, 2002). One gram air-dried soil (0.5 mm) was weighed into a clean digestion tube and 3 g of digestion mixture catalyst added followed by concentrated HCl. The sample was digested at 110^oC for 1 hour, then removed and allowed to cool. Three successive 1 ml portion of hydrogen peroxide was added. The temperature was raised to 330^oC and heating continued until the solution turned colourless and any remaining sand white, then contents was allowed to cool. Distilled water (25 ml) was added and mixed well, then the content was allowed to cool. Thereafter the content was put in a volumetric flask and distilled water was added to 100 ml, then allowed to settle. A clear solution was taken from the top of the tube for analysis. The reagent blank was also made. Ten ml of above clear solution was introduced into a distillation tube, and 10 ml of distilled water and 10 ml of 50% NaOH were added. The content was distilled and 100 ml of distillate was collected in an Erlenmeyer of 250 ml containing 5 ml of 2% boric acid. The collected distillate was titrated with HCl until a pink colour appeared. The blank was also titrated. The quantity of HCl used was recorded. The total N in percentage was calculated using the formula below:

Total N (%) = (T - bl) * N * 0.014 * (100/w) * (100/v) …………………………(10)

Where : T is titre of the sample, bl is title of the blank, N is the normality of HCl used (i.e. 0.01N), 0.014 is Nitrogen correction factor, w is weight of the sample (i.e. 1 g), and v is volume of the distillate titrated (i.e. 10 ml).

Available phosphorus: The available phosphorus was determined using Bray II method which is the specific method for acidic soils (Pal, 2013; Okalebo *et al.*, 2002). The standard series was first prepared. Volumes of 0, 1, 2, 5, 10, 15 and 20 ml of phosphate standard stock solution (1.0984 g of oven-dry KH_2PO_4 dissolved and filled to 1000 ml with distilled water) were put in 500 ml volumetric flasks. Then 100 ml of Bray II extracting solution (0.03N NH_4F and 0.1N HCl) was added and filled to 500 ml mark with distilled water. The standard series solutions contained 0, 0.5, 1.0, 2.5, 5.0, 7.5 and 10.0 mg P per liter. For extraction, five g of air-dried soil (2 mm) was weighted into a plastic 250 ml bottle, then 50 ml of the Bray II extracting solution was added and the content was shaken by hand for 5 minutes. Then the content was filtered. Colorimetric measurement of phosphorus was made. Ten ml for each P standard series solutions and 10 ml for extract were put 50 ml volumetric flasks, 20 ml of distilled water and 5 ml of H_3BO_3 0.8 M were added. Beginning with the standards, 10 ml of ascorbic acid was added, then content was shaken by hand. The content was filled to 50 ml mark with distilled water, then shaken again. Then after 1 hour, the intensity of blue colour was read at 880 nm. The calibration curve was done in Excel using readings of standards, then concentrations of samples were calculated using the formula below:

P (ppm) = P (from calibration curve) * DF * (1/w) ………………………………. (11)

Where: DF is the dilution factor and w is the weight of the sample (i.e. 5g).

Cation exchange capacity: The cation exchange capacity (CEC) was determined using the ammonium acetate method (Okalebo *et al.*, 2002). A 2.5 g of air-dried soil (2 mm) was extracted with excess of 1 M NH_4OAc (ammonium acetate) solution at pH 7 such that the maximum exchange occurred between the NH_4^+ and the cations originally occupying exchange sites on the soil surface. Excess salts was removed with a 95% ethanol (percolated 10 times the sample and blank with 10 ml of ethanol). A sodium salt (10% NaCl) solution was used to replace and leach out adsorbed NH_4^+ (percolated 10 times with 10 ml of NaCl), then the volume was made up to 100 ml mark with 10% NaCl. A 25 ml of aliquot was introduced into a tube of Kjeldahl distillation, 10 ml of 40% NaOH and 10 ml of distilled water was added. The content was then distilled and 150 ml collected in a 250 ml Erlenmeyer flask containing H_3BO_3 2%. The 150 ml were titrated with HCl 0.1 N. The quantity of HCl used was recorded and the CEC was calculated using the formula below:

CEC ($cmol_{(+)}$ kg^{-1}) = (T – bl)*N * (V/v)* (100/w) ...………………….…..…….(12)

Where: T is titre of the sample, bl is title of the blank, N is normality of HCl used (i.e. 0.1N), V is total volume of the filtrate (i.e. 100 ml), v is volume of aliquot taken (i.e. 25 ml) and w is weight of sample (i.e. 2.5 g).

The amount of exchangeable K^+, Ca^{2+} and Mg^{2+} in the extract was determined by atomic absorption spectrophotometry. Effective cation exchange capacity (ECEC) was determined as the sum of exchangeable bases (Na^+, K^+, Mg^{2+}, Ca^{2+}) and exchangeable Al^{3+} (Hazelton and Murphy, 2007). It represents the soil's cation exchange capacity at field conditions (Driessen *et al.,* 2001).

3.2.4 Analysis of soil biological properties: bacteria and fungi populations

Soil samples for biological analysis were kept in fridge at 4^{o}C for a maximum of 48 hours before analysis. One gramme of soil was used to make the 10^o dilution. For total bacteria population, plate-count technique was used (Wallenius, 2011; Vieira and Nahas, 2005). It is based on incubating dilutions of soil suspension on Plate Count Agar (PCA), and counting colony-forming units (CFU). The dilutions used for planting were from 10^{-2} to 10^{-4} and incubation was done at 28^{o}C for 36 hours. Three replicates were done. For fungi population, the acidified Potato Dextrose Agar (PDA) was used as medium (Wallenius, 2011). The dilutions used for planting were 10^{-1} to 10^{-3} and incubation was done at 28°C for 5 days. Three replicates were done. Colony forming units per gram (CFU g^{-1}) of soil was calculated using the equation of Johnson and Case (2007) below:

$$\text{CFU g}^{-1} \text{ soil} = [\text{Number of colonies / Volume plated (ml)}]^* \text{ Dilution factor} \ldots\ldots \quad (13)$$

3.2.5 Statistical data analysis

Data were organized using Excel data sheet and subjected to Bartlett Chi-square test of homogeneity. Analysis of variance (ANOVA) was performed using statistical analysis system (SAS), version 9.2 (SAS, 2008). Duncan's Multiple Range Test (DMRT) was performed for means comparison. A 5% probability level was used for the significance of all statistical analyses (Meyers *et al.,* 2009; Gomez and Gomez, 1984). The analysis fits the statistical model below:

$$Y_{ijklm} = \mu + T_i + S_j + D_k + R_l + (TS)_{ij} + (TD)_{ik} + (SD)_{jk} + (TSD)_{ijk} + \varepsilon_{ijklm} \ldots\ldots (14)$$

Where: Y_{ijklm} is overall observation, μ is overall mean, T_i is effect of i^{th} terracing ($i = 1, 2$), S_j is effect of j^{th} slope position ($j = 1, 2, 3$), D_k is effect of k^{th} depth, R_l is effect of l^{th} replicate and ε_{ijklm} is random error term.

3.3 Trial two: effects of nitrogen and phosphorus application rates on maize growth and yields in terraced soils

The study was conducted to obtain P fertilizer rate for use in trial three. The test crop for the trials was maize (*Zea mays* L.), Tamira pool 9A (Base). Chemical fertilizers used were urea (46% N), triple super phosphate (TSP: 45% P_2O_5).

3.3.1 Experimental design and treatments

A field experiment was set up in the middle slope of terraced lands in both Rwagamana and Gicumbi Districts (same site as for trial one; see section 3.2). The trial was carried out for two seasons; B 2017 (March to August 2017) and A 2018 (September 2017 to February 2018). Initial characterization of soil physical, chemical and biological properties was done in trial one, i.e., section 3.2. A '4 × 4' factorial experiment in a Randomized Complete Block Design (RCBD) with 3 replications was established (Figure 3.3). There were four levels of nitrogen (0, 60, 120 and 180 kg N ha^{-1}) and four levels of phosphorus (0, 40, 80 and 120 kg P_2O_5 ha^{-1}) resulting in a total of 16 treatment combinations. The N and P rates were selected on the basis of current mineral fertilizer application rates in the areas; 41 – 88.5 kg N ha^{-1} and 42.5 – 46 kg P_2O_5 ha^{-1}.

3.3.2 Application of treatments and maintenance of sites

The agronomic practices done consisted of land preparation, plots establishment, fertilizer application, sowing and maintenance, as described below.

Land preparation: the experimental land was ploughed manually to loosen soil while removing weeds in order to facilitate decomposition and improve mineralization. This created a favourable condition for seed placement, root penetration and plant growth. This first digging was followed by secondary cultivation, raking and soil levelling before sowing.

Plots establishment: field layout was done immediately after ploughing. The land, on middle slope, was divided into three blocks. Each block was set up on a separate terrace and each subdivided into 16 plots, with foot path of 30 cm between plots. Each plot or experimental unit size was 8.4 m^2 (2.8 m × 3 m). Four rows were established in each plot with inter-row spacing of 70 cm and intra-row spacing of 30 cm (i.e. 10 plants per row).

Block 1	N2P1	N0P0	N3P1	N1P2	N1P0	N0P2	N1P3	N2P0	N3P3	N1P1	N0P1	N3P2	N0P3	N2P2	N3P0	N2P3
Block 2	N3P1	N1P1	N2P3	N1P0	N0P2	N1P3	N2P1	N3P3	N2P0	N0P0	N2P2	N0P1	N3P0	N0P3	N3P2	N1P2
Block 3	N2P3	N3P0	N0P3	N1P2	N2P0	N0P0	N3P1	N0P1	N2P2	N3P2	N1P3	N1P1	N0P2	N3P3	N2P1	N1P0

(a)

Block 1	N0P2	N1P2	N1P1	N0P0	N1P3	N2P1	N1P0	N2P0	N3P0	N3P1	N2P2	N3P2	N2P3	N0P1	N3P3	N0P3
Block 2	N1P0	N1P3	N2P1	N3P1	N0P2	N1P1	N2P3	N3P3	N2P0	N0P1	N3P2	N2P2	N0P3	N1P2	N0P0	N3P0
Block 3	N3P0	N2P3	N1P2	N0P0	N3P2	N0P3	N2P0	N0P1	N3P3	N2P2	N1P3	N1P0	N2P1	N1P1	N0P2	N3P1

(b)

Figure 3.3 Layout of treatments for determination effect of N and P application rates on maize growth and yield in terraced soils in (a) medium altitude site and (b) high altitude site

Key:

N0 = 0 kg N ha^{-1} — P0 = 0 kg P_2O_5 ha^{-1}

N1 = 60 kg N ha^{-1} — P1 = 40 kg P_2O_5 ha^{-1}

N2 = 120 kg N ha^{-1} — P2 = 80 kg P_2O_5 ha^{-1}

N3 = 180 kg N ha^{-1} — P3 = 120 kg P_2O_5 ha^{-1}

Fertilizer application: Urea and TSP (treatments) were applied in planting hole (banding). However, seed or seedling did not come into direct contact with the fertilizer. Half rate of urea (46% N) was applied at the time of sowing and the other half was top dressed 30 days after sowing. TSP (45% P_2O_5) was applied at sowing time.

Sowing: sowing was done by dibbling method. Two seeds were planted manually per hole at 5 cm depth, with spacing of 70 cm between rows and 30 cm within rows (MINAGRI, 2009). Thinning to one seedling per hill was done to retain the recommended population of 47,619 plants per hectare (MINAGRI, 2009). The sowing dates were 3rd and 4th March 2017 for the first season and the 6th and 7th September 2017 for the second season, at the high and medium altitude sites, respectively.

Maintenance: manual weeding was done twice during the vegetative cycle of maize to prevent competition between seedlings and weeds for light, space, water and minerals, and also aerate soil. Rocket pesticide was applied with interval of 5 days since 15 days after sowing to tasselling stage to control armyworm pest.

3.3.3 Crop data collection and analysis

Growth and phenology parameters: the assessment of treatments' effects on maize growth and phenology was performed on 8 tagged plants from two central rows in each plot. Plant height (cm) was measured from ground surface to the top of plant using a measuring tape, at 30, 60, and 90 days after sowing (DAS). Collar diameter (cm) was measured at the first node from the ground surface using a Vernier calliper on the same dates. Number of leave plant^{-1} were counted on the same dates. Number of days to 50% tasselling was recorded.

Yield parameters: yield parameters were collected at maize physiological maturity from two central rows on a surface area of 1.68 m^2 (1.4 m long and 1.2 m wide). Number of cobs plant^{-1} was recorded. The above ground portion of the plant was harvested and separated into stover and cobs. The stover (stalks and leaves) was chopped into small pieces and weighed. Sub-samples were weighed and oven-dried at 70°C in a ventilated oven to constant weight. The weights of oven-dry sub-samples were recorded and used to calculate total above-ground biomass yield. Grains on the cobs were shelled and weighted. The grain weight was adjusted to 13% moisture level and converted into grain yield (kg ha^{-1}). Hundred grain weight was measured using an electronic balance. Grain yield (at 13% moisture content) and total above-ground biomass yield (stover + cobs + grains) were determined using the formulae below (Tuyishime, 2012; Wasonga *et al.*, 2008):

GY (kg ha^{-1}) = (GW/PLS)*10000 * [(100 - GMH)/ (100 – GMD)]……............. (15)

Total dry matter yield (above-ground) = (GY + SY + CY)………………...…… (16)

Where: GY, GW, PLS, GMH and GMD are grain yield, grain weight at harvest, plot size harvested, grain moisture content at harvest and grain moisture content at 13%, respectively. GY, SY and CY are grain, stover, and cob dry matter yields, respectively.

Harvest index (H.I %) was calculated using the formula below:

H.I = (Grain yield / Total biomass yield) * 100 (Kaur, 2016; Bakht *et al.*, 2006).... (17)

Nitrogen Use Efficiency (NUE %): The agronomic nitrogen use efficiency (NUE) was calculated using the formula below (Chen, 2015) :

NUE (%) = [(YF –YC)/FN)]*100……………………………………………….…... (18)

Where, YF = Yield of fertilized plot, YC = Yield of control plot and FN = Fertilizer N applied (kg ha^{-1}).

3.3.4 Statistical data analysis

Data were organized using Excel data sheet and subjected to Bartlett Chi-square test of homogeneity. ANOVA was performed using SAS, version 9.2 (SAS, 2008). DMRT was performed for means comparison. A 5% probability level was used for tests of statistical significance (Meyers *et al.*, 2009; Gomez and Gomez, 1984). Correlation analysis was done to establish relationship among variables (Meyers *et al.,* 2009). The analysis fits the statistical model shown below:

$$Y_{ijklmn} = \mu + E_i + S_j + (ES)_{ij} + R_k + N_l + (NE)_{il} + (NS)_{jl} + (NES)_{ijl} + P_m + (PE)_{im} + (PS)_{jm} + (PES)_{ijm} + (NP)_{lm} + (NPE)_{ilm} + (NPS)_{jlm} + (NPES)_{ijlm} + \varepsilon_{ijklmn} \quad (19)$$

Where: Y_{ijklmn} is overall observation, μ is overall mean, E_i is effect of i^{th} environment or location or site (i = 1, 2), S_j is effect of j^{th} season (j = 1, 2), R_k is effect of k^{th} replicate (k = 1, 2, 3), N_l is effect of l^{th} nitrogen rate (l = 1, 2, 3, 4), P_m is effect of m^{th} phosphorus rate (m = 1, 2, 3, 4) and ε_{ijklmn} is random error term.

3.3.5 Quadratic regression analysis

To estimate optimum fertilizer rates, a quadratic regression analysis was performed between experimental factors (N, P_2O_5 fertilizer rates), which are predictors or explanatories, and grain yield (predicted). Only main effects of factors were considered. By projecting grain yield as a function of increasing rates of N and P_2O_5 fertilizers, the optimum rates were estimated by the zero-solutions of the derivatives of the projection equations. The general model of the response depicted by a quadratic equation is represented by the equation below (Cassman and Plant, 1992):

$$y = \beta_0 + \beta_1 x + \beta_2 x^2 \quad (20)$$

Where: y is the predicted response (grain yield), β_1 the linear terms, β_2 the squared terms, x represents independent variable (N, P_2O_5) and β_0 is the intercept coefficient.

3.4 Trial three: effects of bioslurry and mineral nitrogen application rates on soil properties and growth, N uptake and yields of maize in terraced soils

3.4.1 Test crop and fertilizers

The test crop for the trials was maize (*Zea mays* L.), Tamira pool 9A (Base). The mineral nitrogen source was urea (46% N). Bioslurry in liquid form was collected from the storage of domestic biogas plants belonging to farmers. Cow dung was the feeding raw material in the biogas plant.

The bioslurry was analyzed for pH, dry matter and nutrient composition before use. The pH of liquid bioslurry was measured using the glass electrode method. Dry matter content was determined by oven drying bioslurry liquid (semi-liquid) at 110°C (Peters *et al.*, 2003). Organic carbon was determined using dry ashing method (Peters *et al.*, 2003). Total nitrogen was determined using the Kjeldahl method (Peters *et al.*, 2003; Okalebo *et al.*, 2002) on bioslurry dry matter passed through a 0.5 mm sieve. Total phosphorus was determined using vanado – molybdate method after complete digestion with nitric and perchloric acid (Peters *et al.*, 2003). Potassium, Calcium and magnesium were measured by atomic absorption spectrophotometry after complete digestion with nitric and perchloric acid (Peters *et al.*, 2003). The bioslurry characteristics and nutrients content on dry-matter basis in medium and high altitude areas are presented in Table 3.3.

Table 3.3 Bioslurry characteristics and nutrients content on dry-matter basis

Bioslurry characteristics	Site location	
	Medium altitude	**High altitude**
pH	7.27	7.83
Dry matter content (%)	16.69	8.89
Organic Carbon (%)	18.36	31.90
Total Nitrogen (%)	0.97	1.16
Total Phosphorus (mg kg^{-1})	2.5	6.3
Potassium (mg kg^{-1})	1.1	0.7
Magnesium (mg kg^{-1})	9.9	6.8
Calcium (mg kg^{-1})	10	8.4

3.4.2 Experimental design and treatments

Field trials were carried out concurrently in both Rwamagana and Gicumbi Districts, in seasons A 2018 (September 2017- February 2018) and B 2018 (March 2018 – August 2018). The trials were done in the middle slope on terraced lands directly neighbouring fields for trial two. A ‘4 × 4’ factorial experiment in a Randomized Complete Block Design (RCBD) with 3 replications was established (Figure 3.4). The land was divided into three blocks. Each block was set up on a separate terrace and each subdivided into 16 plots, with foot path of 30 cm between plots. Each plot or experimental unit size was 8.4 m2 (2.8 m × 3 m). There were four levels of mineral nitrogen (0, 30, 60 and 90 kg N ha^{-1}) and four levels of bioslurry (0, 5, 10 and 15 t ha^{-1} in high altitude site and 0, 6, 12 and 18 t ha-1 in medium altitude) resulting in a total of 16 treatment combinations. The bioslurry collected and used for trials in medium altitude site had lower nitrogen (0.97% N) compared to that in high altitude site (1.16% N) (Table 3.2). Bioslurry rates applied in the two sites were uniform in terms of bioslurry N (i.e. 0, 60, 120, 180 kg bioslurry N ha^{-1}, equivalent to 0, 5, 10 and 15 t bioslurry ha^{-1} in high altitude site and 0, 6, 12 and 18 t bioslurry ha^{-1} in medium altitude).

Block 1	B3N2	B1N0	B2N3	B0N1	B1N2	B2N0	B3N1	B0N2	B1N1	B3N0	B0N0	B2N1	B3N3	B1N3	B2N2	B0N3
Block 2	B0N1	B2N0	B3N3	B1N3	B3N0	B1N2	B0N0	B2N1	B2N3	B0N2	B3N1	B1N0	B0N3	B2N2	B3N2	B1N1
Block 3	B1N3	B3N3	B0N1	B2N0	B2N1	B0N2	B1N2	B3N1	B3N0	B1N1	B2N2	B0N0	B1N0	B3N2	B0N3	B2N3

(a)

Block 1	B2N3	B3N1	B1N2	B2N0	B1N3	B0N1	B2N1	B0N2	B1N1	B0N3	B3N3	B1N0	B2N2	B3N2	B0N0	B3N0
Block 2	B3N3	B0N1	B0N0	B3N0	B2N0	B2N1	B1N0	B1N2	B0N3	B0N2	B1N3	B3N2	B2N3	B1N1	B2N2	B3N1
Block 3	B0N3	B2N1	B3N2	B2N2	B3N3	B1N1	B1N3	B1N0	B2N3	B0N2	B2N0	B1N2	B3N1	B0N1	B3N0	B0N0

(b)

Figure 3.4 Layout of treatments for evaluating effects of bioslurry (B) and mineral nitrogen (N) in (a) medium and (b) high altitude sites

Key:

(a) B0 = 0 t bioslurry ha^{-1} = 0 kg bioslurry N ha^{-1} N0 = 0 kg N ha^{-1}

B1 = 6 t bioslurry ha^{-1} = 60 kg bioslurry N ha^{-1} N1 = 30 kg N ha^{-1}

B2 = 12 t bioslurry ha^{-1} = 120 kg bioslurry N ha^{-1} N2 = 60 kg N ha^{-1}

B3 = 18 t bioslurry ha^{-1} = 180 kg bioslurry N ha^{-1} N3 = 90 kg N ha^{-1}

(b) B0 = 0 t bioslurry ha^{-1} = 0 kg bioslurry N ha^{-1} N0 = 0 kg N ha^{-1}

B1 = 5 t bioslurry ha^{-1} = 60 kg bioslurry N ha^{-1} N1 = 30 kg N ha^{-1}

B2 = 10 t bioslurry ha^{-1} = 120 kg bioslurry N ha^{-1} N2 = 60 kg N ha^{-1}

B3 = 15 t bioslurry ha^{-1} = 180 kg bioslurry N ha^{-1} N3 = 90 kg N ha^{-1}

3.4.3 Application of treatments and maintenance of sites

Land preparation and plots establishment were done as described in section 3.3.2.

Bioslurry and fertilizer application: Liquid bioslurry was uniformly spread in rows and immediately covered with 5 cm of soil layer. Urea, TSP and muriate of potash were applied in planting hole (banding). However, seed or seedling did not come into direct contact with the fertilizer. Regarding time of fertilizer application, full rates of bioslurry were applied two weeks before sowing. Half rate of urea (46% N) was applied at the time of sowing and the other half was top dressed 30 days after sowing. TSP (45% P_2O_5) and muriate of potash (60% K_2O) were applied at sowing time as flat blanket rates; 80 kg P_2O_5 ha^{-1} and 42.5 kg K_2O ha^{-1}, respectively. Selection of P_2O_5 rate was based on results of trial two (see section 4.2) while K_2O rate referred to current rate of Potassium applied (MINAGRI, 2009).

Sowing and trial maintenance: the sowing dates were 8th and 9th September 2017 for the first season and the 5th and 6th March 2018 for the second season, at the high and medium altitude sites, respectively. Sowing and maintenance of trials were done as described in section 3.3.2.

3.4.4 Crop data collection and analysis

Growth and phenology parameters: the assessment of treatments' effects on maize growth and phenology was performed on 8 tagged plants from two central rows in each plot. Emergence percent was measured by counting the number of seeds germinated out of the total seeds sown in each plot at 15 days after sowing (DAS). Plant height (cm), collar diameter (cm), number of leaves plant^{-1} and number of days to 50% tasselling were measured as described in section 3.3.3.

Yield parameters: yield parameters were collected at maize physiological maturity from two central rows on a surface area of 1.68 m^2 (1.4 m long and 1.2 m wide). Number of cobs plant^{-1}, above-ground biomass, grain yield, hundred grain weight and harvest index were measured as described in section 3.3.3.

Nitrogen concentration: total tissue N content was determined by Kjeldahl method (Manjula and Yichang, 2006; Okalebo *et al.*, 2002). Plant sampling was done at 50% tasseling and physiological maturity of maize. At 50% tasseling stage, two plants were considered per plot. The leaf opposite ear from each plant was chopped and mixed. At harvest, the stover was chopped and mixed. The sub-sample was taken and oven dried at 65°C to a constant weight and ground. A sub-sample was taken and used in the nutrient (N) extraction process. N uptake

(N concentration × dry matter yield) was then calculated using the formulae below (Wasonga *et al.*, 2008):

Stover nitrogen uptake = NCS × SY ……….........……………………….....……. (21)

Grain nitrogen uptake = NCG × GY ……………..........……………..…………. (22)

Where: NCS and NCG are nitrogen concentrations in stover and grain, respectively. SY and GY are stover and grain yields, respectively.

3.4.5 Evaluation of treatment effect on soil properties

Soil composite samples (0 - 30 cm) were collected from each plot (treatment), at harvesting time in both cropping seasons, to evaluate any residual effect of treatments. The samples were analyzed for bulk density, moisture content, pH, organic carbon, nitrogen, available phosphorus, CEC, exchangeable K^+, Mg^{2+} and Ca^{2+} and populations of bacteria and fungi. The methods used are described in section 3.2.3.

3.4.6 Statistical data analysis

Statistical data analysis was performed (see section 3.3.4). For populations of bacteria and fungi, log-transformation was performed for homogeneity of data. The analysis fits the statistical model shown below:

$$Y_{ijklmn} = \mu + E_i + S_j + (ES)_{ij} + R_k + N_l + (NE)_{il} + (NS)_{jl} + (NES)_{ijl} + B_m + (BE)_{im} + (BS)_{jm} + (BES)_{ijm} + (BN)_{lm} + (BNE)_{ilm} + (BNS)_{jlm} + (BNES)_{ijlm} + \varepsilon_{ijklmn} \quad (24)$$

Where: Y_{ijklmn} is overall observation, μ is overall mean, E_i is effect of i^{th} environment or location or site (i = 1, 2), S_j is effect of j^{th} season (j = 1, 2); R_k is effect of k^{th} replicate (k = 1, 2, 3), N_l is effect of l^{th} mineral N rate (l = 1, 2, 3, 4), B_m is effect of m^{th} bioslurry rate (m = 1, 2, 3, 4) and ε_{ijklmn} is random error term.

3.4.7 Quadratic regression analysis

To estimate optimum bioslurry and mineral N rates, a quadratic regression analysis was performed between experimental factors (bioslurry and mineral N) which are predictors or explanatories and grain yield (predicted). Only main effects of factors were considered. By projecting grain yield as a function of increasing rates of bioslurry and mineral N, the optimum rates were estimated by the zero-solutions of the derivatives of the projection equations. The general model of the response depicted by a quadratic equation is represented by the Equation 20 (see section 3.3.5).

CHAPTER FOUR
RESULTS

4.1 Physical, chemical and biological properties across slope positions and profile depths in terraced and non-terraced soils of medium and high altitudes

4.1.1 Soil texture

Terraced and non-terraced soils in both study areas were sandy clay loams except for the middle slope terraced soils of the high altitude area which were sandy loams (Tables 4.1 and 4.2). At the medium altitude, average contents of sand, silt and clay were 52.5%, 19.1% and 28.5%, respectively. At high altitude, they were 65.3%, 12.9% and 21.8% for the respective fractions (Table 4.2). At the medium altitude area, there was a significant ($P < 0.05$) interaction effect between land terracing and slope position for sand and clay content but not on silt. Clay contents were higher in soils of the top slope on both terraced and non-terraced lands (dystric Regosols / dystric Leptosols) than in soils of middle and bottom slopes [haplic (humic) Ferralsols / haplic Lixisols] (Table 4.1). Conversely, higher contents of sand were found in soils of terraced and non-terraced lands on the bottom slope compared to those on the top slope. At high altitude, the interaction effect between land terracing and slope position was significant ($P < 0.05$) for sand and non-significant for silt and clay contents. Soils of top and middle slopes (humic Alisols / humic Acrisols) had higher contents of sand than those of the bottom slopes (humic Acrisols / humic (Ferralic) Cambisols) for both terraced and non-terraced lands (Table 4.2).

There was no significant interaction effect between land terracing and profile depth on soil texture in both study areas. The main effect of profile depth on soil texture was significant ($P < 0.05$). At medium altitude, clay contents were significantly ($P < 0.05$) higher in the deepest layer (60 – 90 cm) than in the 30-60 cm and 0-30 cm layers. The mean values were 26.9%, 28.5% and 30.1% in the 0-30, 30-60 and 60-90 cm layers, respectively. For silt and sand, significantly ($P < 0.05$) higher contents were obtained in surface layers than in sub and deeper layers (Figure 4.1). Similarly, at high altitude, significantly ($P < 0.05$) higher clay contents were recorded in sub surface and deeper layers while higher silt contents were found in surface layer (Figure 4.2).

Table 4.1 Interaction effect of land terracing and slope position on soil texture and saturated hydraulic conductivity (Ks) in the medium altitude area

Site location	**Type of Land**	**Slope position**	**Soil types**	**Soil texture**			**Textural class**	**Ks (mm hr^{-1})**
				Sand (%)	**Silt (%)**	**Clay (%)**		
Medium altitude	Terraced	Top	Dystric Regosols / dystric Leptosols	49.8 ± 0.3^{c}	18.4 ± 0.6^{a}	31.9 ± 0.7^{a}	SCL	459.3 ± 11.9^{a}
		Middle	Haplic (humic) Ferralsols / haplic Lixisols	49.7 ± 0.3^{c}	22.7 ± 0.5^{a}	27.7 ± 0.5^{b}	SCL	219.0 ± 113.9^{b}
		Bottom	Haplic (humic) Ferralsols / haplic Lixisols	58.4 ± 0.4^{a}	17.7 ± 0.6^{a}	23.9 ± 0.9^{c}	SCL	35.4 ± 5.4^{d}
	Non-terraced	Top	Dystric Regosols / dystric Leptosols	51.4 ± 0.8^{c}	16.6 ± 0.6^{a}	32.4 ± 0.3^{a}	SCL	213.1 ± 117.6^{b}
		Middle	Haplic (humic) Ferralsols / haplic Lixisols	50.7 ± 0.6^{c}	22.2 ± 0.8^{a}	27.2 ± 0.6^{b}	SCL	120.1 ± 56.8^{c}
		Bottom	Haplic (humic) Ferralsols / haplic Lixisols	55.1 ± 0.9^{b}	16.9 ± 0.8^{a}	27.9 ± 1.4^{b}	SCL	56.2 ± 24.4^{d}
Mean				**52.5**	**19.1**	**28.5**		**183.8**
n				**54**	**54**	**54**		**24**
CV (%)				**2.9**	**8.9**	**5.8**		**7.9**

Different letters in the same column indicate significantly different values at $P < 0.05$; SCL - Sandy clay loam; SL - Sandy loam;
n – Number of observations / samples; CV - Coefficient of variation; ± Values after the means represent the means standard error.

Table 4.2 Interaction effect of land terracing and slope position on soil texture and saturated hydraulic conductivity (Ks) in the high altitude area

Site location	Type of Land	Slope position	Soil types	Soil texture			Textural class	Ks (mm hr^{-1})
				Sand (%)	**Silt (%)**	**Clay (%)**		
High altitude	Terraced	Top	Humic Alisols / humic Acrisols	68.4 ± 0.7[a]	10.1 ± 0.5[a]	21.5 ± 0.8[a]	SCL	176.8 ± 71.7[b]
		Middle	Humic Alisols / humic Acrisols	69.1 ± 0.4[a]	11.2 ± 0.6[a]	19.7 ± 0.6[a]	SL	394.7 ± 29.8[a]
		Bottom	Humic Acrisols / humic (Ferralic) Cambisols	59.2 ± 0.2[c]	16.7 ± 0.5[a]	24.1 ± 0.4[a]	SCL	11.3 ± 2.9[c]
	Non-terraced	Top	Humic Alisols / humic Acrisols	68.3 ± 0.4[a]	11.0 ± 0.8[a]	20.7 ± 0.9[a]	SCL	193.9 ± 58.8[b]
		Middle	Humic Alisols / humic Acrisols	66.1 ± 0.4[b]	12.3 ± 0.2[a]	21.6 ± 0.3[a]	SCL	163.4 ± 71.9[b]
		Bottom	Humic Acrisols / humic (Ferralic) Cambisols	60.6 ± 0.9[c]	16.2 ± 0.9[a]	23.2 ± 0.8[a]	SCL	15.1 ± 4.5[c]
Mean				**65.3**	**12.9**	**21.8**		**159.2**
n				**54**	**54**	**54**		**24**
CV (%)				**2.8**	**13.0**	**8.9**		**13.3**

Different letters in the same column indicate significantly different values at $P < 0.05$; SCL - Sandy clay loam; SL - Sandy loam;
n – Number of observations / samples; CV - Coefficient of variation; ± Values after the means represent the means standard error.

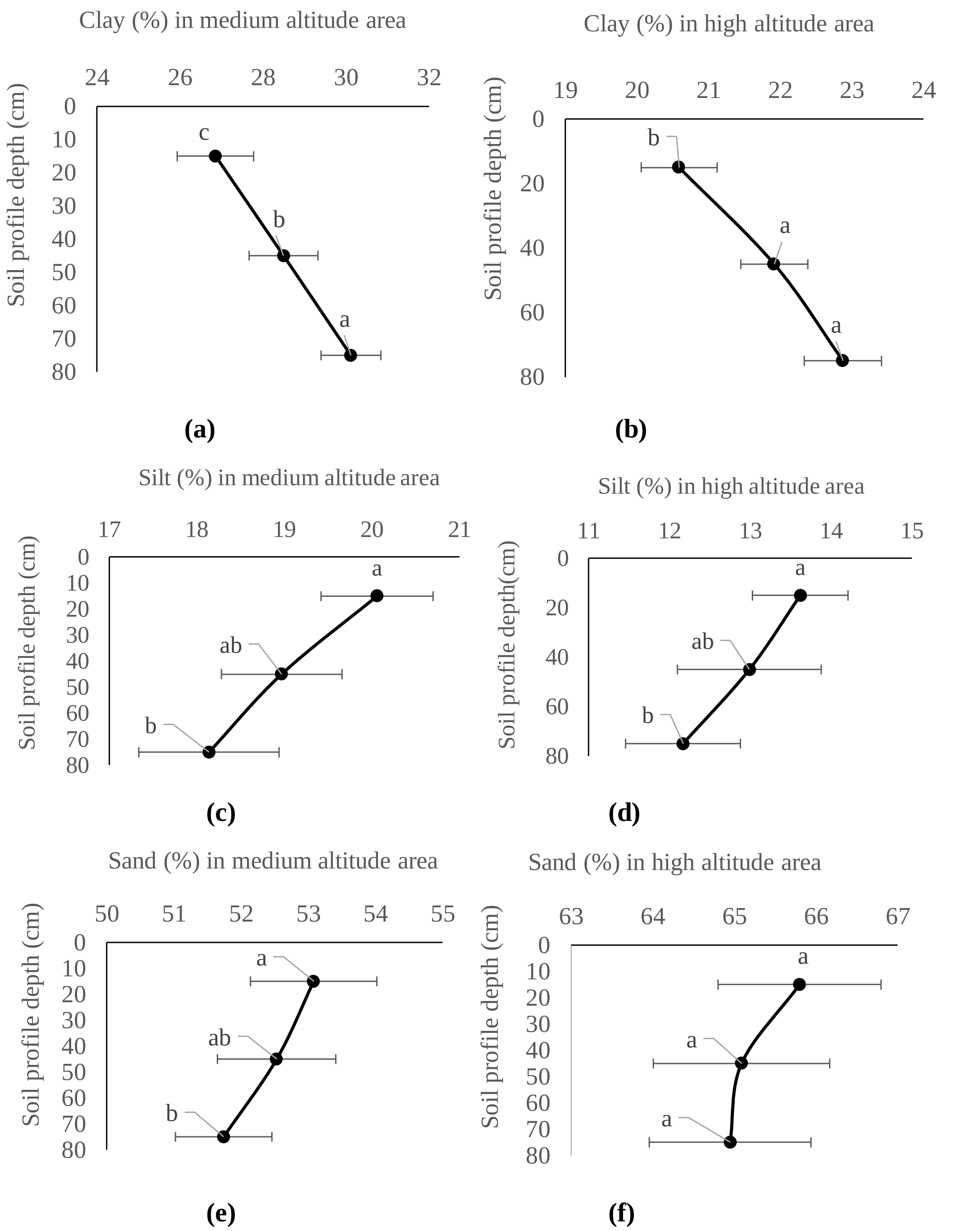


Figure 4. 1 Variation of clay (a, b), silt (c, d) and sand (e, f) with profile depth at medium and high altitude sites

The main effect of land terracing on soil texture was significant ($P < 0.05$) for silt and clay fractions and non-significant for sand at medium altitude area. The percentage of silt was higher in terraced soil (19.6%) than those on non-terraced soil (18.6%) while the percentage of clay was higher in non-terraced soils (29.2%) than those on terraced soil (27.8%) (Table 4.3).

Table 4.3 Main effect of terracing on silt, clay, moisture content at pF0, 2.0 and 4.2, total available water content (TAWC) and saturated hydraulic conductivity (Ks) in the medium and high altitude areas

Site location	Type of land	Silt (%)	Clay (%)	pF0 (% water content)	pF2.0 (% water content)	pF4.2 (% water content)	TAWC (mm m^{-1})	Ks (mm hr^{-1})
Medium altitude	Terraced	19.6 ± 0.5^a	27.8 ± 0.8^b	32.5 ± 2.2^a	21.9 ± 0.8^a	12.8 ± 0.4^a	202.7 ± 6.4^b	237.9 ± 62.7^a
	Non-terraced	18.6 ± 0.6^b	29.2 ± 0.7^a	29.8 ± 1.7^b	22.3 ± 0.9^a	12.8 ± 0.3^a	222.2 ± 9.7^a	129.8 ± 44.5^b
Mean		**19.1**	**28.5**	**31.1**	**22.1**	**12.8**	**212.4**	**183.8**
n		**54**	**54**	**24**	**24**	**24**	**24**	**24**
CV (%)		**8.9**	**5.8**	**1.4**	**3.8**	**3.6**	**7.9**	**7.9**
High altitude	Terraced	12.7 ± 0.6^a	21.8 ± 0.5^a	36.8 ± 3.0^a	22.7 ± 1.2^b	11.5 ± 0.2^b	235.3 ± 13.7^b	194.3 ± 52.8^a
	Non-terraced	13.2 ± 0.6^a	21.8 ± 0.5^a	35.0 ± 3.0^b	23.5 ± 1.5^a	12.0 ± 0.3^a	251.0 ± 19.5^a	124.1 ± 36.6^b
Mean		**12.9**	**21.8**	**35.9**	**23.1**	**11.8**	**243.2**	**159.2**
n		**54**	**54**	**24**	**24**	**24**	**24**	**24**
CV (%)		**13.0**	**8.9**	**2.0**	**3.4**	**3.7**	**6.7**	**13.3**

Different letters in the same column indicate significantly different values at $P < 0.05$;

n – Number of observations / samples; CV - Coefficient of variation;

± Values after the means represent the means standard error.

4.1.2 Bulk density

Soil bulk density ranged from 1.33 to 1.57 g cm^{-3} at medium altitude site (Figure 4.2) and from 1.20 to 1.66 g cm^{-3} at high altitude (Figures 4.3). There was a significant ($P < 0.05$) interaction effect between land terracing and slope position on soil bulk density in both study areas. At the medium altitude study area, significantly ($P < 0.05$) higher bulk density was found in soils of the middle and bottom slopes whereas at the high altitude, the highest bulk density was found in soils of the bottom slope followed by those on the middle and top slopes (Figures 4.2 and 4.3).

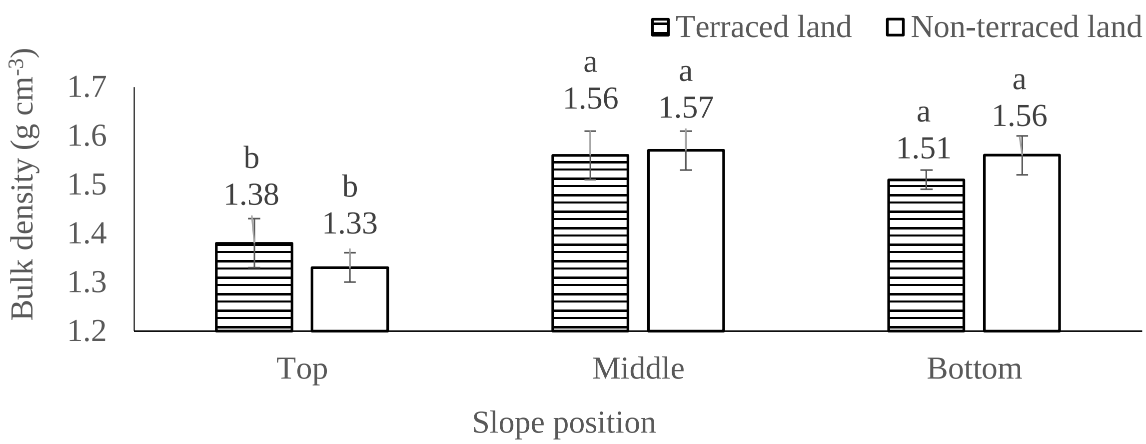


Figure 4.2 Bulk density of soils on terraced and non-terraced lands across the top, middle and bottom slopes of medium altitude area

Error bars represent standard error and different letters indicate significantly different values at $P < 0.05$.

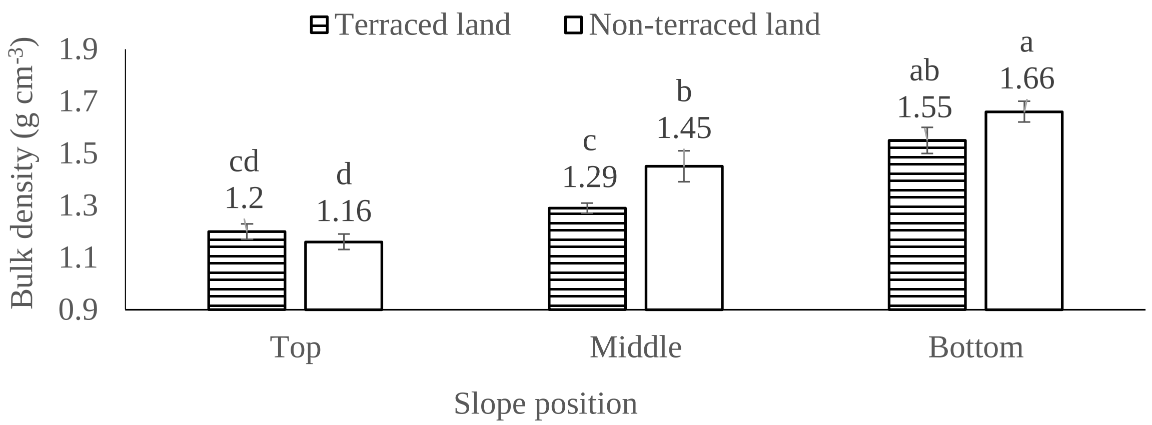


Figure 4.3 Bulk density of soils on terraced and non-terraced lands across the top, middle and bottom slopes of high altitude area

Error bars represent standard error and different letters indicate significantly different values at $P < 0.05$.

There was a significant (P < 0.05) interaction effect between land terracing and soil depth on bulk density at both study areas. The deeper soil layers (40 – 60 and 60 – 80 cm) had higher bulk density than the upper layers (0 – 20 cm and 20 – 40 cm) in both the terraced and non-terraced soils at both medium and high altitude areas (Figure 4.4).

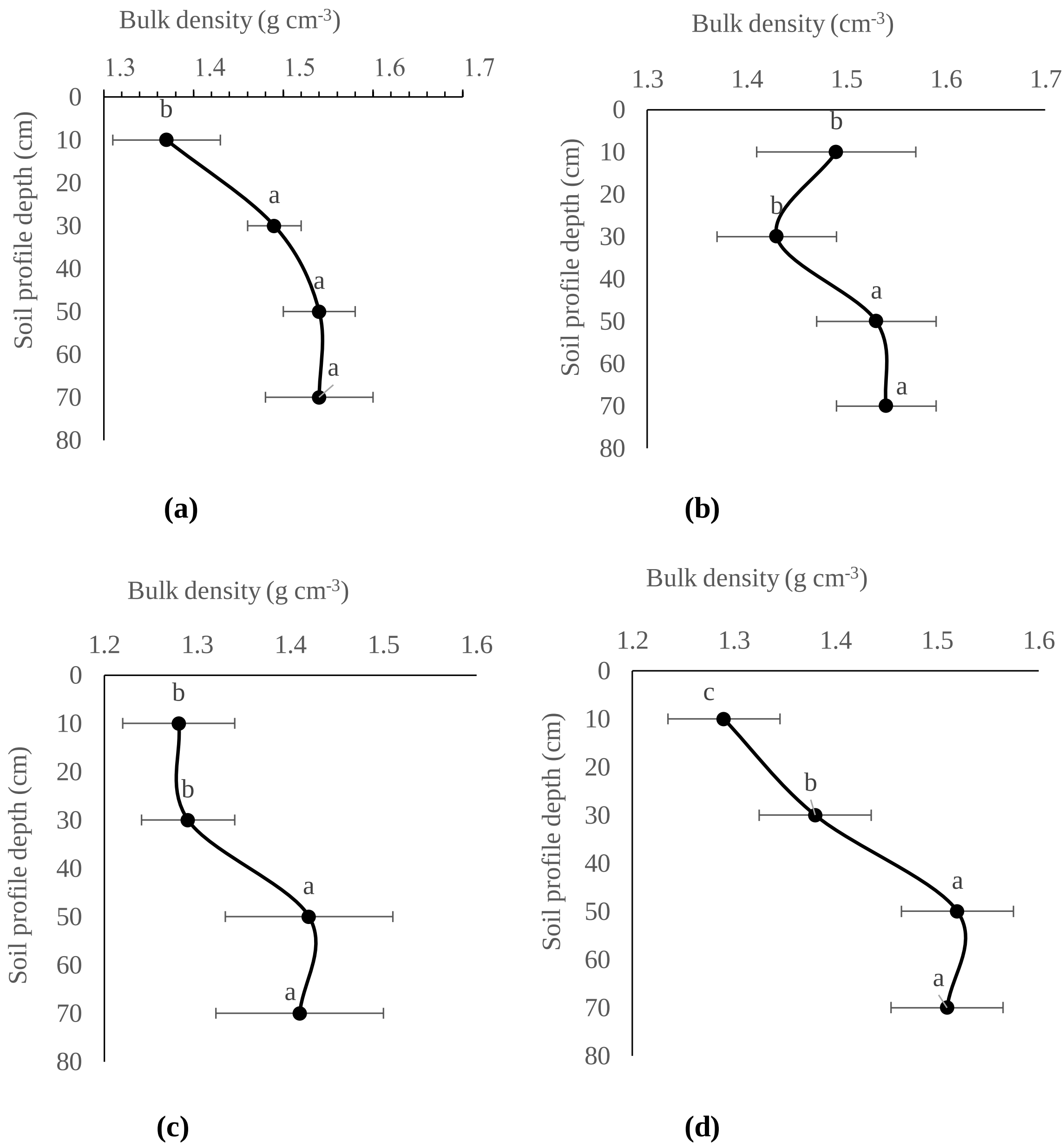


Figure 4.4 Variation of soil bulk density with profile depth in (a) terraced and (b) non-terraced land of the medium altitude area, and (c) terraced and (d) non-terraced land of the high altitude area

Error bars represent standard error and different letters indicate significantly different values at P < 0.05.

4.1.3 Soil water holding capacity

Soil moisture contents at various pF values in the top 60 cm of terraced and non-terraced soils in medium and high altitude areas are presented in Tables 4.4 and 4.5, respectively. Mean TAWCs were 212.4 mm m^{-1} at medium altitude and 243.2 mm m^{-1} at high altitude areas.

The interaction effect between land terracing and slope position on total available content (TAWC) was significant ($P<0.05$). Higher TAWCs were obtained in top slope soils on non-terraced lands, i.e., 255.7 mm m^{-1} at medium altitude site and 335.4 mm m^{-1} at high altitude site (Tables 4.4 and 4.5). There was no significant interaction effect between terracing and soil depth on TAWC at both study areas. The main effect of profile depths on TAWC was non-significant at the high altitude but significant ($P < 0.05$) at the medium altitude, where a higher TAWC of 221.5 mm m^{-1} was found in the 30-60 cm layer compared to 203.4 mm m^{-1} in the surface layer (0-30 cm) (Figure 4.5).

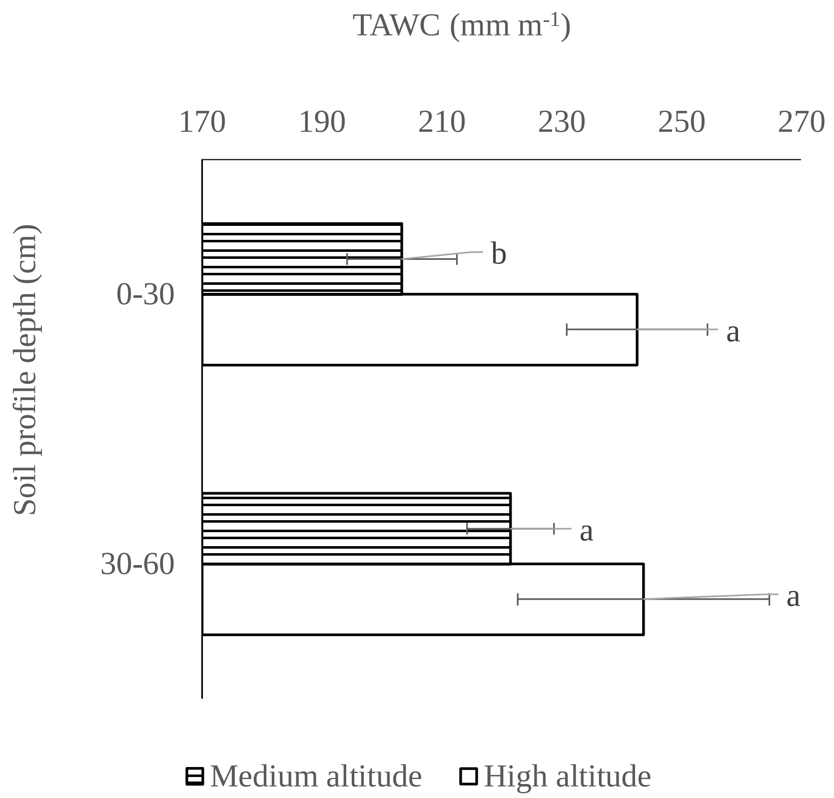


Figure 4.5 Total available water content (TAWC) in the 0-30 and 30-60 cm soil layers at the medium and high altitude sites

Error bars represent standard error;

Different letters indicate significantly different values at $P < 0.05$.

Table 4.4 Variation of moisture content with suction 'pF' in soils of the top, middle and bottom of terraced and non-terraced lands in the medium altitude area

Site location	Type of land	Slope position	pF0 (% water content)	pF2.0 (% water content)	pF2.3 (% water content)	pF2.5 (% water content)	pF3.7 (% water content)	pF4.2 (% water content)	Available moisture (%)	TAWC (mm m^{-1} soil)
Medium altitude	Terraced	Top	42.3 ± 0.2[a]	24.9 ± 0.3[a]	21.8 ± 0.2[a]	20.91 ± 0.18[a]	16.1 ± 0.3[a]	14.1 ± 0.1[a]	10.7 ± 0.2[a]	214.0 ± 6.4[b]
		Middle	30.2 ± 0.7[c]	21.0 ± 0.6[a]	19.0 ± 0.4[a]	18.19 ± 0.33[a]	13.8 ± 0.3[a]	12.9 ± 0.2[a]	8.1 ± 0.5[a]	191.9 ± 5.0[b]
		Bottom	25.0 ± 0.7[f]	19.7 ± 1.3[a]	16.9 ± 1.1[a]	15.58 ± 0.78[a]	13.2 ± 0.3[a]	11.2 ± 0.5[a]	8.5 ± 1.0[a]	202.1 ± 17.5[b]
	Non-terraced	Top	35.8 ± 3.2[b]	25.8 ± 1.0[a]	23.0 ± 0.8[a]	22.09 ± 0.70[a]	15.8 ± 0.4[a]	14.0 ± 0.3[a]	11.8 ± 0.8[a]	255.7 ± 7.4[a]
		Middle	26.1 ± 1.3[e]	21.1 ± 0.5[a]	19.1 ± 0.4[a]	18.33 ± 0.39[a]	14.2 ± 0.3[a]	12.6 ± 0.3[a]	8.5 ± 0.7[a]	218.7 ± 13.4[b]
		Bottom	27.0 ± 1.3[d]	20.0 ± 0.4[a]	17.3 ± 0.5[a]	16.43 ± 0.51[a]	13.8 ± 0.3[a]	11.8 ± 0.3[a]	8.2 ± 0.3[a]	192.3 ± 10.8[b]
Mean			**31.1**	**22.1**	**19.5**	**18.59**	**14.5**	**12.8**	**9.3**	**212.4**
n			**24**	**24**	**24**	**24**	**24**	**24**	**24**	**24**
CV (%)			**1.4**	**3.8**	**4.3**	**4.38**	**4.9**	**3.6**	**9.6**	**7.9**

Different letters in the same column indicate significantly different values at $P < 0.05$; TAWC - Total available water content;
n – Number of observations / samples; CV - Coefficient of variation; ± Values after the means represent the means standard error.

Table 4.5 Variation of moisture content with suction 'pF' in soils of the top, middle and bottom of terraced and non-terraced lands in the high altitude area

Site location	**Type of land**	**Slope position**	**pF0 (% water content)**	**pF2.0 (% water content)**	**pF2.3 (% water content)**	**pF2.5 (% water content)**	**pF3.7 (% water content)**	**pF4.2 (% water content)**	**Available moisture (%)**	**TAWC (mm m^{-1} soil)**
High altitude	Terraced	Top	44.5 ± 5.0^{b}	28.0 ± 1.1^{b}	23.6 ± 0.7^{b}	22.30 ± 0.62^{b}	15.4 ± 0.4^{a}	12.4 ± 0.3^{a}	15.6 ± 0.9^{b}	296.5 ± 11.0^{b}
		Middle	40.7 ± 0.1^{c}	21.1 ± 0.5^{c}	16.9 ± 0.2^{d}	15.64 ± 0.16^{d}	11.8 ± 0.3^{a}	10.8 ± 0.1^{a}	10.3 ± 0.4^{c}	209.8 ± 4.1^{c}
		Bottom	25.1 ± 0.6^{e}	19.1 ± 0.3^{d}	16.7 ± 0.4^{d}	16.06 ± 0.49^{d}	12.9 ± 0.5^{a}	11.3 ± 0.3^{a}	7.8 ± 0.2^{e}	199.5 ± 5.2^{c}
	Non-terraced	Top	46.1 ± 3.0^{a}	30.3 ± 0.5^{a}	25.7 ± 0.8^{a}	24.22 ± 0.86^{a}	15.3 ± 0.4^{a}	13.0 ± 0.2^{a}	17.4 ± 0.6^{a}	335.4 ± 18.7^{a}
		Middle	34.6 ± 2.7^{d}	20.0 ± 0.4^{cd}	15.9 ± 0.1^{d}	14.47 ± 0.10^{e}	11.8 ± 0.3^{a}	10.9 ± 0.4^{a}	9.0 ± 0.7^{d}	200.4 ± 9.6^{c}
		Bottom	24.3 ± 1.1^{e}	20.2 ± 0.7^{cd}	18.4 ± 0.7^{c}	17.81 ± 0.58^{c}	13.9 ± 0.2^{a}	12.2 ± 0.3^{a}	8.0 ± 0.5^{de}	217.2 ± 11.0^{c}
Mean			**35.9**	**23.1**	**19.5**	**18.42**	**13.5**	**11.8**	**11.3**	**243.2**
n			**24**	**24**	**24**	**24**	**24**	**24**	**24**	**24**
CV (%)			**2.0**	**3.4**	**3.6**	**3.48**	**5.5**	**3.7**	**6.6**	**6.7**

Different letters in the same column indicate significantly different values at $P < 0.05$; TAWC - Total available water content;

n – Number of observations / samples; CV - Coefficient of variation; ± Values after the means represent the means standard error.

The main effect of land terracing on TAWC was significant (P<0.05). Higher mean values of TAWC were found in non-terraced land than terraced land, i.e. 222.2 mm m^{-1} versus 202.7 mm m^{-1} at medium altitude area and 251.0 mm m^{-1} versus 235.3 mm m^{-1} at high altitude (Table 4.3).

The entire soil moisture characteristic curves showed similar trends for both terraced and non-terraced soils at both medium and high altitude areas (Figure 4.6).

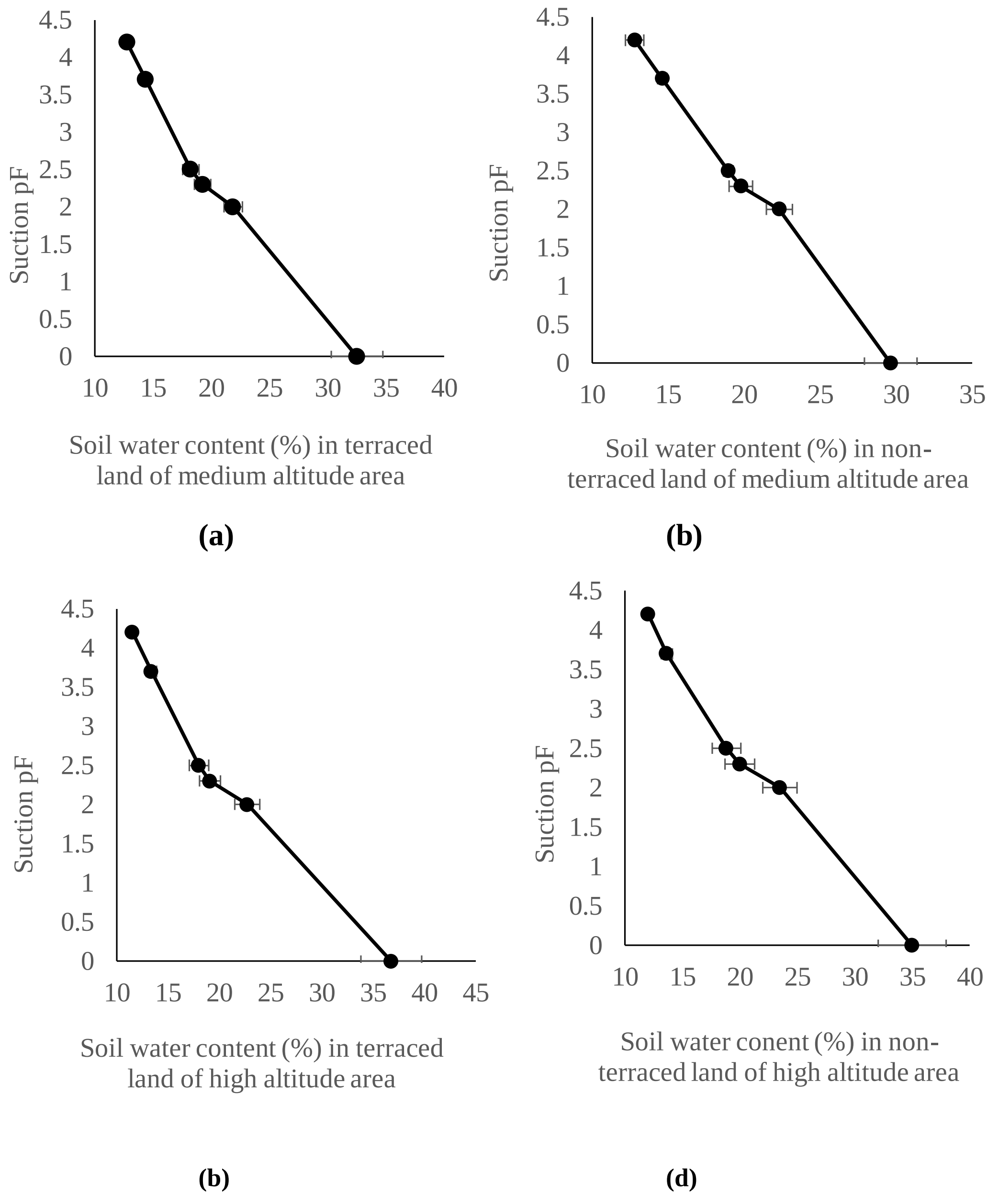


Figure 4.6 Water retention curves of soils from (a) terraced and (b) non-terraced Lixisols of the medium altitude area, and (c) terraced and (d) non-terraced Acrisols of the high altitude area

Error bars represent standard error.

At the medium altitude, at pF0, soils of terraced land held more water (32.5%) than those of non-terraced land (29.8%), while non-significant differences were found at other pF values, including field capacity (pF2.0) and permanent wilting point (pF4.2) (Tables 4.4 and 4.5). At the high altitude, a similar effect was found at pF0 as soils of terraced land held more water (36.8%) than those on non-terraced land (35.0%). At field capacity (pF2.0) higher water retention capacity was found in non-terraced soils (23.5%) than on terraced soil (22.7%). A similar trend was obtained at permanent wilting point, with a water content of 12.0% on non-terraced soil, compared to 11.5% on terraced soil (Tables 4.4 and 4.5).

4.1.4 Saturated hydraulic conductivity

The saturated hydraulic conductivity (Ks) of soils ranged from 35.4 to 459.3 mm hr^{-1} at medium altitude and from 11.3 to 394.7 mm hr^{-1} at high altitude (Tables 4.1 and 4.2). The soil permeability was moderate to rapid according to the rating by Moore (2001). There was a significant ($P < 0.05$) interaction effect between land terracing and slope positions on Ks in both study areas. At medium altitude, higher Ks was found in the top slope soils of terraced land (459.3 mm hr^{-1}) with lower Ks in soils on the bottom slope of terraced (35.4 mm hr^{-1}) and non-terraced (56.2 mm hr^{-1}) lands (Table 4.1). At high altitude, soils of top and middle slopes on both terraced and non-terraced lands (humic Alisols / humic Acrisols) were more permeable than those on the bottom slopes of both terraced and non-terraced lands [humic Acrisols/ humic (Ferralic) Cambisols] (Table 4.2).

The interaction effect between land terracing and soil profile depths on Ks was not significant in high altitude soils but significant ($P < 0.05$) at medium altitude. The soils from the 0 - 30 cm layer of both terraced and non-terraced lands were more permeable than those from the 30 - 60 cm layer (Figure 4.7). The main effect of terracing on Ks was significant ($P < 0.05$) in both the medium and high altitude study areas. Higher values of 237.9 mm hr^{-1} and 194.3 mm hr^{-1} were found in soils of terraced land of medium and high altitudes, respectively, compared to 129.8 mm hr^{-1} and 124.1 mm hr^{-1} in those on non-terraced land (Table 4.3).

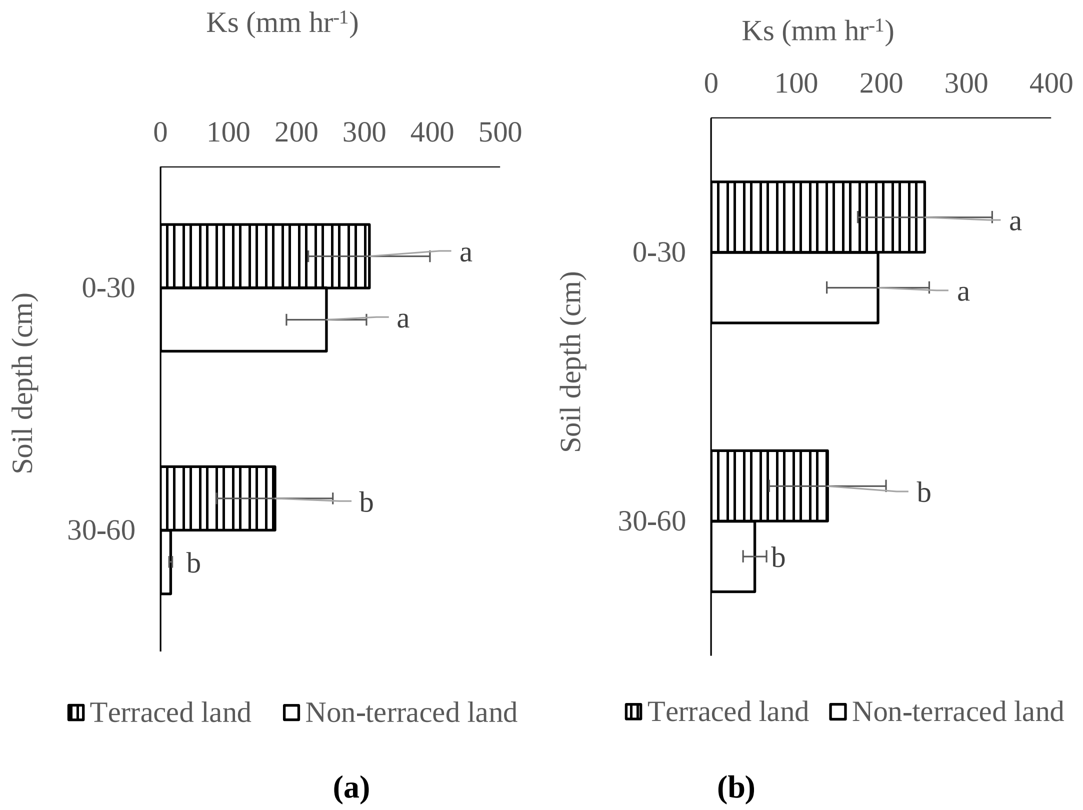


Figure 4.7 Saturated hydraulic conductivity (Ks) in the 0-30 cm and 30-60 cm soil layers of terraced and non-terraced lands at (a) medium and (b) high altitude areas
Error bars represent standard error;
Different letters indicate significantly different values at $P < 0.05$.

4.1.5 Soil reaction (pH)

Soil pH was very acidic to fairly acidic, according to rating by Landon (1991). In the medium altitude, average $pH_{(water)}$ and $pH_{(KCl)}$ values varied from 5.00 to 5.79 and 4.20 to 5.04, respectively (Table 4.6). In high altitude, $pH_{(water)}$ varied from 4.45 to 5.50, while $pH_{(KCl)}$ varied from 3.78 to 4.91 (Table 4.7). There were no significant interaction effects between terracing and slope position nor between terracing and profile depth on soil pH in both study areas. Main effect of slope positions was significant ($P < 0.05$). Soils in bottom slopes were relatively less acidic (higher pH values) than those in middle and top slopes (Figures 4.8 and 4.9).

4.1.6 Influence of exchangeable aluminium on soil acidity

The average exchangeable Al^{3+} varied from 0.00 to 1.04 $cmol_{(+)}\ kg^{-1}$ in medium altitude (Table 4.6) and from 0.00 to 0.91 $cmol_{(+)}\ kg^{-1}$ in high altitude (Table 4.7). These values are ranked as null and low to medium (Moore, 2001).

Table 4.6 Soil pH, exchangeable aluminium (Al^{3+}), soil organic carbon (SOC) and total nitrogen (N) in terraced and non-terraced lands across slope positions in the medium altitude area

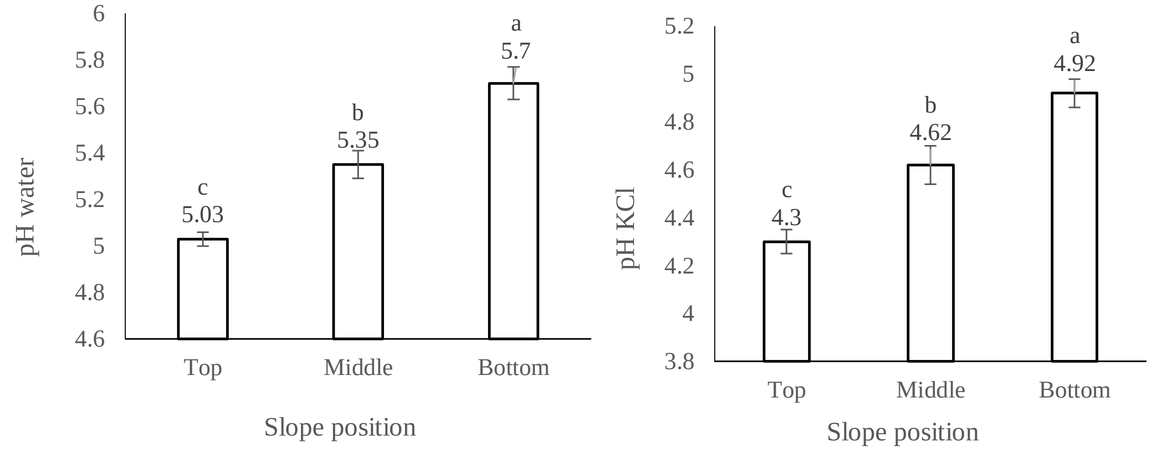
Site location	Type of land	Slope position	$pH_{(water)}$	$pH_{(KCl)}$	Exch. Al^{3+} ($Cmol_{(+)}$ kg^{-1})	SOC (%)	Total N (%)	Ratio C/N
Medium altitude	Terraced land	Top	4.82 - 5.37	4.01 – 4.53	0.30 ± 0.12^{b}	1.23 ± 0.04^{a}	0.08 ± 0.01^{a}	15.3 ± 0.9^{a}
		Middle	5.04 – 5.87	4.31 – 5.17	0.00 ± 0.00^{c}	0.80 ± 0.05^{a}	0.06 ± 0.00^{a}	13.2 ± 1.4^{a}
		Bottom	5.52 – 5.95	4.75 – 5.16	0.00 ± 0.00^{c}	1.09 ± 0.04^{a}	0.07 ± 0.01^{a}	16.2 ± 1.5^{a}
	Non-terraced land	Top	4.98 – 5.17	4.17 – 4.66	1.04 ± 0.16^{a}	1.51 ± 0.02^{a}	0.08 ± 0.00^{a}	20.3 ± 0.8^{a}
		Middle	4.90 – 5.64	4.05 – 5.04	0.03 ± 0.02^{c}	1.16 ± 0.11^{a}	0.07 ± 0.00^{a}	16.5 ± 1.9^{a}
		Bottom	4.76 – 6.22	4.12 – 5.39	0.00 ± 0.00^{c}	1.38 ± 0.03^{a}	0.07 ± 0.00^{a}	18.9 ± 0.8^{a}
Mean			**5.36**	**4.61**	**0.23**	**1.19**	**0.07**	**16.8**
n			**54**	**54**	**54**	**54**	**54**	**54**
CV (%)			**4.37**	**5.66**	**59.94**	**13.62**	**15.10**	**23.0**

Different letters in the same column indicate significantly different values at $P < 0.05$; n – Number of observations / samples;
CV - Coefficient of variation; ± Values after the means represent the means standard error.

Table 4.7 Soil pH, exchangeable aluminium (Al^{3+}), soil organic carbon (SOC) and total nitrogen (N) in terraced and non-terraced lands across slope positions in the high altitude area

Site location	Type of land	Slope position	$pH_{(water)}$	$pH_{(KCl)}$	Exch. Al^{3+} ($Cmol_{(+)}$ kg^{-1})	SOC (%)	Total N (%)	Ratio C/N
High altitude	Terraced land	Top	4.24 – 4.66	3.71 – 3.99	0.91 ± 0.06^{a}	2.38 ± 0.11^{a}	0.10 ± 0.01^{a}	25.7 ± 2.4^{a}
		Middle	4.60 – 5.50	3.83 – 4.83	0.32 ± 0.07^{c}	1.90 ± 0.06^{a}	0.08 ± 0.00^{a}	25.3 ± 1.1^{a}
		Bottom	5.28 – 5.80	4.81 - 5.01	0.00 ± 0.00^{d}	0.85 ± 0.05^{a}	0.08 ± 0.00^{a}	10.9 ± 0.8^{a}
	Non-terraced land	Top	4.34 – 4.57	3.70 – 3.85	0.63 ± 0.04^{b}	2.53 ± 0.16^{a}	0.11 ± 0.01^{a}	24.7 ± 2.0^{a}
		Middle	4.64 – 5.35	3.99 – 4.71	0.72 ± 0.08^{b}	1.94 ± 0.08^{a}	0.09 ± 0.01^{a}	22.4 ± 1.6^{a}
		Bottom	5.10 – 5.65	4.12 – 5.16	0.01 ± 0.01^{d}	0.94 ± 0.10^{a}	0.08 ± 0.00^{a}	11.8 ± 0.9^{a}
Mean			**4.91**	**4.26**	**0.43**	**1.75**	**0.09**	**20.1**
n			**54**	**54**	**54**	**54**	**54**	**54**
CV (%)			**4.05**	**5.95**	**43.63**	**14.72**	**26.28**	**26.8**

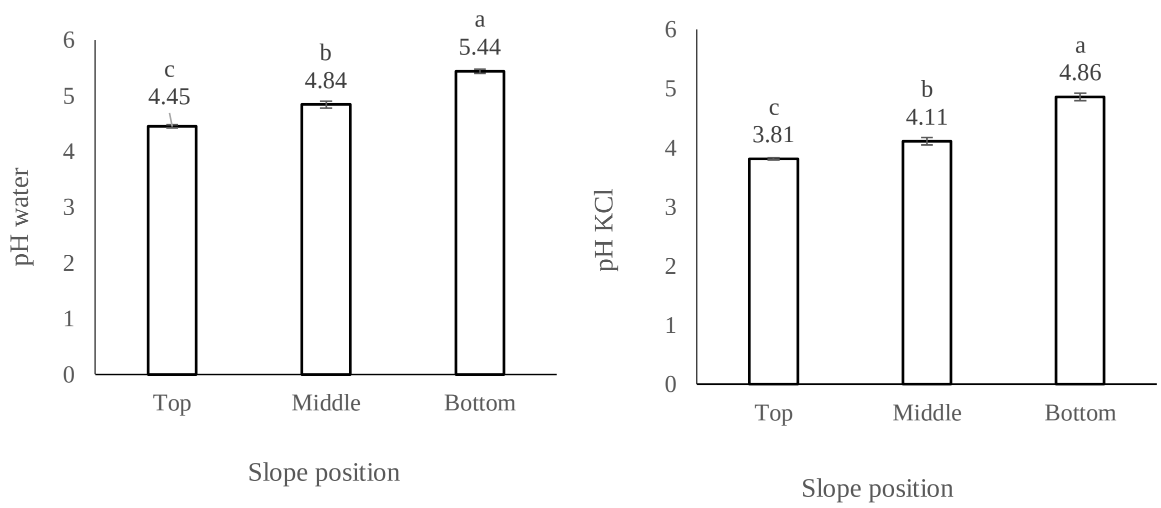
Different letters in the same column indicate significantly different values at $P < 0.05$; n – Number of observations / samples;
CV - Coefficient of variation; ± Values after the means represent the means standard error.



(a) (b)

Figure 4. 8 Soil (a) pH water and (b) pH KCl at the top, middle and bottom slopes of medium altitude area

Error bars represent standard error and different letters indicate significantly different values at P < 0.05.



(a) (b)

Figure 4. 9 Soil (a) pH water and (b) pH KCl at the top, middle and bottom slopes of high altitude area

Error bars represent standard error and different letters indicate significantly different values at P < 0.05.

4.1.7 Organic carbon

Soil organic carbon (SOC) contents in the top, middle and bottom slopes ranged from 0.80 to 1.51% in medium altitude (Table 4.6) and from 0.85 to 2.53% in high altitude (Table 4.7). These values are ranked as weak (Landon, 1991). There were no significant interaction effects between terracing and slope positions or between terracing and profile depth on SOC contents in both study areas. Main effect of terracing on SOC was significant ($P < 0.05$) in medium altitude where contents were slightly higher in non-terraced (1.35%) than terraced land (1.04%). Thus, land terracing slightly reduced soil organic matter (SOM) from 2.32 to 1.79%. The main effect of slope positions on SOC was significant ($P<0.05$) in both study areas. In medium altitude, higher SOC contents were found in the top slope (1.34%) followed by bottom slope (1.23%) and lastly middle slope (0.98%). Similarly in the high altitude, higher values were obtained in top slope (2.44%) followed by middle slope (1.92%) and lastly bottom slope (0.89%). Main effect of profile depth on SOC was also significant ($P < 0.05$) in both study areas. Higher contents were found in surface layer than in sub-soil and deeper layers (Table 4.8).

4.1.8 Total nitrogen

Total nitrogen contents ranged from 0.06 to 0.08% in medium altitude (Table 4.6) and from 0.08 to 0.11% in the high altitude (Table 4.7). These values can be categorized as low (Hazelton and Murphy, 2007; Landon, 1991). There were no significant interaction effects on total N contents between land terracing and slope positions nor between terracing and soil depths in both study areas. The main effect of terracing on total N was also non-significant in both study areas.

There was significant ($P < 0.05$) main effect of slope positions on total N contents in both study areas. In medium altitude, higher total N contents were found in top slope (0.08%) than in middle (0.07%) and bottom (0.07%) slopes. A similar trend was found in the high altitude site. Higher contents of total N were obtained in top slope (0.10%) than in middle (0.08%) and bottom (0.08%) slopes. Main effect of soil depth on total N was non-significant in high altitude and significant ($P < 0.05$) in medium altitude, where higher contents were found in surface soils (0.09% N) than in sub soils (0.07% N) and deeper soils (0.06% N) (Table 4.8).

Table 4.8 Variation of soil pH, soil organic carbon (SOC), total nitrogen (N), available phosphorus (P), cation exchange capacity (CEC) and exchangeable potassium (K^+), magnesium (Mg^{2+}) and calcium (Ca^{2+}) with profile depths in the study areas

Site location	Profile depth (cm)	$pH_{(water)}$	SOC (%)	Total N (%)	Available P (ppm)	CEC ($cmol_{(+)}$ kg^{-1})	ECEC ($cmol_{(+)}$ kg^{-1})	Exch. K^+ ($cmol_{(+)}$ kg^{-1})	Exch. Mg^{2+} ($cmol_{(+)}$ kg^{-1})	Exch. Ca^{2+} ($cmol_{(+)}$ kg^{-1})
Medium altitude	0 – 30	4.76 – 5.95	1.30 ± 0.06^a	0.09 ± 0.00^a	17.94 ± 0.65^a	8.06 ± 0.76^a	7.06 ± 0.36^a	0.19 ± 0.01^b	1.10 ± 0.07^a	5.15 ± 0.45^a
	30 - 60	4.89 – 5.90	1.19 ± 0.07^b	0.07 ± 0.00^b	16.10 ± 0.71^b	8.14 ± 0.70^a	7.05 ± 0.36^a	0.22 ± 0.01^{ab}	1.08 ± 0.07^a	5.42 ± 0.42^a
	60 - 90	4.82 – 6.22	1.09 ± 0.07^b	0.06 ± 0.00^c	13.88 ± 0.46^c	8.28 ± 0.73^a	7.11 ± 0.38^a	0.24 ± 0.01^a	1.14 ± 0.07^a	5.42 ± 0.40^a
Mean		**5.36**	**1.19**	**0.07**	**15.97**	**8.16**	**7.07**	**0.22**	**1.11**	**5.33**
n		**54**	**54**	**54**	**54**	**54**	**54**	**54**	**54**	**54**
CV (%)		**4.37**	**13.62**	**15.10**	**11.74**	**25.49**	**8.65**	**19.55**	**25.54**	**10.55**
High altitude	0 – 30	4.34 – 5.53	1.87 ± 0.18^a	0.09 ± 0.01^a	33.47 ± 4.56^a	7.61 ± 0.63^a	4.80 ± 0.26^b	0.17 ± 0.01^c	1.00 ± 0.09^b	2.88 ± 0.23^b
	30 - 60	4.24 – 5.56	1.76 ± 0.16^{ab}	0.09 ± 0.01^a	29.07 ± 4.36^b	7.53 ± 0.52^a	5.21 ± 0.25^b	0.20 ± 0.01^b	1.12 ± 0.07^b	3.14 ± 0.24^b
	60 - 90	4.32 – 5.80	1.63 ± 0.16^b	0.08 ± 0.01^a	26.97 ± 4.09^b	8.22 ± 0.51^a	5.95 ± 0.16^a	0.22 ± 0.01^a	1.26 ± 0.05^a	3.69 ± 0.17^a
Mean		**4.91**	**1.75**	**0.09**	**29.83**	**7.79**	**5.32**	**0.20**	**1.13**	**3.24**
n		**54**	**54**	**54**	**54**	**54**	**54**	**54**	**54**	**54**
CV (%)		**4.05**	**14.72**	**26.28**	**13.87**	**24.10**	**12.62**	**14.22**	**17.93**	**13.84**

Different letters in the same column indicate significantly different values at $P < 0.05$; n – Number of observations / samples;
CV - Coefficient of variation; ± Values after the means represent the means standard error.

Ratios of carbon to nitrogen (C/N) in soil varied from 13.2 to 20.3 in medium altitude (Table 4.6) and from 10.9 to 25.7 in high altitude (Table 4.7). These ratios are ranked as low to medium (Hazelton and Murphy, 2007) indicating that the level of mineralization was normal to low (Landon, 1991) in both study areas.

4.1.9 Available phosphorus

The average available P values ranged from 13.97 to 18.63 ppm, in medium altitude (Table 4.9), which are in the weak to middle rating (Landon, 1991) and from 14.82 to 56.43 ppm in high altitude (Table 4.10) and ranked weak to high (Landon, 1991). There were no significant interaction effects between terracing and slope positions nor between terracing and profile depths on available P.

Main effect of terracing on available P was also non-significant in both study areas. Main effect of slope positions on available P was significant ($P < 0.05$) in both study areas. In medium altitude, higher contents of available P were found in middle slope (18.23 ppm) followed by top slope (15.05 ppm) and lastly bottom slope (14.64 ppm). In the high altitude area, a higher value was obtained in bottom slope (54.35 ppm), which is ranked very high, compared to contents in top (19.71 ppm) and middle (15.43 ppm) slopes, which are ranked in the middle rating (Landon, 1991). Main effect of profile depths on available soil P was also significant ($P < 0.05$) in both study areas. Higher contents were found in surface soils compared to sub and deeper soils; the respective values were 17.94, 16.10 and 13.90 ppm in medium altitude, and 33.47, 29.07 and 27.00 ppm in high altitude (Table 4.8).

4.1.10 Cation Exchange Capacity (CEC)

The average CEC ranged from 5.80 to 11.89 $cmol_{(+)}$ kg^{-1} in medium altitude (Table 4.9) and from 5.40 to 9.66 $cmol_{(+)}$ kg^{-1} in high altitude (Table 4.10). These values are rated low (Landon, 1991; Hazelton and Murphy, 2007), for both medium and high altitude areas. The interaction effects between terracing and slope positions and terracing and soil depths and the main effects of terracing and profile depth on CEC were non-significant. Main effect of slope positions on CEC was significant ($P < 0.05$) in both study areas. In medium altitude, higher CEC were found in bottom slope (11.49 $cmol_{(+)}$ kg^{-1}) than in top (6.51 $cmol_{(+)}$ kg^{-1}) and middle (6.48 $cmol_{(+)}$ kg^{-1}) slopes. In high altitude, higher CEC was also obtained in bottom (9.30 $cmol_{(+)}$ kg^{-1}) and top (8.45 $cmol_{(+)}$ kg^{-1}) slopes than middle slope (5.61 $cmol_{(+)}$ kg^{-1}).

Table 4.9 Available phosphorus (P), cation exchange capacity (CEC) and exchangeable potassium (K^+), magnesium (Mg^{2+}) and calcium (Ca^{2+}) in terraced and non-terraced lands across slope positions in the medium altitude area

Site location	**Type of land**	**Slope position**	**Available P (ppm)**	**CEC ($cmol_{(+)}\ kg^{-1}$)**	**ECEC ($cmol_{(+)}\ kg^{-1}$)**	**Exch. K^+ ($cmol_{(+)}\ kg^{-1}$)**	**Exch. Mg^{2+} ($cmol_{(+)}\ kg^{-1}$)**	**Exch. Ca^{2+} ($cmol_{(+)}\ kg^{-1}$)**
Medium altitude	Terraced land	Top	15.39 ± 0.79^a	5.80 ± 0.53^a	5.80 ± 0.19^d	0.20 ± 0.01^a	1.23 ± 0.11^a	3.69 ± 0.12^e
		Middle	18.63 ± 1.18^a	7.12 ± 0.35^a	6.10 ± 0.21^d	0.25 ± 0.01^a	1.10 ± 0.12^a	4.55 ± 0.12^d
		Bottom	13.97 ± 0.02^a	11.08 ± 0.80^a	9.32 ± 0.20^a	0.23 ± 0.02^a	1.33 ± 0.06^a	7.77 ± 0.16^a
	Non-terraced land	Top	14.71 ± 0.74^a	7.23 ± 0.59^a	5.98 ± 0.22^d	0.19 ± 0.01^a	0.84 ± 0.05^a	3.41 ± 0.08^e
		Middle	17.84 ± 1.24^a	5.83 ± 0.39^a	6.77 ± 0.31^c	0.22 ± 0.02^a	1.01 ± 0.11^a	5.45 ± 0.35^c
		Bottom	15.31 ± 0.83^a	11.89 ± 0.90^a	8.45 ± 0.28^b	0.20 ± 0.02^a	1.13 ± 0.06^a	7.12 ± 0.31^b
Mean			**15.97**	**8.16**	**7.07**	**0.22**	**1.11**	**5.33**
n			**54**	**54**	**54**	**54**	**54**	**54**
CV (%)			**11.74**	**25.49**	**8.65**	**19.55**	**25.54**	**10.55**

Different letters in the same column indicate significantly different values at $P < 0.05$; n – Number of observations / samples;
CV - Coefficient of variation; ± Values after the means represent the means standard error.

Table 4.10 Available phosphorus (P), cation exchange capacity (CEC) and exchangeable potassium (K^+), magnesium (Mg^{2+}) and calcium (Ca^{2+}) in terraced and non-terraced lands across slope positions in the high altitude area

Site location	Type of land	Slope position	Available P (ppm)	CEC ($cmol_{(+)}$ kg^{-1})	ECEC ($cmol_{(+)}$ kg^{-1})	Exch. K^+ ($cmol_{(+)}$ kg^{-1})	Exch. Mg^{2+} ($cmol_{(+)}$ kg^{-1})	Exch. Ca^{2+} ($cmol_{(+)}$ kg^{-1})
High altitude	Terraced land	Top	19.30 ± 1.83[a]	8.07 ± 0.71[a]	4.65 ± 0.36[a]	0.18 ± 0.01[a]	0.84 ± 0.09[a]	2.39 ± 0.27[c]
		Middle	14.82 ± 1.51[a]	5.81 ± 0.43[a]	5.03 ± 0.32[a]	0.15 ± 0.01[a]	0.94 ± 0.08[a]	3.30 ± 0.23[b]
		Bottom	52.29 ± 1.12[a]	8.94 ± 0.71[a]	6.37 ± 0.09[a]	0.25 ± 0.01[a]	1.43 ± 0.01[a]	4.35 ± 0.10[a]
	Non-terraced land	Top	20.11 ± 0.73[a]	8.84 ± 0.74[a]	4.96 ± 0.22[a]	0.18 ± 0.01[a]	1.10 ± 0.07[a]	2.70 ± 0.12[c]
		Middle	16.04 ± 2.01[a]	5.40 ± 0.41[a]	4.77 ± 0.41[a]	0.16 ± 0.01[a]	1.00 ± 0.12[a]	2.55 ± 0.25[c]
		Bottom	56.43 ± 2.28[a]	9.66 ± 0.51[a]	6.15 ± 0.14[a]	0.25 ± 0.01[a]	1.43 ± 0.01[a]	4.12 ± 0.14[a]
Mean			**29.83**	7.79	**5.32**	**0.20**	**1.13**	**3.24**
n			**54**	**54**	**54**	**54**	**54**	**54**
CV (%)			**13.87**	**24.10**	**12.62**	**14.22**	**17.93**	**13.84**

Different letters in the same column indicate significantly different values at $P < 0.05$; n – Number of observations / samples;

CV - Coefficient of variation; ± Values after the means represent the means standard error.

4.1.11 Effective Cation Exchange Capacity

The effective cation exchange capacity (ECEC) varied from 5.80 to 9.32 $cmol_{(+)}$ kg^{-1} in medium altitude (Table 4.9) and from 4.65 to 6.37 $cmol_{(+)}$ kg^{-1} in high altitude (Table 4.10). These values are ranked in the middle rating (Landon, 1991). The interaction effect between terracing and slope positions on ECEC was non-significant in high altitude and significant ($P< 0.05$) in medium altitude, where higher ECEC was found in bottom slopes; in both terraced land (9.32 $cmol_{(+)}$ kg^{-1}) and non-terraced land (8.45 $cmol_{(+)}$ kg^{-1}) (Table 4.9).

There were no significant interaction effects of terracing and profile depths and main effect of terracing on ECEC in both study areas. The main effect of profile depth on ECEC was also not significant in medium altitude but significant ($P < 0.05$) in high altitude, where higher ECEC of 5.95 $cmol_{(+)}$ kg^{-1} was found in deeper layers compared to that in sub soils (5.21 $cmol_{(+)}$ kg^{-1}) and surface soils (4.80 $cmol_{(+)}$ kg^{-1}) (Table 4.8).

4.1.12 Exchangeable Potassium, Magnesium and Calcium

The average exchangeable potassium (K^+) in soil varied from 0.19 to 0.25 $cmol_{(+)}$ kg^{-1} in medium altitude (Table 4.9) and from 0.15 to 0.25 $cmol_{(+)}$ kg^{-1} in high altitude (Table 4.10). These values are ranked in low/weak to middle rating (Hazelton and Murphy, 2007; Landon, 1991). Contents of exchangeable Mg^{2+} varied from 1.01 to 1.33 $cmol_{(+)}$ kg^{-1} in medium altitude (Table 4.9) and from 0.84 to 1.43 $cmol_{(+)}$ kg^{-1} in high altitude (Table 4.10), and rated low to moderate (Hazelton and Murphy, 2007; Landon, 1991). Contents of exchangeable Ca^{2+} varied from 3.41 to 7.77 $cmol_{(+)}$ kg^{-1} in medium altitude (Table 4.9) and from 2.39 to 4.35 $cmol_{(+)}$ kg^{-1} in high altitude (Table 4.10), and are rated low to moderate (Hazelton and Murphy, 2007; Landon, 1991).

There were no significant interaction effects between terracing and slope positions or terracing and profile depths on exchangeable K^+ and Mg^{2+} in both study sites. Main effects of terracing on exchangeable K^+, Mg^{2+} and Ca^{2+} were also non-significant in both study areas. Main effect of slope positions on exchangeable K^+ was significant ($P < 0.05$) in both study areas. In medium altitude, higher contents of exchangeable K^+ (0.24 $cmol_{(+)}$ kg^{-1}) were found in middle slope compared to bottom (0.21 $cmol_{(+)}$ kg^{-1}) and top (0.20 $cmol_{(+)}$ kg^{-1}) slopes. In high altitude, a higher exchangeable K^+ value of 0.25 $cmol_{(+)}$ kg^{-1} was observed in bottom slope compared to top (0.18 $cmol_{(+)}$ kg^{-1}) and middle (0.16 $cmol_{(+)}$ kg^{-1}) slopes. Main effect of profile depths on exchangeable K^+ was significant ($P < 0.05$). Respective exchangeable K^+

contents of 0.24, 0.22 and 0.19 $cmol_{(+)}$ kg^{-1} were found in deeper, sub and surface soils in medium altitude, and 0.22, 0.20 and 0.17 $cmol_{(+)}$ kg^{-1} in high altitude (Table 4.8).

The main effect of slope positions on exchangeable Mg^{2+} was non-significant in medium altitude and significant ($P < 0.05$) in high altitude, where higher exchangeable Mg^{2+} was found in bottom slope (1.43 $cmol_{(+)}$ kg^{-1}) than top (0.97 $cmol_{(+)}$ kg^{-1}) and middle (0.97 $cmol_{(+)}$ kg^{-1}) slopes. Main effect of profile depth on exchangeable Mg^{2+} was non-significant in medium altitude and significant ($P < 0.05$) in high altitude; higher exchangeable Mg^{2+} contents of 1.26 $cmol_{(+)}$ kg^{-1} were found in the deeper depth compared to 1.12 $cmol_{(+)}$ kg^{-1} in sub-soils and 1.00 $cmol_{(+)}$ kg^{-1} in surface soils (Table 4.8).

Interaction effect between terracing and profile depth on exchangeable Ca^{2+} was non-significant while interaction effect between terracing and slope positions was significant ($P< 0.05$). Higher Ca^{2+} contents were found at the bottom slope in terraced and non-terraced lands of medium (7.77 and 7.12 $cmol_{(+)}$ kg^{-1}) and high (4.35 and 4.12 $cmol_{(+)}$ kg^{-1}) altitudes (Tables 4.9 and 4.10). Main effect of profile depth on exchangeable Ca^{2+} was non-significant in medium altitude and significant ($P < 0.05$) in high altitude; higher values were found in deeper soils (3.69 $cmol_{(+)}$ kg^{-1}) than sub (3.14 $cmol_{(+)}$ kg^{-1}) and surface (2.88 $cmol_{(+)}$ kg^{-1}) soils (Table 4.8).

4.1.13 Soil bacteria and fungi populations

Bacteria population varied from 2.39 x 10^6 to 4.03 x 10^6 colony forming units per gram (CFU g^{-1}) of soil in medium altitude and from 1.66 x 10^6 to 2.72 x 10^6 CFU g^{-1} in high altitude (Table 4.11). There was no significant interaction effect between land terracing and slope positions on bacteria population in both study areas. Main effect of terracing on bacteria population was non-significant in high altitude and significant ($P < 0.05$) in medium altitude, where a higher population was observed in terraced land (3.59 x 10^6 CFU g^{-1}) than non-terraced land 2.61 x 10^6 CFU g^{-1}) land (Figure 4.10). Main effect of slope positions on bacteria population was non-significant in both study areas.

Fungi population varied from 1.45 x 10^4 to 2.77 x 10^4 CFU g^{-1} in medium altitude and from 1.55 x 10^4 to 2.38 x 10^4 CFU g^{-1} in high altitude (Table 4.11). There was no significant interaction effect between land terracing and slope positions on fungi population in both study areas. Main effect of terracing on fungi population was non-significant in high altitude and significant ($P < 0.05$) in medium altitude, where terraced land had higher fungi population (2.51

x 10^4 CFU g^{-1}) than non-terraced land (1.57 x 10^4 CFU g^{-1}) (Figure 4.10). Main effect of slope positions on fungi population was non-significant in both study areas.

Table 4.11 Bacteria and fungi populations in terraced and non-terraced lands across the top, middle and bottom slopes of the medium and high altitude sites

Site location	Type of land	Slope position	Bacteria population (CFUx10^6 g^{-1})	Fungi population (CFUx10^4 g^{-1})
Medium altitude	Terraced land	Top	3.65 ± 0.34 [a]	2.27 ± 0.22 [a]
		Middle	3.10 ± 0.43 [a]	2.48 ± 0.76 [a]
		Bottom	4.03 ± 0.58 [a]	2.77 ± 0.26 [a]
	Non-terraced land	Top	2.68 ± 0.59 [a]	1.45 ± 0.40 [a]
		Middle	2.39 ± 0.43 [a]	1.50 ± 0.28 [a]
		Bottom	2.75 ± 0.24 [a]	1.77 ± 0.19 [a]
Mean			**3.10**	**2.04**
n			**18**	**18**
CV (%)			**24.77**	**34.23**
High altitude	Terraced land	Top	2.36 ± 0.20 [a]	2.07 ± 0.20 [a]
		Middle	2.03 ± 0.45 [a]	2.38 ± 0.30 [a]
		Bottom	2.72 ± 0.29 [a]	1.98 ± 0.29 [a]
	Non-terraced land	Top	1.69 ± 0.11 [a]	1.75 ± 0.26 [a]
		Middle	2.23 ± 0.57 [a]	2.05 ± 0.48 [a]
		Bottom	2.52 ± 0.28 [a]	1.55 ± 0.12 [a]
Mean			**2.43**	**1.96**
n			**18**	**18**
CV (%)			**25.56**	**23.28**

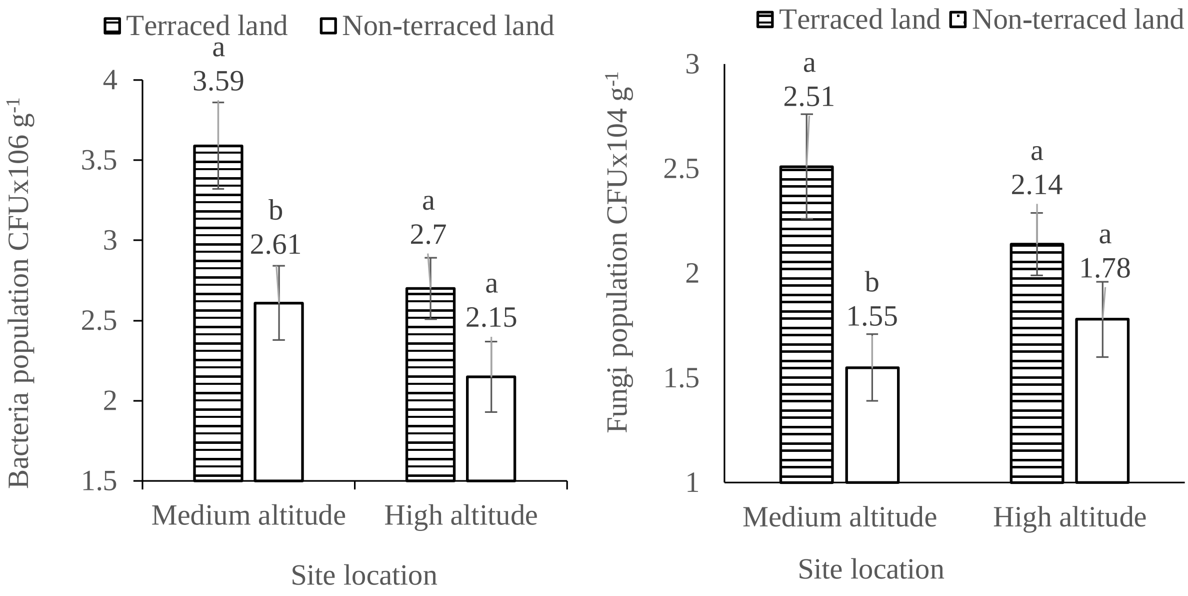
CFU - Colony forming unit;

n – Number of observations / samples;

CV - Coefficient of variation;

Same letters in the same column indicate values with non-significant differences at $P < 0.05$;

± Values after the means represent the means standard error.



(a) **(b)**

Figure 4. 10 Populations of (a) bacteria and (b) fungi in terraced and non-terraced lands of the study areas

CFU - Colony forming unit; Error bars represent means standard error and different letters indicate significantly different values at $P < 0.05$.

4.2 Effect of nitrogen and phosphorus application rates on growth and yields of maize (*Zea mays* L.) in medium and high altitude areas

4.2.1 Maize height, collar diameter and number of leaves

Maize height was significantly ($P < 0.05$) influenced by nitrogen and phosphorus fertilizer rates, at 30, 60 and 90 days after sowing (DAS). In terraced Lixisols of medium altitude site, higher nitrogen and phosphorus fertilizer rates resulted in significantly ($P < 0.05$) taller plants at all evaluated dates (Table 4.12). At 30 DAS, the tallest plants of 74.9 cm were attained in plots treated with the combination rates of 120:120 $N:P_2O_5$ kg ha^{-1} with height increase of 45.4% over the control. Similarly at 60 and 90 DAS, the same fertilizer rates resulted in significantly ($P < 0.05$) taller plants of 187.0 and 270.0 cm with height increases of 50.4% and 63.1% over the control, respectively. At 90 DAS, significantly ($P < 0.05$) higher performance was also recorded for combination rates of 180:120, 180:80 and 120:80 $N:P_2O_5$ kg ha^{-1} with respective height increases of 56.8%, 57.2% and 59.5% over the control (Table 4.12).

Table 4.12 Interaction effect between nitrogen (N) and phosphorus (P_2O_5) fertilizer rates on maize growth parameters for combined analysis of two cropping season's data B 2017 and A 2018 at medium altitude site

N	P_2O_5	Plant height (cm)			Stem collar diameter (cm)			Number of leaves plant^{-1}		
(kg ha^{-1})		30 DAS	60 DAS	90 DAS	30 DAS	60 DAS	90 DAS	30 DAS	60 DAS	90 DAS
0	0	51.5 ± 2.3^{fg}	124.3 ± 10.0^{g}	165.6 ± 15.43^{e}	0.8 ± 0.1^{e}	1.7 ± 0.2^{h}	1.9 ± 0.2^{g}	6.0 ± 0.3^{a}	10.7 ± 0.5^{a}	11.8 ± 0.5^{a}
	40	59.1 ± 3.2^{def}	139.4 ± 11.0^{efg}	189.8 ± 15.80^{de}	0.9 ± 0.1^{bcde}	1.9 ± 0.2^{fgh}	2.3 ± 0.1^{efg}	6.8 ± 0.2^{a}	11.4 ± 0.5^{a}	12.4 ± 0.6^{a}
	80	58.9 ± 3.9^{def}	146.8 ± 11.3^{cdefg}	220.6 ± 18.90^{cd}	1.0 ± 0.1^{bcde}	2.2 ± 0.2^{cdefgh}	2.5 ± 0.2^{bcdef}	6.9 ± 0.3^{a}	11.8 ± 0.4^{a}	12.8 ± 0.5^{a}
	120	56.2 ± 2.6^{efg}	137.7 ± 11.5^{efg}	213.4 ± 17.88^{d}	0.9 ± 0.1^{cde}	2.1 ± 0.2^{defgh}	2.4 ± 0.2^{defg}	6.5 ± 0.4^{a}	11.2 ± 0.5^{a}	12.3 ± 0.6^{a}
60	0	50.3 ± 3.4^{g}	131.7 ± 13.8^{fg}	166.3 ± 16.34^{e}	0.9 ± 0.1^{de}	1.8 ± 0.2^{gh}	2.1 ± 0.2^{fg}	6.5 ± 0.3^{a}	11.5 ± 0.5^{a}	12.4 ± 0.7^{a}
	40	63.4 ± 2.5^{abcd}	160.5 ± 11.3^{abcdef}	215.2 ± 5.41^{d}	1.0 ± 0.1^{bcde}	2.3 ± 0.2^{bcdefg}	2.9 ± 0.2^{abcde}	7.9 ± 0.3^{a}	12.2 ± 0.5^{a}	13.1 ± 0.4^{a}
	80	67.7 ± 3.0^{abc}	163.4 ± 13.6^{abcde}	252.6 ± 11.09^{abc}	1.1 ± 0.1^{abc}	2.5 ± 0.2^{abcde}	2.9 ± 0.2^{abcd}	7.7 ± 0.2^{a}	12.2 ± 0.6^{a}	13.4 ± 0.5^{a}
	120	72.1 ± 3.4^{ab}	175.0 ± 13.8^{abc}	257.7 ± 11.11^{ab}	1.2 ± 0.1^{abc}	2.6 ± 0.2^{abcd}	3.0 ± 0.2^{ab}	7.6 ± 0.3^{a}	12.8 ± 0.6^{a}	13.4 ± 0.4^{a}
120	0	55.0 ± 1.6^{efg}	140.7 ± 8.3^{defg}	194.1 ± 4.65^{de}	0.9 ± 0.1^{de}	1.8 ± 0.2^{gh}	2.0 ± 0.2^{fg}	6.7 ± 0.2^{a}	11.8 ± 0.8^{a}	12.7 ± 0.6^{a}
	40	63.2 ± 2.3^{cde}	161.3 ± 8.2^{abcdef}	225.5 ± 5.63^{bcd}	1.1 ± 0.1^{abcd}	2.4 ± 0.1^{abcdef}	2.8 ± 0.1^{abcde}	7.5 ± 0.2^{a}	12.2 ± 0.4^{a}	13.3 ± 0.3^{a}
	80	70.6 ± 2.3^{abc}	180.7 ± 7.7^{ab}	264.1 ± 9.05^{a}	1.2 ± 0.1^{ab}	2.7 ± 0.2^{ab}	3.1 ± 0.2^{a}	7.5 ± 0.3^{a}	12.9 ± 0.3^{a}	13.4 ± 0.6^{a}
	120	74.9 ± 1.8^{a}	187.0 ± 8.7^{a}	270.0 ± 8.1^{a}	1.2 ± 0.1^{ab}	2.6 ± 0.1^{abcd}	3.0 ± 0.1^{ab}	7.7 ± 0.2^{a}	13.0 ± 0.4^{a}	13.4 ± 0.4^{a}
180	0	56.7 ± 3.0^{efg}	145.0 ± 3.2^{cdefg}	192.8 ± 1.8^{de}	0.9 ± 0.1^{cde}	2.0 ± 0.2^{efgh}	2.2 ± 0.2^{fg}	6.4 ± 0.1^{a}	11.9 ± 0.4^{a}	12.7 ± 0.4^{a}
	40	62.5 ± 1.0^{cde}	153.2 ± 4.5^{bcdefg}	222.0 ± 4.2^{cd}	1.0 ± 0.1^{bcde}	2.5 ± 0.2^{abcde}	2.8 ± 0.2^{abcde}	7.8 ± 0.1^{a}	12.2 ± 0.3^{a}	13.3 ± 0.3^{a}
	80	65.6 ± 2.5^{bcd}	168.9 ± 5.1^{abcde}	260.3 ± 6.0^{a}	1.3 ± 0.1^{a}	2.7 ± 0.1^{abc}	3.2 ± 0.1^{a}	7.3 ± 0.2^{a}	12.5 ± 0.3^{a}	13.4 ± 0.3^{a}
	120	67.4 ± 1.9^{abc}	171.9 ± 5.1^{abcd}	259.6 ± 8.1^{a}	1.4 ± 0.1^{a}	2.9 ± 0.1^{a}	3.3 ± 0.1^{a}	7.5 ± 0.2^{a}	12.4 ± 0.5^{a}	13.4 ± 0.3^{a}
Mean		**62.2**	**155.5**	**223.1**	**1.0**	**2.3**	**2.6**	**7.1**	**12.0**	**12.9**

Different letters in the same column indicate significantly different values at $P < 0.05$; DAS – days after sowing;

± values after the means represent the means standard error

In terraced Acrisols of high altitude site, interaction effect between nitrogen and phosphorus fertilizer application rates on maize height was significant at 60 and 90 DAS with non-significant differences observed at 30 DAS (Table 4.13). At 60 DAS, significantly ($P < 0.05$) taller plants of 172.2 cm height were recorded in plots receiving the combination rates of 120:120 $N:P_2O_5$ kg ha^{-1} which increased plant height by 76.8% over the control. At 90 DAS, combinations of 120:80, 180:40, 180:80, 180:120 and 120:120 $N:P_2O_5$ kg ha^{-1} resulted in significantly ($P < 0.05$) taller plants, with height increases of 53.3%, 55.5%, 59.0%, 63.9% and 69.8% over the control, respectively (Table 4.13).

Stem collar diameter also increased as fertilizer rates increased with similar effects at 30, 60 and 90 DAS. In medium altitude site, at 30 DAS, significantly ($P<0.05$) largest diameters of 1.3 and 1.4 cm were obtained in plots receiving combinations of 180:80 and 180:120 $N:P_2O_5$ kg ha^{-1} with respective diameter increases of 62.5% and 75.0% over the control. Similar effects were observed at 60 DAS with largest diameter of 2.9 cm recorded for the combination of 180:120 $N:P_2O_5$ kg ha^{-1} with diameter increase of 42.7% over the control. At 90 DAS, significantly ($P < 0.05$) larger diameters of 3.1, 3.2 and 3.3 cm were observed for combination rates of 120:80, 180:80 and 180:120 $N:P_2O_5$ kg ha^{-1} with diameter increases of 63.2%, 68.4% and 73.7% over the control, respectively (Table 4.12).

In high altitude site, at 30 DAS, significantly ($P<0.05$) largest collar diameter of 0.9 cm was obtained in plots treated with combination rates of 180:120 $N:P_2O_5$ kg ha^{-1} with diameter increase of 80% over the control (Table 4.13). Similar effects were observed at 60 and 90 DAS for the combination rates 120:120 $N:P_2O_5$ kg ha^{-1} with highest diameters of 2.4 and 3.0 cm and respective increases of 60% and 42.9% obtained over the control (Table 4.13).

Table 4.13 Interaction effect between nitrogen (N) and phosphorus (P_2O_5) fertilizer rates on maize growth parameters for combined analysis of two cropping season's data of B 2017 and A 2018 at high altitude site

N	**P_2O_5**	**Plant height (cm)**			**Stem collar diameter (cm)**			**Number of leaves plant^{-1}**		
(kg ha^{-1})		30 DAS	60 DAS	90 DAS	30 DAS	60 DAS	90 DAS	30 DAS	60 DAS	90 DAS
0	0	41.7 ± 1.8^{a}	97.4 ± 3.8^{e}	135.0 ± 5.8^{e}	0.5 ± 0.1^{e}	1.5 ± 0.2^{efg}	2.1 ± 0.2^{cde}	5.9 ± 0.5^{a}	11.4 ± 0.8^{a}	12.0 ± 0.9^{a}
	40	43.9 ± 7.6^{a}	104.4 ± 4.2^{de}	139.1 ± 7.6^{e}	0.5 ± 0.0^{e}	1.5 ± 0.1^{fg}	2.0 ± 0.1^{e}	6.5 ± 0.3^{a}	12.1 ± 0.7^{a}	12.6 ± 0.6^{a}
	80	51.1 ± 4.5^{a}	117.2 ± 7.1^{cd}	150.6 ± 6.0^{de}	0.6 ± 0.0^{cde}	1.6 ± 0.1^{defg}	2.2 ± 0.1^{cde}	6.8 ± 0.2^{a}	12.0 ± 0.6^{a}	12.7 ± 0.4^{a}
	120	52.8 ± 2.6^{a}	117.9 ± 3.6^{cd}	148.9 ± 3.5^{de}	0.5 ± 0.0^{de}	1.7 ± 0.1^{cdefg}	2.2 ± 0.1^{cde}	7.0 ± 0.2^{a}	12.4 ± 0.6^{a}	12.8 ± 0.5^{a}
60	0	43.1 ± 2.4^{a}	98.8 ± 5.3^{de}	150.7 ± 6.7^{de}	0.5 ± 0.0^{e}	1.5 ± 0.2^{fg}	2.1 ± 0.1^{cde}	5.9 ± 0.3^{a}	11.6 ± 0.7^{a}	12.1 ± 0.6^{a}
	40	53.6 ± 3.5^{a}	117.0 ± 5.1^{cd}	165.2 ± 5.3^{bcd}	0.7 ± 0.1^{abc}	1.7 ± 0.2^{cdefg}	2.2 ± 0.2^{cde}	6.6 ± 0.1^{a}	12.6 ± 0.3^{a}	13.2 ± 0.4^{a}
	80	57.8 ± 3.5^{a}	124.5 ± 6.9^{c}	178.7 ± 8.7^{bc}	0.8 ± 0.1^{ab}	1.9 ± 0.1^{bcdef}	2.3 ± 0.1^{bcde}	6.8 ± 0.2^{a}	13.4 ± 0.4^{a}	13.5 ± 0.4^{a}
	120	59.5 ± 1.1^{a}	132.1 ± 3.9^{c}	184.9 ± 5.4^{b}	0.8 ± 0.1^{ab}	2.0 ± 0.1^{abcd}	2.5 ± 0.1^{bcd}	7.1 ± 0.2^{a}	13.2 ± 0.5^{a}	13.5 ± 0.5^{a}
120	0	48.8 ± 2.7^{a}	112.8 ± 7.7^{cde}	157.8 ± 9.7^{cde}	0.5 ± 0.0^{e}	1.5 ± 0.2^{fg}	2.0 ± 0.2^{de}	5.9 ± 0.4^{a}	11.3 ± 0.5^{a}	12.1 ± 0.7^{a}
	40	57.2 ± 3.6^{a}	129.8 ± 6.1^{c}	184.9 ± 10.4^{b}	0.7 ± 0.1^{bcd}	2.0 ± 0.2^{abcd}	2.5 ± 0.2^{bcd}	6.9 ± 0.3^{a}	12.9 ± 0.3^{a}	13.4 ± 0.5^{a}
	80	67.5 ± 4.8^{a}	153.0 ± 5.5^{b}	206.9 ± 7.4^{a}	0.8 ± 0.1^{ab}	2.1 ± 0.1^{abc}	2.7 ± 0.1^{ab}	6.9 ± 0.2^{a}	12.6 ± 0.6^{a}	13.4 ± 0.5^{a}
	120	73.8 ± 3.6^{a}	172.2 ± 10.6^{a}	229.2 ± 8.3^{a}	0.8 ± 0.1^{ab}	2.4 ± 0.2^{a}	3.0 ± 0.2^{a}	7.0 ± 0.1^{a}	13.2 ± 0.4^{a}	13.7 ± 0.5^{a}
180	0	46.4 ± 2.4^{a}	113.4 ± 7.3^{cde}	166.6 ± 9.4^{bcd}	0.5 ± 0.1^{e}	1.4 ± 0.2^{g}	1.9 ± 0.2^{e}	5.6 ± 0.3^{a}	11.3 ± 0.4^{a}	11.9 ± 0.5^{a}
	40	65.6 ± 2.9^{a}	155.5 ± 8.2^{ab}	209.9 ± 6.4^{a}	0.7 ± 0.1^{bcd}	2.0 ± 0.2^{abcde}	2.5 ± 0.2^{bcd}	7.0 ± 0.2^{a}	12.9 ± 0.3^{a}	13.3 ± 0.4^{a}
	80	67.2 ± 1.8^{a}	150.9 ± 2.9^{b}	214.7 ± 5.6^{a}	0.9 ± 0.1^{ab}	2.2 ± 0.1^{abc}	2.6 ± 0.1^{abc}	7.0 ± 0.2^{a}	13.1 ± 0.6^{a}	13.3 ± 0.6^{a}
	120	67.8 ± 2.7^{a}	157.4 ± 7.4^{ab}	221.3 ± 5.7^{a}	0.9 ± 0.1^{a}	2.3 ± 0.1^{ab}	2.8 ± 0.2^{ab}	7.1 ± 0.2^{a}	13.0 ± 0.7^{a}	13.9 ± 0.4^{a}
Mean		**56.1**	**128.4**	**177.8**	**0.7**	**1.8**	**2.3**	**6.6**	**12.4**	**13.0**

Different letters in the same column indicate significantly different values at $P < 0.05$; DAS – days after sowing;

± values after the means represent the means standard error.

In regards to number of leaves plant^{-1}, interaction effects between nitrogen and phosphorus fertilizer rates were not significant while main effects were significant ($P < 0.05$) in both medium and high altitude sites. In medium altitude site, responses to N and P_2O_5 rates were higher than the control but with non-significant differences observed between the N rates applied, at 30, 60 and 90 DAS (Figures 4.11 and 4.12).

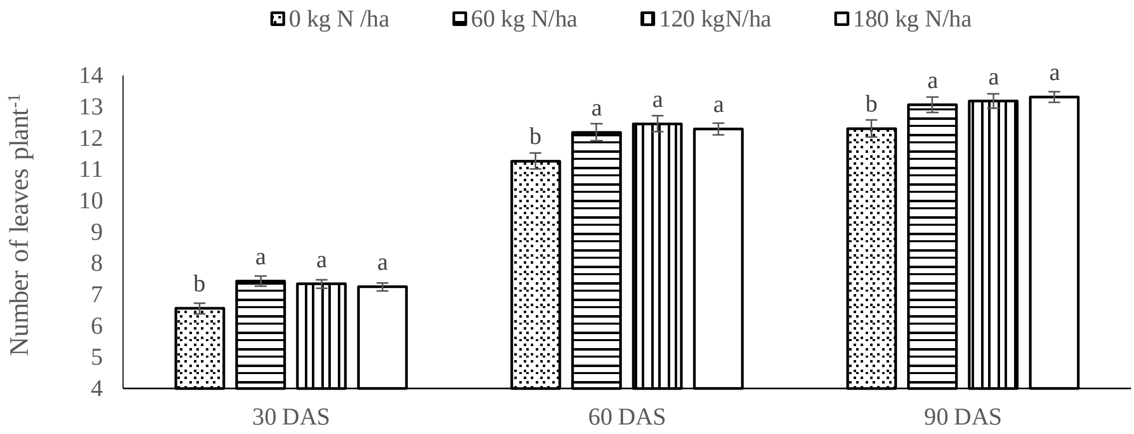


Figure 4.11 Main effect of N rates on number of leaves plant^{-1} at 30, 60 and 90 DAS in medium altitude site

DAS – Days after sowing; Error bars represent means standard error and different letters for same DAS indicate significantly different values at $P < 0.05$.

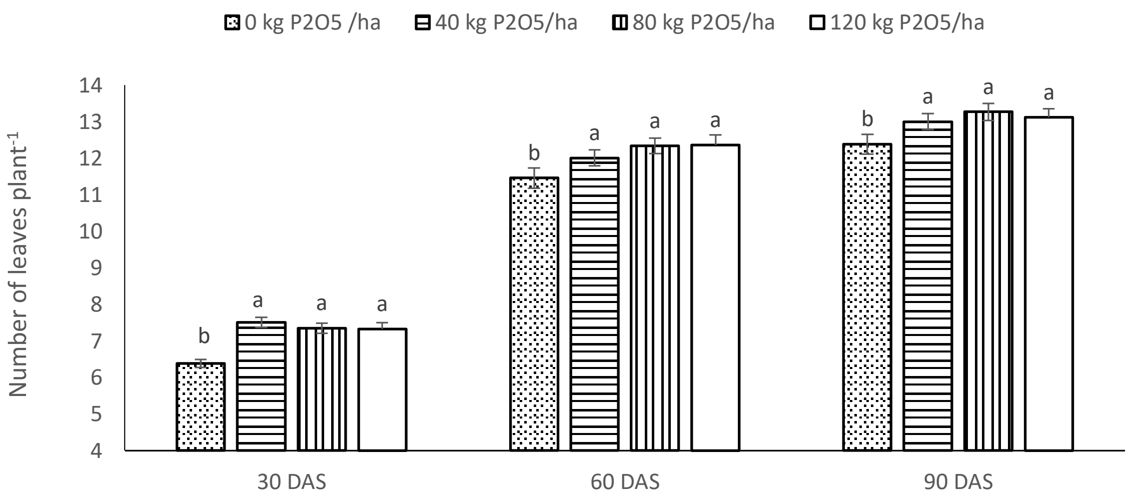


Figure 4. 12 Main effect of P_2O_5 rates on number of leaves plant^{-1} at 30, 60 and 90 DAS in medium altitude site

DAS – Days after sowing; Error bars represent means standard error and different letters for same DAS indicate significantly different values at $P < 0.05$.

In high altitude site, nitrogen fertilizer increased number of leaves plant^{-1} at 60 and 90 DAS. Responses to N rates were significantly (P < 0.05) higher than the control but with non-significant differences observed between N rates applied. At 30 DAS, no significant effect was recorded (Figure 4.13).

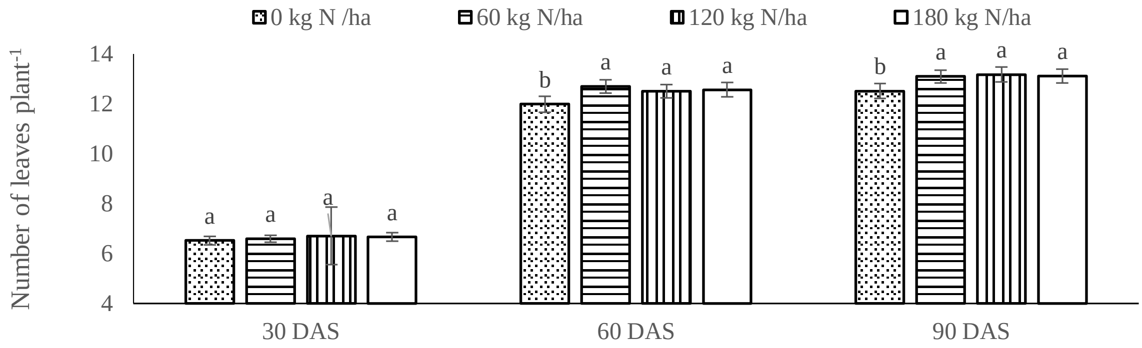


Figure 4.13 Main effect of N rates on number of leaves plan^{-1} at 30, 60 and 90 DAS in high altitude site

DAS – Days after sowing; Error bars represent means standard error and different letters for same DAS indicate significantly different values at P < 0.05.

Similarly, phosphorus fertilizer increased number of leaves per plant. At 30 and 90 DAS, responses to P_2O_5 rates were significantly (P < 0.05) higher than the control but with non-significant differences observed between P_2O_5 rates applied. At 60 DAS, significantly (P < 0.05) higher number of leaves was recorded in plots treated with 120 kg P_2O_5 ha^{-1} with an increase of 14.0% obtained over the control (Figures 4.14).

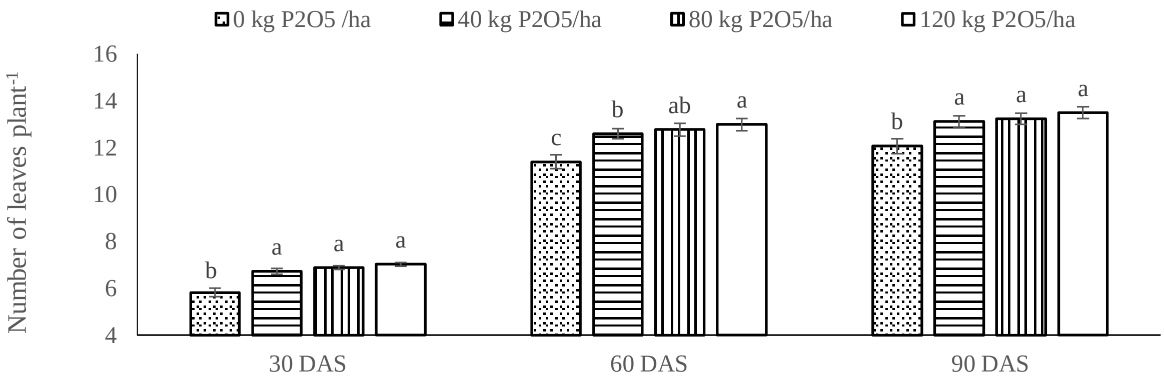
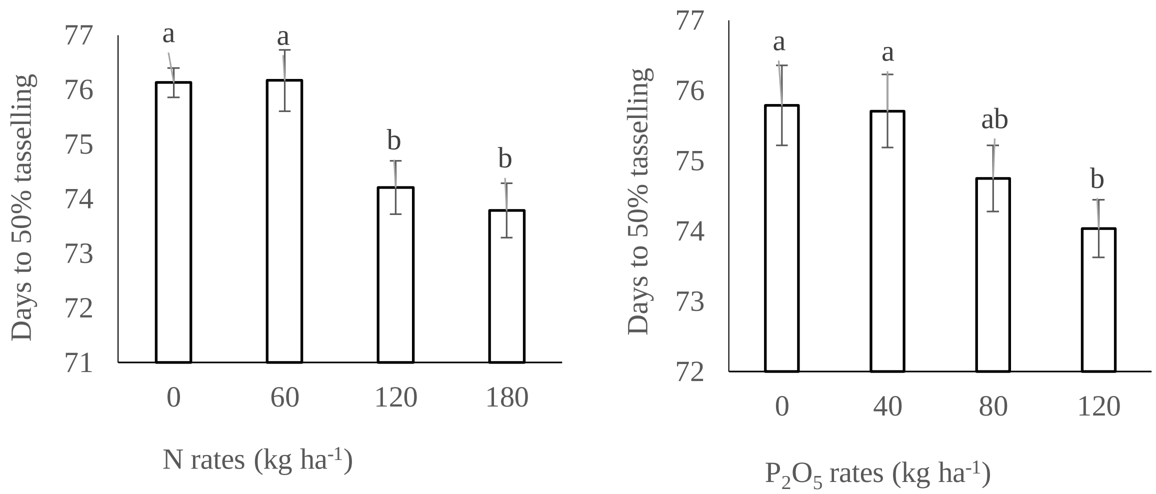


Figure 4.14 Main effect of P_2O_5 rates on number of leaves plan^{-1} at 30, 60 and 90 DAS high altitude site

DAS – Days after sowing; Error bars represent means standard error and different letters for same DAS indicate significantly different values at P < 0.05.

4.2.2 Days to 50% tasselling

The phenology of maize was significantly ($P < 0.05$) influenced by nitrogen and phosphorus fertilizer rates. In medium altitude site, plants which took less days to 50% tasselling were observed for the combination rates of 120:120 N:P_2O_5 kg ha^{-1} with a decrease of three days to the control (Table 4.14). In high altitude site, there was no significant interaction effect between nitrogen and phosphorus rates on number of days to 50% tasselling, while their main effects were significant ($P < 0.05$) (Table 4.15). Plants with less number of days to 50% tasselling were recorded for 120 and 180 kg N ha^{-1} rates with respective decreases of two and four days to the control, and phosphorus application rate of 120 kg P_2O_5 ha^{-1} with a decrease of two days to the control (Figure 4.15).



(a) **(b)**

Figure 4.15 Main effects of (a) nitrogen and (b) phosphorus rates on number of days to 50% tasselling at high altitude site

Error bars represent means standard error and different letters indicate significantly different values at $P < 0.05$.

4.2.3 Yield and yield components

In terraced Lixisols of medium altitude site, significant ($P < 0.05$) interaction effect between nitrogen and phosphorus rates on number of cobs $plant^{-1}$, above-ground biomass yield and grain yields was observed (Table 4.14). Significantly ($P < 0.05$) higher number of cobs $plant^{-1}$ were attained for the combination rates of 120:120, 180:120, 180:80 and 120:80 N: P_2O_5 kg ha^{-1} which equally increased the number of cobs by 23.1% over the control. Significantly ($P < 0.05$) higher grain yields of 6.4 and 6.5 t ha^{-1} were attained in plots applied with N: P_2O_5

combination rates of 120:120 and 180:120 kg ha^{-1} which equally increased grain yield by 2.9 times over the control, and 180:80 and 120:80 kg ha^{-1} with equal yield increase of 3.0 times over the control (Table 4.14).

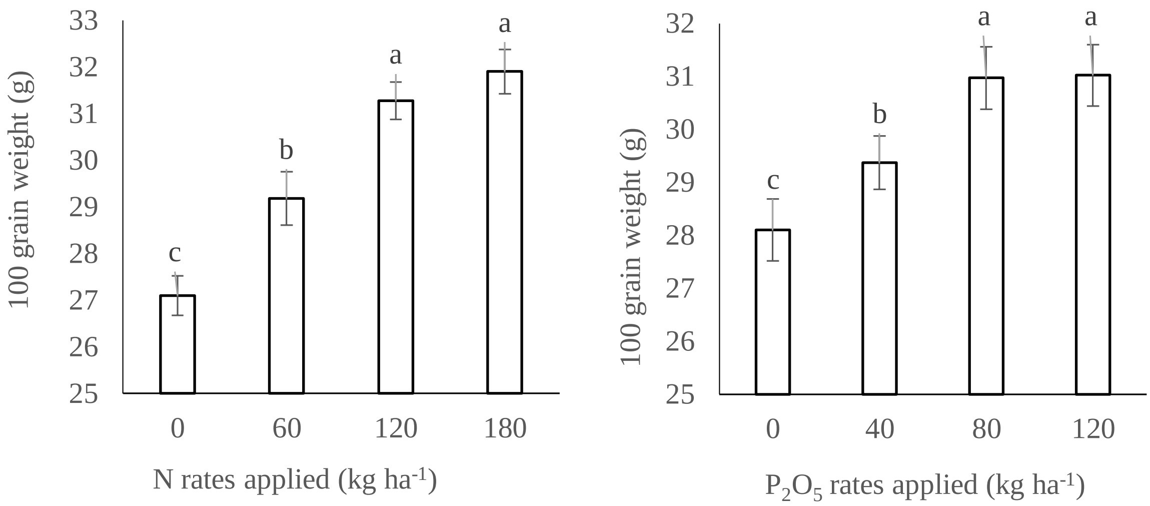
Table 4.14 Interaction effect of nitrogen (N) and phosphorus (P_2O_5) fertilizer rates on maize yield parameters for combined analysis of two cropping season's data B 2017 and A 2018 at medium altitude site

N (kg ha^{-1})	P_2O_5 (kg ha^{-1})	Days to 50% tasselling	Number of cobs plant^{-1}	Grain yield (t ha^{-1})	100 grain weight (g)	AGB (t ha^{-1})	Harvest index (%)
0	0	65.0 ± 0.0^{a}	1.0 ± 0.0^{b}	2.2 ± 0.1^{e}	25.3 ± 0.6^{a}	7.3 ± 0.9^{d}	31.4 ± 2.9^{a}
	40	64.2 ± 0.3^{abc}	1.1 ± 0.1^{ab}	2.8 ± 0.2^{de}	27.0 ± 1.0^{a}	8.8 ± 0.3^{cd}	31.9 ± 1.7^{a}
	80	63.3 ± 0.3^{cd}	1.1 ± 0.1^{ab}	3.0 ± 0.2^{d}	27.6 ± 0.6^{a}	9.7 ± 0.7^{c}	31.5 ± 2.6^{a}
	120	63.7 ± 0.2^{bcd}	1.3 ± 0.1^{ab}	3.3 ± 0.3^{d}	28.5 ± 0.7^{a}	9.7 ± 0.9^{c}	34.0 ± 3.0^{a}
60	0	64.3 ± 0.2^{abc}	1.0 ± 0.0^{b}	3.2 ± 0.3^{d}	26.8 ± 0.9^{a}	10.0 ± 0.7^{c}	31.6 ± 1.5^{a}
	40	64.7 ± 0.2^{ab}	1.1 ± 0.0^{ab}	4.3 ± 0.3^{c}	28.8 ± 0.7^{a}	13.2 ± 0.7^{b}	32.9 ± 1.1^{a}
	80	63.7 ± 0.2^{bcd}	1.1 ± 0.0^{ab}	4.6 ± 0.2^{c}	30.8 ± 0.9^{a}	13.1 ± 1.0^{b}	35.8 ± 1.2^{a}
	120	62.5 ± 0.6^{de}	1.2 ± 0.1^{ab}	4.3 ± 0.4c	30.3 ± 1.4^{a}	13.9 ± 0.9^{b}	31.1 ± 2.0^{a}
120	0	64.0 ± 0.5^{abc}	1.1 ± 0.0^{b}	4.1 ± 0.2^{c}	29.7 ± 0.5^{a}	13.5 ± 0.7^{b}	30.6 ± 1.4^{a}
	40	62.7 ± 0.6^{de}	1.2 ± 0.1^{ab}	5.8 ± 0.1^{ab}	30.2 ± 0.9^{a}	18.1 ± 0.5^{a}	31.9 ± 1.1^{a}
	80	64.0 ± 0.5^{abc}	1.3 ± 0.1^{a}	6.5 ± 0.2^{a}	32.5 ± 0.7^{a}	19.4 ± 0.2^{a}	33.4 ± 1.0^{a}
	120	62.0 ± 0.5^{e}	1.3 ± 0.1^{a}	6.4 ± 0.2^{a}	32.8 ± 0.5^{a}	19.7 ± 0.3^{a}	32.5 ± 0.9^{a}
180	0	63.3 ± 0.4^{cd}	1.2 ± 0.1^{ab}	4.1 ± 0.2^{c}	30.6 ± 1.1^{a}	12.9 ± 0.7^{b}	31.8 ± 1.3^{a}
	40	63.7 ± 0.3^{bcd}	1.2 ± 0.1^{ab}	5.5 ± 0.3^{b}	31.5 ± 0.3^{a}	17.7 ± 0.7^{a}	31.4 ± 1.8^{a}
	80	63.3 ± 0.5^{cd}	1.3 ± 0.1^{a}	6.5 ± 0.2^{a}	33.0 ± 1.0^{a}	19.7 ± 0.4^{a}	32.7 ± 0.7^{a}
	120	63.2 ± 0.4^{bce}	1.3 ± 0.1^{a}	6.4 ± 0.2^{a}	32.5 ± 1.0^{a}	19.7 ± 0.5^{a}	32.5 ± 1.1^{a}
Mean		**63.6**	**1.2**	**4.6**	**29.9**	**14.1**	**32.3**
n		**96**	**96**	**96**	**96**	**96**	**96**
CV (%)		**1.6**	**13.0**	**12.1**	**5.8**	**11.5**	**11.3**

AGB – Above-ground biomass; Different letters in the same column indicate significantly different values at $P < 0.05$; n – Number of observations / treatments; CV - Coefficient of variation; ± Values after the means represent the means standard error.

Significantly ($P < 0.05$) higher above-ground biomass was recorded for the combinations of 120:40 and 120:80 N:P_2O_5 kg ha^{-1} which yielded respective biomass increases of 2.4 and 2.5 times over the control, and 120:120, 180:40, 180:80 and 180:120 kg ha^{-1} with an equal biomass increase of 2.7 times over the control (Table 4.14). There was no significant interaction effect between nitrogen and phosphorus rates on harvest index nor were their main effects significant.

In regards to hundred grain weight, there was no significant interaction effect between nitrogen and phosphorus rates, but their main effects were significant ($P < 0.05$). Significantly ($P < 0.05$) higher hundred grain weights were obtained for 120 and 180 kg N ha^{-1}, which increased hundred grain weights by 15.5% and 18.2%, respectively over the control, and 80 and 120 kg P_2O_5 ha^{-1} with equal weight increase of 10.3% over the control (Figure 4.16).



(a) ***(b)***

Figure 4.16 Hundred grain weight as affected by (a) nitrogen and (b) phosphorus rates in terraced Lixisols of medium altitude

Error bars represent standard error and different letters indicate significantly different values at $P < 0.05$.

In terraced Acrisols of high altitude site, there was significant ($P < 0.05$) interaction effect between nitrogen and phosphorus fertilizer application rates on grain yield and above-ground biomass (Table 4.15). Significantly ($P < 0.05$) higher grain yields of 6.1 and 6.0 t ha^{-1} and above-ground biomass yield of 16.0 and 15.8 t ha^{-1} were recorded for the combination rates of 120:120 and 180:80 N: P_2O_5 kg ha^{-1} with equal grain yield increase of 2.9 times over the control and biomass increase of 2.5 and 2.4 times over the control (Table 4.15).

Table 4.15 Interaction effect between nitrogen (N) and phosphorus (P_2O_5) fertilizer rates on maize yield parameters for combined analysis of two cropping season's data of B 2017 and A 2018 at high altitude site

N (kg ha^{-1})	P_2O_5 (kg ha^{-1})	Days to 50% tasselling	Number of cobs plant^{-1}	Grain yield (t ha^{-1})	AGB (t ha^{-1})	Harvest index (%)	100 grain weight (g)
0	0	76.8 ± 0.5^{a}	1.0 ± 0.0^{a}	2.1 ± 0.1^{g}	6.5 ± 0.4^{h}	32.1 ± 1.9^{a}	24.5 ± 0.1^{a}
	40	76.7 ± 0.4^{a}	1.1 ± 0.1^{a}	2.8 ± 0.2^{efg}	8.4 ± 0.9^{fgh}	34.4 ± 2.3^{a}	25.5 ± 0.8^{a}
	80	76.0 ± 0.5^{a}	1.1 ± 0.1^{a}	2.8 ± 0.3^{efg}	8.6 ± 0.9^{fgh}	32.8 ± 2.1^{a}	27.1 ± 1.5^{a}
	120	75.0 ± 0.5^{a}	1.1 ± 0.1^{a}	3.7 ± 0.3^{cde}	10.5 ± 1.0^{def}	35.2 ± 2.1^{a}	28.1 ± 2.0^{a}
60	0	78.0 ± 1.3^{a}	1.0 ± 0.0^{a}	2.5 ± 0.2^{fg}	7.2 ± 0.5^{gh}	34.3 ± 1.8^{a}	25.1 ± 0.4^{a}
	40	77.3 ± 1.0^{a}	1.2 ± 0.1^{a}	3.9 ± 0.2^{cde}	9.8 ± 0.4^{ef}	39.9 ± 1.6^{a}	25.1 ± 0.6^{a}
	80	75.7 ± 0.3^{a}	1.1 ± 0.1^{a}	3.9 ± 0.2^{cde}	10.6 ± 0.8^{def}	36.9 ± 1.9^{a}	28.5 ± 1.8^{a}
	120	73.7 ± 0.9^{a}	1.2 ± 0.1^{a}	4.4 ± 0.2^{cd}	11.8 ± 0.8^{cde}	37.6 ± 1.3^{a}	28.8 ± 1.4^{a}
120	0	74.5 ± 0.8^{a}	1.0 ± 0.0^{a}	3.1 ± 0.2^{def}	8.7 ± 0.6^{fgh}	36.0 ± 1.4^{a}	26.2 ± 1.2^{a}
	40	75.5 ± 1.2^{a}	1.2 ± 0.1^{a}	4.6 ± 0.4^{bc}	13.1 ± 0.8^{bc}	35.1 ± 1.7^{a}	26.3 ± 1.0^{a}
	80	72.8 ± 0.9^{a}	1.4 ± 0.1^{a}	5.3 ± 0.3^{ab}	13.9 ± 0.8^{abc}	37.8 ± 1.4^{a}	27.9 ± 1.0^{a}
	120	74.0 ± 1.0^{a}	1.4 ± 0.1^{a}	6.1 ± 0.3^{a}	16.0 ± 0.8^{a}	38.2 ± 1.0^{a}	30.0 ± 1.1^{a}
180	0	73.8 ± 1.1^{a}	1.1 ± 0.1^{a}	3.2 ± 0.4^{def}	9.1 ± 0.7^{fg}	34.6 ± 1.7^{a}	26.4 ± 1.8^{a}
	40	73.3 ± 0.8^{a}	1.2 ± 0.1^{a}	4.6 ± 0.5^{bc}	12.8 ± 1.3^{bcd}	36.2 ± 1.3^{a}	27.7 ± 1.3^{a}
	80	74.5 ± 1.3^{a}	1.4 ± 0.1^{a}	6.0 ± 0.3^{a}	15.8 ± 0.7^{a}	38.2 ± 1.2^{a}	30.6 ± 0.9^{a}
	120	73.5 ± 0.9^{a}	1.4 ± 0.1^{a}	5.3 ± 0.4^{ab}	14.3 ± 0.9^{ab}	37.0 ± 1.3^{a}	30.5 ± 1.5^{a}
Mean		**75.1**	**1.2**	**4.0**	**11.1**	**36.0**	**27.4**
n		**96**	**96**	**96**	**96**	**96**	**96**
CV (%)		**3.1**	**11.5**	**16.2**	**14.6**	**11.2**	**10.7**

AGB – Above-ground biomass; Different letters in the same column indicate significantly different values at $P < 0.05$; n – Number of observations / treatments; CV - Coefficient of variation; ± Values after the means represent the means standard error.

There were no significant interaction effects between nitrogen and phosphorus rates on number of cobs plant^{-1}, hundred grain weight and harvest index while their main effects were significant ($P < 0.05$). For nitrogen, higher number of cobs plant^{-1} was found in plots treated with 120 and 180 kg N ha^{-1} with increase of 9.1% over the control. Significantly ($P < 0.05$)

higher hundred grain weight was recorded for 180 kg N ha^{-1} with weight increase of 9.5% over the control. Application of N increased the harvest index compared to the control but with non-significant differences recorded between the N rates applied (Table 4.16).

Table 4.16 Main effect of nitrogen (N) and phosphorus (P_2O_5) fertilizer rates on number of cobs $plant^{-1}$, 100 grain weight and harvest index for combined analysis of two cropping season's data of B 2017 and A 2018 at high altitude site

Fertilizer	Rates (kg ha^{-1})	Number of cobs $plant^{-1}$	100 grain weight (g)	Harvest index (%)
N	0	1.1 ± 0.0^{b}	26.3 ± 0.7^{b}	33.6 ± 1.0^{b}
	60	1.1 ± 0.0^{b}	26.9 ± 0.7^{b}	37.2 ± 0.9^{a}
	120	1.2 ± 0.0^{a}	27.6 ± 0.6^{ab}	36.8 ± 0.7^{a}
	180	1.2 ± 0.0^{a}	28.8 ± 0.8^{a}	36.5 ± 0.7^{a}
Mean		**1.2**	**27.4**	**36.0**
n		**96**	**96**	**96**
CV (%)		**11.5**	**10.7**	**11.2**
P_2O_5	0	1.0 ± 0.1^{c}	25.6 ± 0.5^{b}	34.3 ± 0.9^{b}
	40	1.2 ± 0.0^{b}	26.2 ± 0.5^{b}	36.4 ± 0.9^{ab}
	80	1.2 ± 0.0^{ab}	28.5 ± 0.7^{a}	36.4 ± 0.9^{ab}
	120	1.3 ± 0.0^{a}	29.3 ± 0.7^{a}	37.0 ± 0.7^{a}
Mean		**1.2**	**27.4**	**36.0**
n		**96**	**96**	**96**
CV (%)		**11.5**	**10.7**	**11.2**

Different letters in the same column indicate significantly different values at $P < 0.05$;
n – Number of observations / treatments;
CV - Coefficient of variation;
± Values after the means represent the means standard error.

For phosphorus, significantly ($P < 0.05$) higher performances on number of cobs $plant^{-1}$ and harvest index were recorded for 120 kg P_2O_5 ha^{-1} with respective increases of 30.0% and 7.9% over the control. Higher hundred grain weight was attained for 80 and 120 kg P_2O_5 ha^{-1} with respective weight increases of 11.3% and 14.5% over the control (Table 4.16).

4.2.4 Effect of cropping seasons on maize growth and yields

Maize growth and yields were influenced by cropping seasons. Significantly ($P < 0.05$) taller plants, larger stem collar diameters, higher number of leaves plant^{-1} and higher above-biomass and grain yields were found in season A 2018 compared to season B 2017 at both medium and high altitude sites separately and for pooled sites (Table 4.17 and 4.18). There was no significant effect of cropping season on days to 50% tasselling (Table 4.17).

Table 4.17 Effect of cropping seasons on maize growth and tasselling for medium and high altitude separately and pooled sites

Site location	Season	Plant height at 90 DAS (cm)	Collar diameter 90 DAS (cm)	Number of leaves plant^{-1} 90 DAS	Number of days to 50% tasselling
Medium	B 2017	203.6 ± 5.9^{b}	2.3 ± 0.1^{b}	12.0 ± 0.1^{b}	63.6 ± 0.2^{a}
altitude	A 2018	242.6 ± 5.0^{a}	2.9 ± 0.1^{a}	13.9 ± 0.1^{a}	63.6 ± 0.2^{a}
Mean		**223.1**	**2.6**	**13.0**	**63.6**
n		**96**	**96**	**96**	**96**
CV (%)		**5.1**	**7.8**	**4.2**	**1.7**
High altitude	B 2017	174.2 ± 5.0^{b}	2.1 ± 0.1^{b}	11.9 ± 0.1^{b}	75.3 ± 0.4^{a}
	A 2018	181.3 ± 4.8^{a}	2.5 ± 0.1^{a}	14.0 ± 0.1^{a}	74.9 ± 0.4^{a}
Mean		**177.8**	**2.3**	**13.0**	**75.1**
n		**96**	**96**	**96**	**96**
CV (%)		**9.4**	**12.4**	**4.8**	**3.1**
PSL	B 2017	188.9 ± 4.1^{b}	2.2 ± 0.1^{b}	12.0 ± 0.1^{b}	69.5 ± 0.7^{a}
PSL	A 2018	212.0 ± 3.4^{a}	2.7 ± 0.1^{a}	14.0 ± 0.1^{a}	69.2 ± 0.6^{a}
Mean		**200.4**	**2.5**	**13.0**	**69.3**
n		**192**	**192**	**192**	**192**
CV (%)		**7.6**	**10.6**	**4.7**	**2.6**

Different letters in the same column indicate significantly different values at $P < 0.05$;
n – Number of observations / treatments; PSL – pooled sites location; DAS – days after sowing;
CV - Coefficient of variation; ± values after the means represent the means standard error;
B 2017 – season from March to August 2017; A 2018 - season from September 2017 to February 2018.

Table 4.18 Effect of cropping seasons on maize yields for medium and high altitude separately and pooled sites

Site location	Season	Number of cobs plant^{-1}	100 grain weight (g)	Above-ground biomass (t ha^{-1})	Grain yield (t ha^{-1})
Medium	B 2017	1.2 ± 0.0^{a}	29.5 ± 0.4^{b}	14.1 ± 0.7^{a}	4.4 ± 0.2^{b}
altitude	A 2018	1.2 ± 0.0^{a}	30.3 ± 0.5^{a}	14.2 ± 0.6^{a}	4.7 ± 0.2^{a}
Mean		**1.2**	**29.9**	**14.2**	**4.6**
n		**96**	**96**	**96**	**96**
CV (%)		**13.0**	**5.8**	**11.5**	**12.1**
High	B 2017	1.1 ± 0.0^{b}	27.3 ± 0.5^{a}	10.3 ± 0.5^{b}	3.8 ± 0.2^{b}
altitude	A 2018	1.2 ± 0.0^{a}	27.6 ± 0.5^{a}	11.9 ± 0.5^{a}	4.3 ± 0.2^{a}
Mean		**1.2**	**27.4**	**11.1**	**4.0**
n		**96**	**96**	**96**	**96**
CV (%)		**11.5**	**10.7**	**14.6**	**17.5**
PSL	B 2017	1.2 ± 0.0^{a}	28.4 ± 0.3^{a}	12.2 ± 0.5^{b}	4.1 ± 0.2^{b}
PSL	A 2018	1.2 ± 0.0^{a}	28.9 ± 0.4^{a}	13.0 ± 0.4^{a}	4.5 ± 0.2^{a}
Mean		**1.2**	**28.6**	**12.6**	**4.3**
n		**192**	**192**	**192**	**192**
CV (%)		**12.3**	**8.4**	**13.0**	**14.8**

Different letters in the same column indicate significantly different values at $P < 0.05$; n – Number of observations / treatments; PSL – pooled sites location; DAS – days after sowing; CV - Coefficient of variation; ± values after the means represent the means standard error; B2017 – season from March to August 2017; A2018 - season from September 2017 to February 2018.

There were no significant interaction effects between cropping seasons, sites location, nitrogen and phosphorus rates and between cropping seasons, nitrogen and phosphorus rates on maize growth and yield parameters. There was, however, a significant ($P < 0.05$) interaction effect between cropping seasons and nitrogen rates. Significantly ($P < 0.05$) taller plants at 60 and 90 DAS were obtained for 120 and 180 kg N ha^{-1} in season A 2018 while shorter plants were observed for 60 and 0 kg N ha^{-1} in season B 2017 (Table 4.19).

Table 4.19 Interaction effect between cropping seasons and nitrogen (N) application rates on maize growth and yields

Season	N rates (kg ha^{-1})	Plant height at 60 DAS (cm)	Plant height at 90 DAS (cm)	Collar diameter at 60 DAS (cm)	Collar diameter at 90 DAS (cm)	Days to 50% tasselling	Number of cobs $plant^{-1}$	100 grain weight (g)	AGB (t ha^{-1})	Grain yield (t ha^{-1})
B 2017	0	109.6 ± 2.8^{d}	153.2 ± 5.6^{d}	1.5 ± 0.1^{d}	2.0 ± 0.1^{c}	70.1 ± 1.3^{a}	1.0 ± 0.0^{a}	27.0 ± 0.6^{bc}	8.0 ± 0.5^{c}	2.8 ± 0.2^{d}
	60	124.2 ± 4.0^{cd}	182.4 ± 7.7^{c}	1.7 ± 0.1^{cd}	2.2 ± 0.1^{bc}	69.8 ± 1.3^{a}	1.1 ± 0.0^{a}	17.0 ± 0.4^{c}	11.2 ± 0.6^{b}	3.5 ± 0.2^{bc}
	120	148.7 ± 4.7^{ab}	206.7 ± 7.7^{ab}	1.9 ± 0.1^{bc}	2.4 ± 0.1^{b}	69.2 ± 1.3^{a}	1.2 ± 0.0^{a}	28.9 ± 0.7^{c}	14.8 ± 0.8^{a}	5.1 ± 0.3^{a}
	180	147.5 ± 3.9^{ab}	213.2 ± 5.8^{a}	2.0 ± 0.1^{b}	2.4 ± 0.1^{b}	68.7 ± 1.2^{a}	1.3 ± 0.0^{a}	30.5 ± 0.7^{a}	14.7 ± 0.9^{a}	4.9 ± 0.3^{a}
A 2018	0	136.6 ± 5.5^{bc}	187.5 ± 10.0^{bc}	2.1 ± 0.1^{b}	2.4 ± 0.1^{b}	70.0 ± 1.3^{a}	1.2 ± 0.0^{a}	26.3 ± 0.5^{c}	9.4 ± 0.4^{bc}	3.0 ± 0.1^{cd}
	60	151.6 ± 8.0^{ab}	210.4 ± 9.5^{ab}	2.4 ± 0.1^{a}	2.8 ± 0.1^{a}	70.2 ± 1.4^{a}	1.2 ± 0.0^{a}	29.0 ± 0.8^{abc}	11.2 ± 0.5^{b}	4.1 ± 0.2^{b}
	120	160.7 ± 7.3^{a}	226.4 ± 8.6^{a}	2.4 ± 0.1^{a}	2.9 ± 0.1^{a}	68.2 ± 1.1^{a}	1.2 ± 0.0^{a}	30.0 ± 0.6^{a}	15.8 ± 0.7^{a}	5.4 ± 0.3^{a}
	180	156.6 ± 4.7^{a}	223.5 ± 7.5^{a}	2.5 ± 0.1^{a}	2.9 ± 0.1^{a}	68.5 ± 1.1^{a}	1.2 ± 0.0^{a}	30.2 ± 0.7^{a}	15.7 ± 0.7^{a}	5.5 ± 0.2^{a}
Mean		**141.9**	**200.4**	**2.1**	**2.5**	**69.3**	**1.2**	**28.6**	**12.6**	**4.3**
n		**192**	**192**	**192**	**192**	**192**	**192**	**192**	**192**	**192**
CV (%)		**9.7**	**7.6**	**11.9**	**10.6**	**2.6**	**12.3**	**8.4**	**13.0**	**14.8**

AGB – Above-ground biomass; DAS – Days after sowing; Different letters in the same column indicate significantly different values at $P < 0.05$; n – Number of observations / treatments; CV - Coefficient of variation; ± Values after the means represent the means standard error; Season B 2017 was from March to August 2017 and season A 2018 was from September 2017 to February 2018.

Similarly, larger stem collar diameters at 60 and 90 DAS were recorded in plots receiving 60, 120 and 180 kg N ha^{-1} in season A 2018 while smaller diameters were observed for 60 and 0 kg N ha^{-1} in season B 2017. Significantly ($P < 0.05$) higher above-ground biomass and grain yields were attained with application of 120 and 180 kg N ha^{-1} in season A 2018, and 180 kg N ha^{-1} in season B 2017 (Table 4.19).

4.2.5 Effect of sites location on maize growth and yields

Maize growth and yields were influenced by sites location. Significantly ($P < 0.05$) taller plants and larger stem collar diameters at 60 and 90 DAS, higher hundred grain weight, higher above-ground biomass and grain yields were recorded in terraced Lixisols of medium altitude site compared to terraced Acrisols of high altitude site, for seasons B 2017 and A 2018 separately and for pooled seasons (Tables 4.20 and 4.21). However, significantly ($P < 0.05$) higher number of leaves $plant^{-1}$ and days to 50% tasselling were recorded in high altitude site (Tables 4.20).

Maize growth and yield parameters were not significantly ($P<0.05$) affected by interaction between locations and nitrogen and phosphorus fertilizer rates or between location and phosphorus rates (Table 4.22). However, there was significant ($P < 0.05$) interaction effect between site locations and nitrogen rates. Significantly ($P < 0.05$) taller plants at 60 and 90 DAS were recorded for 120 and 180 kg N ha^{-1} in terraced Lixisols of medium altitude site while smaller plants were observed in plots receiving 60 and 0 kg N ha^{-1} in terraced Acrisols of high altitude site. Similarly, larger stem collar diameters at 60 and 90 DAS were attained for 60, 120 and 180 kg N ha^{-1} at medium altitude site while smaller diameters were recorded for control at high altitude site. Significantly ($P < 0.05$) higher hundred grain weight, above-ground biomass and grain yields were recorded for 120 and 180 kg N ha^{-1} at medium altitude site and lower yields were observed in plots receiving 60 kg N ha^{-1} at high altitude site and for control at both sites. Plants which took less days to 50% tasselling were observed at medium altitude site compared to high altitude site for all applied N rates (Tables 4.22).

Table 4.20 Effect of sites location on maize growth and tasselling for seasons B 2017 and A2018 separately and pooled seasons

Season	Site location (altitude)	Plant height at 90 DAS (cm)	Collar diameter 90 DAS (cm)	Number of leaves plant^{-1} 90 DAS	Number of days to 50% tasselling
B 2017	Medium	203.6 ± 5.9^{a}	2.3 ± 0.1^{a}	12.0 ± 0.1^{a}	63.6 ± 0.2^{b}
	High	174.2 ± 5.0^{b}	2.1 ± 0.1^{b}	11.9 ± 0.1^{b}	75.3 ± 0.4^{a}
Mean		**188.9**	**2.2**	**12.0**	**69.5**
n		**96**	**96**	**96**	**96**
CV (%)		**9.2**	**9.4**	**4.4**	**2.5**
A 2018	Medium	242.6 ± 5.0^{a}	2.9 ± 0.1^{a}	13.9 ± 0.1^{a}	63.6 ± 0.2^{b}
	High	181.3 ± 4.2^{b}	2.5 ± 0.1^{b}	14.0 ± 0.1^{a}	74.9 ± 0.4^{a}
Mean		**212.0**	**2.7**	**14.0**	**69.2**
n		**96**	**96**	**96**	**96**
CV (%)		**5.8**	**11.3**	**4.7**	**2.4**
PS	Medium	223.1 ± 4.3^{a}	2.6 ± 0.1^{a}	13.0 ± 0.1^{a}	63.6 ± 0.1^{b}
PS	High	177.8 ± 3.5^{b}	2.3 ± 0.1^{b}	13.0 ± 0.1^{a}	75.1 ± 0.3^{a}
Mean		**200.4**	**2.5**	**13.0**	**69.3**
n		**192**	**192**	**192**	**192**
CV (%)		**7.6**	**10.6**	**4.7**	**2.6**

Different letters in the same column indicate significantly different values at $P < 0.05$;
DAS – Days after sowing; n – Number of observations / treatments; CV - Coefficient of variation; ± Values after the means represent the means standard error;
PS – pooled seasons B 2017 (March - August 2017) and A 2018 (September 2017 - February 2018).

Table 4.21 **Effect of sites location on maize yield parameters for seasons B 2017 and A 2018 separately and pooled seasons**

Season	**Site location (altitude)**	**Number of cobs plant^{-1}**	**100 grain weight (g)**	**Above-ground biomass (t ha^{-1})**	**Grain yield (t ha^{-1})**
B 2017	Medium	1.2 ± 0.0^a	29.5 ± 0.4^a	14.1 ± 0.7^a	4.4 ± 0.2^a
	High	1.1 ± 0.0^a	27.3 ± 0.5^b	10.3 ± 0.5^b	3.8 ± 0.2^b
Mean		**1.2**	**28.4**	**12.2**	**4.1**
n		**96**	**96**	**96**	**96**
CV (%)		**9.8**	**7.6**	**13.4**	**19.3**
A 2018	Medium	1.2 ± 0.0^a	30.3 ± 0.5^a	14.2 ± 0.6^a	4.7 ± 0.2^a
	High	1.2 ± 0.0^a	27.6 ± 0.5^b	11.9 ± 0.5^b	4.3 ± 0.2^b
Mean		**1.2**	**28.9**	**13.0**	**4.5**
n		**96**	**96**	**96**	**96**
CV (%)		**12.8**	**9.2**	**12.2**	**9.5**
PS	Medium	1.2 ± 0.0^a	29.9 ± 0.3^a	14.2 ± 0.5^a	4.6 ± 0.2^a
PS	High	1.2 ± 0.0^a	27.4 ± 0.3^b	11.1 ± 0.4^b	4.0 ± 0.1^b
Mean		**1.2**	**28.6**	**12.6**	**4.3**
n		**192**	**192**	**192**	**192**
CV (%)		**12.3**	**8.4**	**13.0**	**14.8**

Different letters in the same column indicate significantly different values at $P < 0.05$;
DAS – Days after sowing; n – Number of observations / treatments; CV - Coefficient of variation; ± Values after the means represent the means standard error;
PS – pooled seasons B 2017 (March - August 2017) and A 2018 (September 2017 - February 2018).

4.2.6 Relationship between growth and yield parameters

Correlation analysis indicated that plant height, stem collar diameter, number of leaves plant^{-1}, number of cobs plant^{-1}, above-ground biomass, hundred grain weight and grain yield were significantly ($P < 0.05$) and positively correlated in both study sites (Table 4.22). A negative correlation was observed between these parameters and number of days to 50% tasselling (Table 4.23).

Table 4.22 Interaction effect between sites location and nitrogen (N) application rates on maize growth and yields

Site	N rates (kg ha^{-1})	Plant height at 60 DAS (cm)	Plant height at 90 DAS (cm)	Collar diameter at 60 DAS (cm)	Collar diameter at 90 DAS (cm)	Days to 50% tasselling	Number of cobs plant^{-1}	100 grain weight (g)	AGB (t ha^{-1})	Grain yield (t ha^{-1})
Medium	0	137.0 ± 5.4^{c}	197.3 ± 9.1^{b}	2.0 ± 0.1^{b}	2.3 ± 0.1^{cd}	64.0 ± 0.2^{c}	1.1 ± 0.0^{a}	27.1 ± 0.4^{c}	8.9 ± 0.4^{c}	2.8 ± 0.1^{e}
altitude	60	157.6 ± 7.0^{ab}	222.9 ± 9.4^{a}	2.3 ± 0.1^{a}	2.7 ± 0.1^{ab}	63.8 ± 0.2^{c}	1.1 ± 0.0^{a}	29.2 ± 0.6^{b}	12.5 ± 0.5^{b}	4.1 ± 0.2^{c}
	120	167.4 ± 5.4^{a}	238.4 ± 7.2^{a}	2.4 ± 0.1^{a}	2.7 ± 0.1^{ab}	63.2 ± 0.3^{c}	1.2 ± 0.0^{a}	31.3 ± 0.4^{a}	17.7 ± 0.6^{a}	5.7 ± 0.2^{a}
	180	159.8 ± 3.1^{a}	233.7 ± 6.4^{a}	2.5 ± 0.1^{a}	2.8 ± 0.1^{a}	63.4 ± 0.2^{c}	1.3 ± 0.0^{a}	31.9 ± 0.5^{a}	17.5 ± 0.6^{a}	5.6 ± 0.2^{a}
High	0	109.2 ± 2.9^{d}	143.4 ± 3.1^{d}	1.6 ± 0.1^{c}	2.1 ± 0.1^{d}	76.1 ± 0.3^{a}	1.1 ± 0.0^{a}	26.3 ± 0.7^{c}	8.5 ± 0.5^{c}	3.0 ± 0.2^{de}
altitude	60	118.1 ± 3.6^{d}	169.9 ± 4.2^{c}	1.8 ± 0.1^{bc}	2.3 ± 0.1^{cd}	76.2 ± 0.6^{a}	1.1 ± 0.0^{a}	26.9 ± 0.7^{c}	9.9 ± 0.5^{c}	3.5 ± 0.2^{d}
	120	142.0 ± 5.9^{c}	194.7 ± 6.9^{b}	2.0 ± 0.1^{b}	2.5 ± 0.1^{bc}	74.2 ± 0.5^{b}	1.2 ± 0.0^{a}	27.6 ± 0.6^{bc}	12.9 ± 0.7^{b}	4.8 ± 0.3^{b}
	180	144.3 ± 4.9^{bc}	203.1 ± 5.5^{b}	2.0 ± 0.1^{b}	2.4 ± 0.1^{bc}	73.8 ± 0.5^{b}	1.2 ± 0.0^{a}	28.8 ± 0.8^{b}	13.0 ± 0.7^{b}	4.8 ± 0.3^{b}
Mean		**141.9**	**200.4**	**2.1**	**2.5**	**69.3**	**1.2**	**28.6**	**12.6**	**4.3**
n		**192**	**192**	**192**	**192**	**192**	**192**	**192**	**192**	**192**
CV (%)		**9.7**	**7.6**	**11.9**	**10.6**	**2.6**	**12.3**	**8.4**	**13.0**	**14.8**

AGB – Above-ground biomass; DAS – Days after sowing;

Different letters in the same column indicate significantly different values at $P < 0.05$;

n – Number of observations / treatments; CV - Coefficient of variation;

± Values after the means represent the means standard error;

Season B 2017 was from March to August 2017 and season A 2018 was from September 2017 to February 2018.

Table 4.23 Pearson correlation coefficients for growth and yield parameters as affected by nitrogen and phosphorus fertilizers

Site location	Variable	Plant height 90 DAS	Collar diameter 90 DAS	Number of leaves 90 DAS	Days to 50% tasselling	Number of cobs plant^{-1}	Above-ground biomass	Hundred grain weight	Grain yield
Medium altitude	Plant height 90 DAS	1.000							
	Stem diameter 90 DAS	0.864***	1.000						
	Number of leaves 90 DAS	0.753***	0.785***	1.000					
	Days to 50% tasselling	-0.417***	-0.275**	-0.273**	1.000				
	Number of cobs plant^{-1}	0.470***	0.318**	0.217*	-0.231*	1.000			
	Above-ground biomass	0.613***	0.610***	0.376***	-0.358***	0.407***	1.000		
	Hundred grain weight	0.530***	0.489***	0.276**	-0.302**	0.439***	0.744***	1.000	
	Gain yield	0.570***	0.568***	0.293**	- 0.357***	0.440***	0.946***	0.738***	1.000
High altitude	Plant height 90 DAS	1.000							
	Stem diameter 90 DAS	0.627***	1.000						
	Number of leaves 90 DAS	0.297***	0.686***	1.000					
	Days to 50% tasselling	-0.308**	-0.276**	-0.191ns	1.000				
	Number of cobs plant^{-1}	0.582***	0.570***	0.435***	-0.327**	1.000			
	Above-ground biomass	0.794***	0.494***	0.186ns	-0.326**	0.678***	1.000		
	Hundred grain weight	0.304**	0.287**	0.240*	-0.172ns	0.283**	0.399***	1.000	
	Gain yield	0.799***	0.487***	0.220*	- 0.299**	0.700***	0.955***	0.374***	1.000

ns - Non-significant; * Significant at P < 0.05; ** Significant at P < 0.01; *** Significant at P < 0.001; DAS – Days after sowing.

4.2.7 Estimating optimum rates of nitrogen and phosphorus fertilizers

The results on modeling for optimum fertilizer (N, P_2O_5) rates and responses of maize grain yield to the fertilizer application are shown in Table 4.25 and Figures 4.17 and 4.18. The zero-solutions of the derivative equations were located at the optimum rates of 176.6 kg N ha^{-1} and 96.2 kg P_2O_5 ha^{-1} with respective maximum grain yields of 5.7 and 5.2 t ha^{-1} in terraced Lixisols of medium altitude site. In terraced Acrisols of high altitude site, the coefficient of determination (R^2) was not significant for both N and P_2O_5 and therefore optimum fertilizer rates were not estimated nor maximum yield predicted.

4.2.8 Nitrogen Use Efficiency (NUE)

In medium altitude site, higher agronomic Nitrogen Use Efficiency (NUE) was obtained with application of fertilizer N rate of 120 kg N ha^{-1} followed by that given by 60 kg N ha^{-1} and lastly by 180 kg N ha^{-1}; 24.0%, 21.8% and 15.6%, respectively (Table 4.24). The NUE for the optimum fertilizer rate of 176.6 kg N ha^{-1} is lower (16.3%) than that of 60 and 120 kg N ha^{-1}.

In high altitude site, higher NUE was found in plots received fertilizer N rate of 60 kg N ha^{-1}, followed by that of 120 kg N ha^{-1} and lastly 180 kg N ha^{-1}; 21.2%, 14.8% and 12.0%, respectively (4.24). The NUE decreased with increase of fertilizer N rates applied.

Table 4.24 Nitrogen Use Efficiency (NUE) as influenced by fertilizer N rates applied

Site location	**N rates (kg ha^{-1})**	**Grain Yield (kg ha^{-1})**	**NUE (%)**
Medium altitude	0	2809.6	-
	60	4117.1	21.8
	120	5684.2	24.0
	180	5612.1	15.6
High altitude	0	2710.4	-
	60	3982.9	21.2
	120	4484.2	14.8
	180	4870.0	12.0

Table 4.25 Modeling for optimum fertilizer (N and P_2O_5) rates and predicted maximum maize grain yields

Site	Fertilizer	Interc β_0	ReCoe β_1	ReCoe β_2	Quadratic Equation	R^2	Optimum fertilizer rate	Predicted grain yield
Medium altitude	**N**	2714.38	33.88	-0.10	$Y= 2714.38 + 33.88x – 0.10x^2$	0.60***	176.6 kg ha^{-1}	5.7 t ha^{-1}
	P_2O_5	3388.29	37.79	-0.20	$Y=3388.29 + 37.79x – 0.20x^2$	0.21*	96.2 kg ha^{-1}	5.2 t ha^{-1}
High altitude	**N**	2894.21	17.35	-0.04	$Y= 2894.21 + 17.35x – 0.04x^2$	0.28ns	NA	NA
	P_2O_5	2743.54	34.04	-0.14	$Y= 2743.54 + 34.04x – 0.14x^2$	0.33ns	NA	NA

* Significant at P= 0.05; *** Significant at P = 0.001;

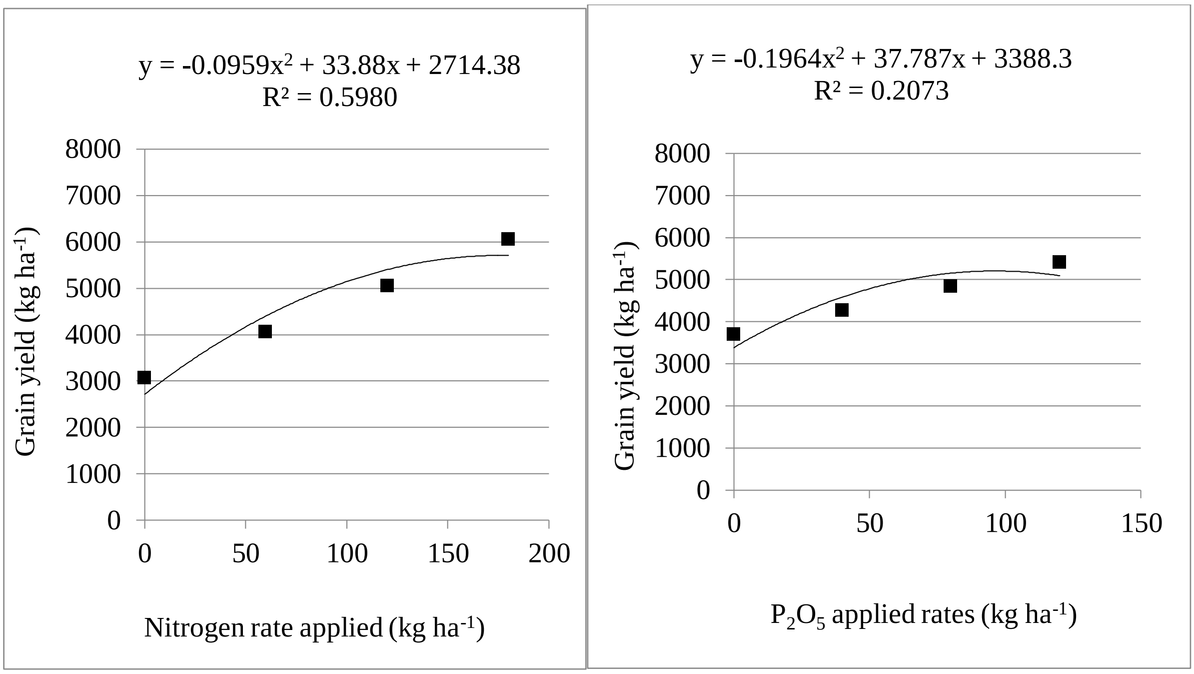
ns - Not significant; NA - Not applied;

Interc - Intercept with β_0 the intercept coefficient;

ReCoe - Regression coefficient with β_1 the linear terms and β_2 the squared terms;

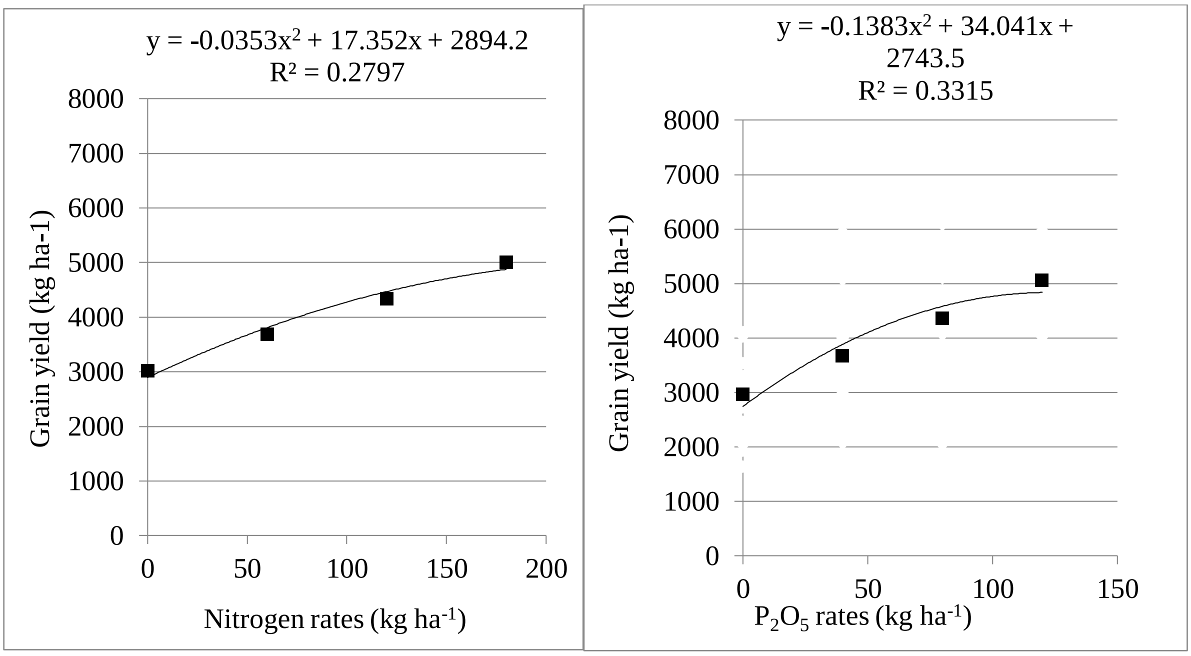
x - Independent variable (N, P_2O_5);

R^2 - coefficient of determination.



(a) (b)

Figure 4.17 Effect of increasing applied rates of (a) nitrogen and (b) phosphorus fertilizers on grain yield in terraced Lixisols of medium altitude site



(a) (b)

Figure 4.18 Effect of increasing applied rates of (a) nitrogen and (b) phosphorus fertilizers on grain yield in terraced Acrisols of high altitude site

4.3 Effect of bioslurry and mineral nitrogen (N) on soil physical, chemical and biological properties at medium and high altitude areas

The initial soil physical and chemical properties prior to the trial and residual effects of treatments at physiological maturity/ harvest of maize in terraced Lixisols of medium and terraced Acrisols of high altitude sites are presented in Tables 4.26, 4.27, 4.28 and 4.29.

Table 4.26 Effect of bioslurry and mineral N application rates on soil bulk density, moisture content, pH, organic carbon and total N in medium altitude site

Bioslurry (t ha^{-1})	N (kg ha^{-1})	Bulk density (g cm^{-3})	Moisture content (%)	pH (water)	Organic carbon (%)	Total N (%)
Initial prior trial		1.56	8.1	5.43	1.08	0.06
0	0	1.57 ± 0.03[a]	9.70 ± 0.74[a]	5.47 ± 0.14[a]	1.09 ± 0.01[a]	0.06 ± 0.01[a]
	30	1.50 ± 0.04[a]	10.63 ± 0.71[a]	5.52 ± 0.12[a]	1.09 ± 0.01[a]	0.07 ± 0.01[a]
	60	1.57 ± 0.04[a]	10.89 ± 0.88[a]	5.67 ± 0.15[a]	1.12 ± 0.02[a]	0.07 ± 0.00[a]
	90	1.59 ± 0.07[a]	9.83 ± 1.00[a]	5.65 ± 0.07[a]	1.12 ± 0.01[a]	0.07 ± 0.01[a]
6	0	1.52 ± 0.04[a]	10.16 ± 0.49[a]	5.51 ± 0.14[a]	1.75 ± 0.13[a]	0.08 ± 0.01[a]
	30	1.59 ± 0.06[a]	9.83 ± 0.48[a]	5.48 ± 0.08[a]	1.69 ± 0.04[a]	0.10 ± 0.01[a]
	60	1.50 ± 0.05[a]	10.28 ± 0.64[a]	5.28 ± 0.06[a]	1.66 ± 0.12[a]	0.10 ± 0.00[a]
	90	1.49 ± 0.06[a]	9.70 ± 0.96[a]	5.43 ± 0.10[a]	1.80 ± 0.08[a]	0.11 ± 0.01[a]
12	0	1.56 ± 0.03[a]	10.20 ± 0.60[a]	5.55 ± 0.13[a]	1.58 ± 0.07[a]	0.11 ± 0.01[a]
	30	1.58 ± 0.03[a]	10.79 ± 0.47[a]	5.50 ± 0.04[a]	1.72 ± 0.06[a]	0.11 ± 0.01[a]
	60	1.51 ± 0.05[a]	10.51 ± 0.74[a]	5.44 ± 0.06[a]	1.99 ± 0.20[a]	0.11 ± 0.01[a]
	90	1.55 ± 0.06[a]	9.24 ± 0.40[a]	5.47 ± 0.17[a]	1.91 ± 0.10[a]	0.11 ± 0.01[a]
18	0	1.54 ± 0.04[a]	10.73 ± 0.79[a]	5.53 ± 0.11[a]	1.91 ± 0.15[a]	0.12 ± 0.00[a]
	30	1.54 ± 0.05[a]	11.36 ± 0.80[a]	5.42 ± 0.11[a]	2.16 ± 0.11[a]	0.12 ± 0.00[a]
	60	1.55 ± 0.04[a]	10.03 ± 0.53[a]	5.44 ± 0.10[a]	2.04 ± 0.15[a]	0.13 ± 0.01[a]
	90	1.55 ± 0.04[a]	10.86 ± 0.58[a]	5.44 ± 0.14[a]	1.98 ± 0.10[a]	0.13 ± 0.00[a]
Mean		**1.54**	**10.30**	**5.49**	**1.66**	**0.10**
n		**96**	**96**	**96**	**96**	**96**
CV (%)		**5.40**	**16.08**	**4.57**	**16.36**	**16.40**

N – Nitrogen; n – number of observations; CV - Coefficient of variation; ± values after the means represent the means standard error; Same letters in the same column indicate values with non-significant differences at $P < 0.05$.

4.3.1 Soil physical properties

In terraced Lixisols of medium altitude site, at physiological maturity/ harvest of maize, soil bulk density and moisture content varied from 1.49 to 1.59 g cm^{-3} and 9.79 to 11.36%, respectively (Table 4.26).

Table 4.27 Effect of bioslurry and mineral N application rates on available P, CEC, exchangeable K^+, Mg^{2+} and Ca^{2+} in medium altitude site

Bioslurry ($t\ ha^{-1}$)	**N ($kg\ ha^{-1}$)**	**Available P (ppm)**	**CEC ($cmol_{(+)}\ kg^{-1}$)**	**K^+ ($cmol_{(+)}\ kg^{-1}$)**	**Mg^{2+} ($cmol_{(+)}\ kg^{-1}$)**	**Ca^{2+} ($cmol_{(+)}\ kg^{-1}$)**
Initial prior trial		18.63	7.12	0.25	1.10	4.55
0	0	16.41 ± 1.84^a	6.74 ± 0.33^a	0.21 ± 0.01^a	1.22 ± 0.07^a	4.04 ± 0.26^a
	30	14.61 ± 1.79^a	7.10 ± 0.44^a	0.20 ± 0.01^a	1.18 ± 0.06^a	4.20 ± 0.17^a
	60	16.21 ± 0.76^a	6.51 ± 0.40^a	0.20 ± 0.01^a	1.21 ± 0.05^a	4.09 ± 0.18^a
	90	17.80 ± 2.12^a	7.00 ± 0.51^a	0.21 ± 0.01^a	1.18 ± 0.04^a	4.23 ± 0.22^a
6	0	16.96 ± 0.77^a	6.44 ± 0.38^a	0.20 ± 0.01^a	1.26 ± 0.05^a	4.29 ± 0.21^a
	30	19.42 ± 1.55^a	6.95 ± 0.46^a	0.21 ± 0.01^a	1.21 ± 0.08^a	4.10 ± 0.15^a
	60	14.32 ± 0.97^a	7.21 ± 0.34^a	0.20 ± 0.01^a	1.21 ± 0.04^a	4.28 ± 0.18^a
	90	16.21 ± 1.90^a	6.29 ± 0.45^a	0.21 ± 0.01^a	1.21 ± 0.04^a	4.18 ± 0.07^a
12	0	14.70 ± 1.49^a	6.60 ± 0.40^a	0.20 ± 0.01^a	1.21 ± 0.04^a	4.21 ± 0.18^a
	30	16.20 ± 1.37^a	6.61 ± 0.47^a	0.20 ± 0.01^a	1.16 ± 0.05^a	3.94 ± 0.11^a
	60	17.74 ± 1.93^a	6.13 ± 0.25^a	0.20 ± 0.01^a	1.16 ± 0.08^a	4.11 ± 0.06^a
	90	17.34 ± 1.07^a	6.55 ± 0.14^a	0.20 ± 0.00^a	1.12 ± 0.06^a	3.99 ± 0.12^a
18	0	13.56 ± 0.99^a	6.97 ± 0.44^a	0.19 ± 0.02^a	1.09 ± 0.06^a	3.91 ± 0.08^a
	30	13.77 ± 1.75^a	6.80 ± 0.24^a	0.19 ± 0.01^a	1.17 ± 0.04^a	4.07 ± 0.08^a
	60	18.26 ± 3.37^a	7.21 ± 0.09^a	0.20 ± 0.01^a	1.14 ± 0.06^a	4.18 ± 0.05^a
	90	19.44 ± 2.04^a	7.15 ± 0.15^a	0.21 ± 0.01^a	1.20 ± 0.07^a	4.19 ± 0.10^a
Mean		**16.12**	**6.76**	**0.20**	**1.18**	**4.12**
n		**96**	**96**	**96**	**96**	**96**
CV (%)		**21.03**	**13.54**	**12.81**	**11.47**	**8.60**

N – Nitrogen; n – number of observations; CV - Coefficient of variation; ± values after the means represent the means standard error; Same letters in the same column indicate values with non-significant differences at $P < 0.05$.

In terraced Acrisols of high altitude, soil bulk density and moisture content varied from 1.25 to 1.31 g cm^{-3} and 11.42 to 15.58%, respectively (Table 4.28). There were no significant interaction or main effects of bioslurry and mineral N on soil bulk density and moisture in both study sites.

Table 4.28 Effect of bioslurry and mineral N application rates on soil bulk density, moisture content, pH, organic carbon and total N in high altitude site

Bioslurry (t ha^{-1})	N (kg ha^{-1})	Bulk density (g cm^{-3})	Moisture content (%)	pH (water)	Organic carbon (%)	Total N (%)
Initial prior trial		1.29	10.3	4.91	1.96	0.08
0	0	1.29 ± 0.02[a]	11.42 ± 1.29[a]	4.86 ± 0.20[a]	1.79 ± 0.29[a]	0.08 ± 0.01[a]
	30	1.30 ± 0.01[a]	14.84 ± 1.99[a]	5.36 ± 0.29[a]	1.61 ± 0.27[a]	0.09 ± 0.01[a]
	60	1.29 ± 0.01[a]	12.70 ± 0.95[a]	4.75 ± 0.15[a]	2.03 ± 0.11[a]	0.09 ± 0.00[a]
	90	1.25 ± 0.02[a]	11.62 ± 1.11[a]	4.79 ± 0.12[a]	2.13 ± 0.11[a]	0.09 ± 0.01[a]
5	0	1.28 ± 0.01[a]	12.54 ± 1.64[a]	4.80 ± 0.19[a]	1.93 ± 0.13[a]	0.10 ± 0.01[a]
	30	1.31 ± 0.01[a]	12.62 ± 1.62[a]	4.80 ± 0.11[a]	2.29 ± 0.15[a]	0.10 ± 0.01[a]
	60	1.27 ± 0.02[a]	12.26 ±1.08[a]	5.01 ± 0.14[a]	2.15 ± 0.10[a]	0.11 ± 0.01[a]
	90	1.32 ± 0.03[a]	12.67 ± 1.11[a]	5.05 ± 0.13[a]	2.14 ± 0.14[a]	0.11 ± 0.01[a]
10	0	1.30 ± 0.03[a]	11.64 ± 0.95[a]	5.20 ± 0.06[a]	2.11 ± 0.18[a]	0.11 ± 0.01[a]
	30	1.29 ± 0.02[a]	13.55 ± 1.31[a]	5.05 ± 0.17[a]	2.41 ± 0.15[a]	0.11 ± 0.00[a]
	60	1.27 ± 0.02[a]	13.48 ± 0.83[a]	4.87 ± 0.21[a]	2.20 ± 0.27[a]	0.12 ± 0.00[a]
	90	1.27 ± 0.01[a]	13.86 ± 1.36[a]	5.88 ± 0.19[a]	2.09 ± 0.16[a]	0.12 ± 0.01[a]
15	0	1.29 ± 0.01[a]	12.93 ± 1.54[a]	4.91 ± 0.11[a]	2.17 ± 0.07[a]	0.11 ± 0.01[a]
	30	1.28 ± 0.01[a]	14.30 ± 0.71[a]	5.06 ± 0.23[a]	2.17 ± 0.17[a]	0.11 ± 0.02[a]
	60	1.27 ± 0.02[a]	15.58 ± 0.79[a]	4.89 ± 0.20[a]	2.28 ± 0.20[a]	0.13 ± 0.01[a]
	90	1.29 ± 0.02[a]	13.62 ± 0.80[a]	5.07 ± 0.19[a]	2.44 ± 0.20[a]	0.14 ± 0.01[a]
Mean		**1.28**	**13.10**	**4.96**	**2.12**	**0.11**
n		**96**	**96**	**96**	**96**	**96**
CV (%)		**3.58**	**20.76**	**7.82**	**17.44**	**20.13**

N – Nitrogen; n – number of observations; CV - Coefficient of variation; ± values after the means represent the means standard error; Same letters in the same column indicate values with non-significant differences at $P < 0.05$.

4.3.2 Soil pH, CEC and exchangeable bases

There were no significant interaction or main effects of bioslurry and mineral N on pH, CEC and exchangeable K^+, Mg^{2+} and Ca^{2+} contents in both study sites (Tables 4.26, 4.27, 2.28 and 4.29).

Table 4.29 Effect of bioslurry and mineral N application rates on available P, CEC, exchangeable K^+, Mg^{2+} and Ca^{2+} in high altitude site

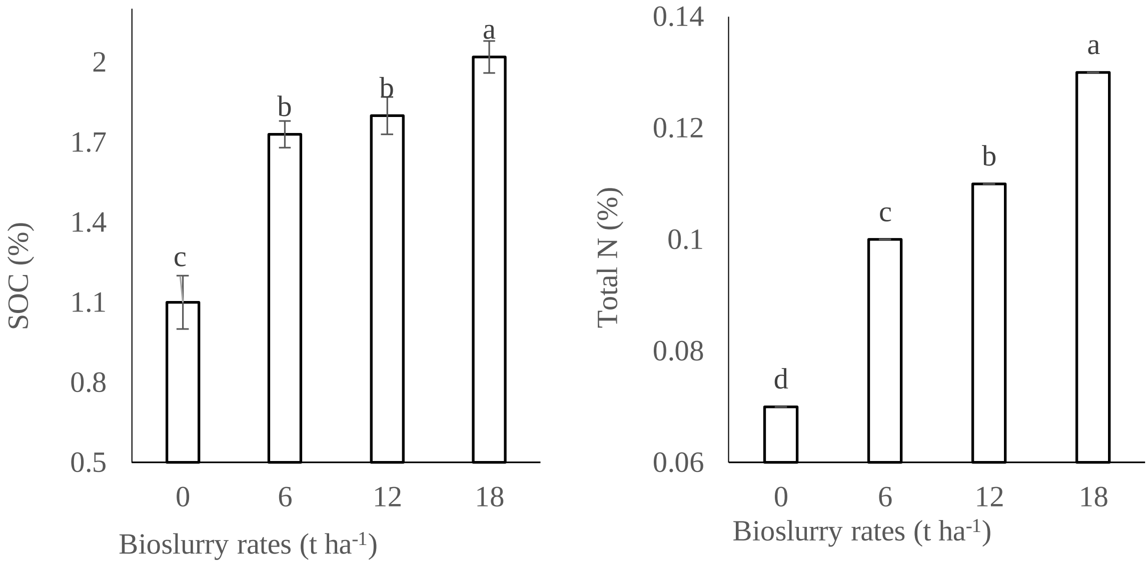
Bioslurry ($t\ ha^{-1}$)	**N ($kg\ ha^{-1}$)**	**Available P (ppm)**	**CEC ($cmol_{(+)}\ kg^{-1}$)**	**K^+ ($cmol_{(+)}\ kg^{-1}$)**	**Mg^{2+} ($cmol_{(+)}\ kg^{-1}$)**	**Ca^{2+} ($cmol_{(+)}\ kg^{-1}$)**
Initial prior trial		14.82	5.81	0.15	0.94	3.30
0	0	13.93 ± o.71[a]	5.72 ± 0.58[a]	0.14 ± 0.01[a]	0.99 ± 0.16[a]	3.24 ± 0.30[a]
	30	12.73 ± 0.78[a]	5.96 ± 0.50[a]	0.13 ± 0.01[a]	1.10 ± 0.16[a]	3.21 ± 0.34[a]
	60	13.55 ± 0.42[a]	6.25 ± 0.68[a]	0.14 ± 0.01[a]	0.79 ± 0.20[a]	3.27 ± 0.32[a]
	90	12.91 ± 0.83[a]	6.63 ± 0.47[a]	0.14 ± 0.01[a]	0.96 ± 0.18[a]	3.16 ± 0.34[a]
5	0	13.90 ± 0.91[a]	5.54 ± 0.48[a]	0.15 ± 0.01[a]	0.83 ± 0.19[a]	2.91 ± 0.32[a]
	30	13.67 ± 0.85[a]	6.51 ± 0.87[a]	0.14 ± 0.01[a]	1.02 ± 0.14[a]	3.34 ± 0.29[a]
	60	13.55 ± 0.93[a]	5.69 ± 0.34[a]	0.14 ± 0.01[a]	0.97 ± 0.13[a]	3.42 ± 0.21[a]
	90	13.29 ± 1.14[a]	5.97 ± 0.75[a]	0.16 ± 0.01[a]	0.86 ± 0.11[a]	3.34 ± 0.13[a]
10	0	14.37 ± 1.33[a]	5.79 ± 0.48[a]	0.14 ± 0.01[a]	0.94 ± 0.14[a]	3.44 ± 0.26[a]
	30	14.38 ± 0.78[a]	6.05 ± 0.38[a]	0.14 ± 0.01[a]	0.90 ± 0.14[a]	3.22 ± 0.22[a]
	60	17.24 ± 1.58[a]	5.50 ± 0.53[a]	0.14 ± 0.01[a]	0.92 ± 0.14[a]	3.12 ± 0.12[a]
	90	13.07 ± 0.40[a]	5.78 ± 0.66[a]	0.15 ± 0.01[a]	1.05 ± 0.14[a]	3.21 ± 0.24[a]
15	0	14.85 ± 1.12[a]	5.77 ± 0.58[a]	0.15 ± 0.01[a]	0.99 ± 0.17[a]	3.27 ± 0.18[a]
	30	16.13 ± 0.79[a]	5.75 ± 0.50[a]	0.15 ± 0.01[a]	0.92 ± 0.21[a]	3.24 ± 0.18[a]
	60	16.31 ± 1.71[a]	6.14 ± 0.77[a]	0.16 ± 0.01[a]	1.06 ± 0.15[a]	3.33 ± 0.26[a]
	90	14.46 ± 1.14[a]	5.68 ± 0.50[a]	0.15 ± 0.01[a]	1.03 ± 0.04[a]	3.19 ± 0.20[a]
Mean		**14.27**	**5.86**	**0.14**	**0.96**	**3.23**
n		**96**	**96**	**96**	**96**	**96**
CV (%)		**15.35**	**23.05**	**16.22**	**34.95**	**15.57**

N – Nitrogen; n – number of observations; CV - Coefficient of variation; ± values after the means represent the means standard error; Same letters in the same column indicate values with non-significant differences at $P < 0.05$.

In terraced Lixisols of medium altitude site, at physiological maturity/ harvest of maize, pH varied from 5.28 to 5.67. The CEC varied from 6.13 to 7.21 $cmol_{(+)}\,kg^{-1}$, and exchangeable K^+, Mg^{2+} and Ca^{2+} varied from 0.19 to 0.21, 1.09 to 1.26 and 3.91 to 4.29 $cmol_{(+)}\,kg^{-1}$, respectively (Tables 4.26 and 4.27). In terraced Acrisols of high altitude site, pH varied from 4.75 to 5.88, CEC varied from 5.50 to 6.63 $cmol_{(+)}\,kg^{-1}$, and exchangeable K^+, Mg^{2+} and Ca^{2+} varied from 0.13 to 0.16, 0.79 to 1.10 and 2.91 to 3.44 $cmol_{(+)}\,kg^{-1}$, respectively (Tables 4.28 and 4.29).

4.3.3 Soil organic carbon, total N and available P

In terraced Lixisols of medium altitude site, effects of interaction between bioslurry and mineral N, and main effects of mineral N on soil organic carbon (SOC), total N and available P were not significant ($P<0.05$) (Tables 4.26 and 4.27). The main effects of bioslurry on SOC and total N were significant ($P < 0.05$) but not significant on available P. Higher SOC of 2.02% and total N of 0.13% were found in plots treated with bioslurry at the rate of 18 t ha^{-1}. The SOC and total N contents in the control were 1.06% and 0.07%, respectively (Figure 4.19).



(a) **(b)**

Figure 4.19 Main effects of bioslurry rates on (a) SOC and (b) total N content in medium altitude area

SOC – Soil organic carbon; Error bars represent standard error;

Different letters indicate significantly different values at $P < 0.05$.

In terraced Acrisols of high altitude site, there were no significant ($P < 0.05$) interaction effects of bioslurry and mineral N or main effects of mineral N on SOC, total N and available P. The main effects of bioslurry rates on SOC, total N and available P were significant ($P < 0.05$). Application of bioslurry increased the SOC compared to the control but with non-significant differences recorded between the bioslurry rates applied. Significantly ($P < 0.05$) higher values of total N (0.12%) and available P (15.43 ppm) were found in plots applied with 15 t bioslurry ha^{-1} (Table 4.30).

Table 4.30 Main effect of bioslurry rates on soil organic carbon (SOC), total nitrogen (N) and available phosphorus (P) contents in high altitude area

Bioslurry ($t\ ha^{-1}$)	**SOC** (%)	**Total N** (%)	**Available P** (ppm)
0	1.89 ± 0.11^{b}	0.09 ± 0.00^{c}	13.28 ± 0.34^{c}
5	2.13 ± 0.07^{a}	0.10 ± 0.00^{b}	13.60 ± 0.45^{bc}
10	2.20 ± 0.09^{a}	0.11 ± 0.00^{ab}	14.76 ± 0.61^{ab}
15	2.26 ± 0.08^{a}	0.12 ± 0.01^{a}	15.43 ± 0.60^{a}

Different letters in the same column indicate significantly different values at $P < 0.05$;
± Values after the means represent the means standard error.

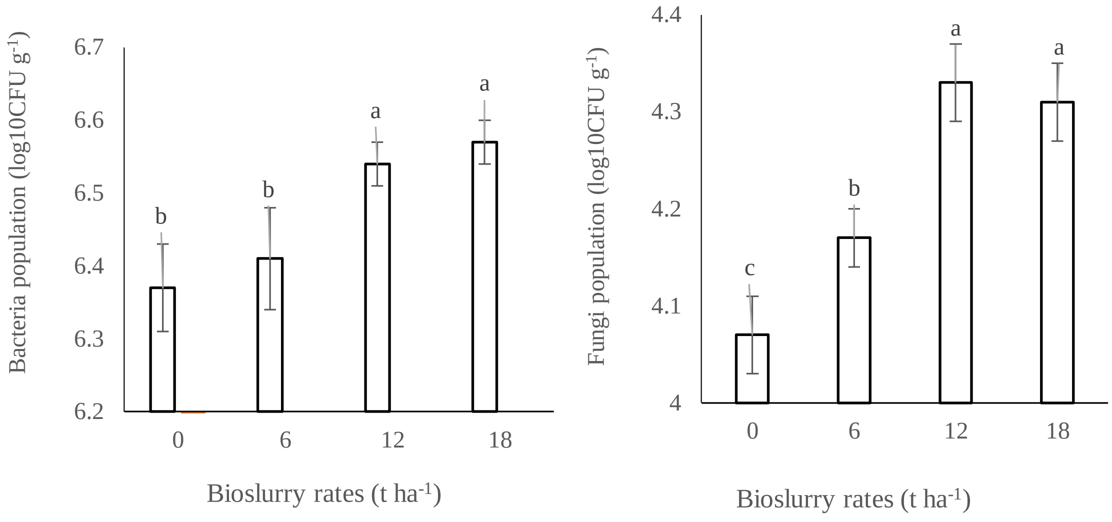
4.3.4 Soil bacteria and fungi populations

There were no significant ($P < 0.05$) bioslurry and mineral N interaction effects on populations of bacteria and fungi (Table 4.31), while their main effects were significant ($P < 0.05$), in both medium and high altitude sites at physiological maturity/ harvest of maize. In terraced Lixisols of medium altitude site, for bioslurry, significantly ($P < 0.05$) higher bacteria populations of 6.54 and 6.57 log_{10} CFU g^{-1}, and higher fungi populations of 4.33 and 4.31 log_{10} CFU g^{-1} were found in plots treated with 12 and 18 t bioslurry ha^{-1}, respectively (Figure 4.20). For mineral N, population of bacteria was higher in plots treated with N compared to the control with non-significant differences in N rates applied. Higher fungi populations of 4.29 and 4.33 log_{10} CFU g^{-1} were observed in plots applied with 60 and 90 kg N ha^{-1} (Figure 4.21).

Table 4.31 Effect of bioslurry and mineral N application rates on soil bacteria and fungi populations in medium and high altitude sites

Bioslurry ($t\ ha^{-1}$)	N ($kg\ ha^{-1}$)	Medium altitude site		High altitude site	
		Bacteria (log_{10} $CFU\ g^{-1}$)	Fungi (log_{10} $CFU\ g^{-1}$)	Bacteria (log_{10} $CFU\ g^{-1}$)	Fungi (log_{10} $CFU\ g^{-1}$)
B0	0	6.14 ± 0.15 [a]	3.95 ± 0.09 [a]	5.88 ± 0.13 [a]	4.02 ± 0.09 [a]
	30	6.47 ± 0.13 [a]	3.99 ± 0.02 [a]	6.12 ± 0.05 [a]	4.09 ± 0.07 [a]
	60	6.45 ± 0.13 [a]	4.14 ± 0.07 [a]	6.11 ± 0.06 [a]	4.23 ± 0.06 [a]
	90	6.42 ± 0.09 [a]	4.20 ± 0.08 [a]	6.22 ± 0.07 [a]	4.23 ± 0.06 [a]
B1	0	6.09 ± 0.17 [a]	4.06 ± 0.04 [a]	5.97 ± 0.07 [a]	3.95 ± 0.05 [a]
	30	6.44 ± 0.10 [a]	4.16 ± 0.04 [a]	6.21 ± 0.06 [a]	4.17 ± 0.08 [a]
	60	6.56 ± 0.11 [a]	4.21 ± 0.05 [a]	6.30 ± 0.09 [a]	4.26 ± 0.08 [a]
	90	6.55 ± 0.09 [a]	4.26 ± 0.06 [a]	6.38 ± 0.07 [a]	4.36 ± 0.07 [a]
B2	0	6.50 ± 0.09 [a]	4.22 ± 0.09 [a]	6.02 ± 0.07 [a]	4.12 ± 0.07 [a]
	30	6.39 ± 0.05 [a]	4.25 ± 0.07 [a]	6.21 ± 0.07 [a]	4.17 ± 0.09 [a]
	60	6.61 ± 0.03 [a]	4.42 ± 0.07 [a]	6.39 ± 0.07 [a]	4.30 ± 0.12 [a]
	90	6.63 ± 0.05 [a]	4.44 ± 0.09 [a]	6.41 ± 0.06 [a]	4.33 ± 0.09 [a]
B3	0	6.45 ± 0.09 [a]	4.14 ± 0.03 [a]	6.22 ± 0.05 [a]	4.04 ± 0.05 [a]
	30	6.58 ± 0.06 [a]	4.30 ± 0.07 [a]	6.43 ± 0.03 [a]	4.23 ± 0.09 [a]
	60	6.59 ± 0.02 [a]	4.38 ± 0.07 [a]	6.48 ± 0.04 [a]	4.37 ± 0.07 [a]
	90	6.64 ± 0.04 [a]	4.42 ± 0.07 [a]	6.53 ± 0.03 [a]	4.38 ± 0.08 [a]
Mean		**6.47**	**4.22**	**6.24**	**4.20**
n		**96**	**96**	**96**	**96**
CV (%)		**3.29**	**2.99**	**2.31**	**3.26**

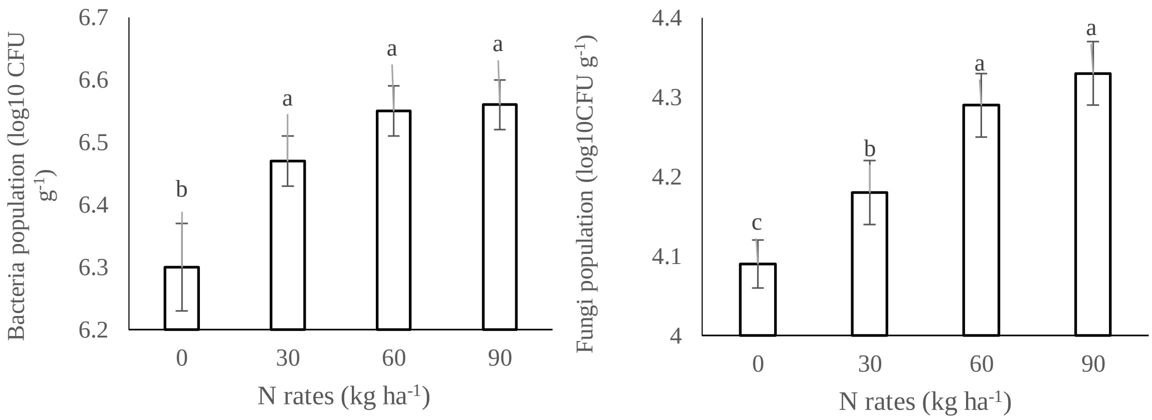
N – Nitrogen; n – Number of observations / treatments; CV - Coefficient of variation;
CFU – Colony forming unit; ± values after the means represent the means standard error;
B0 – Bioslurry 0 $t\ ha^{-1}$; B1- Bioslurry 6 $t\ ha^{-1}$ in medium altitude and 5 $t\ ha^{-1}$ in high altitude;
B2 – Bioslurry 12 $t\ ha^{-1}$ in medium altitude and 10 $t\ ha^{-1}$ in high altitude;
B3 – Bioslurry 18 $t\ ha^{-1}$ in medium altitude and 15 $t\ ha^{-1}$ in high altitude;
Same letters in the same column indicate values with non-significant differences at $P < 0.05$.



(a) (b)

Figure 4.20 Main effect of bioslurry rates on (a) bacteria and (b) fungi populations in medium altitude site

Error bars represent standard error and different letters for same microbial group indicate significantly different values at $P < 0.05$.

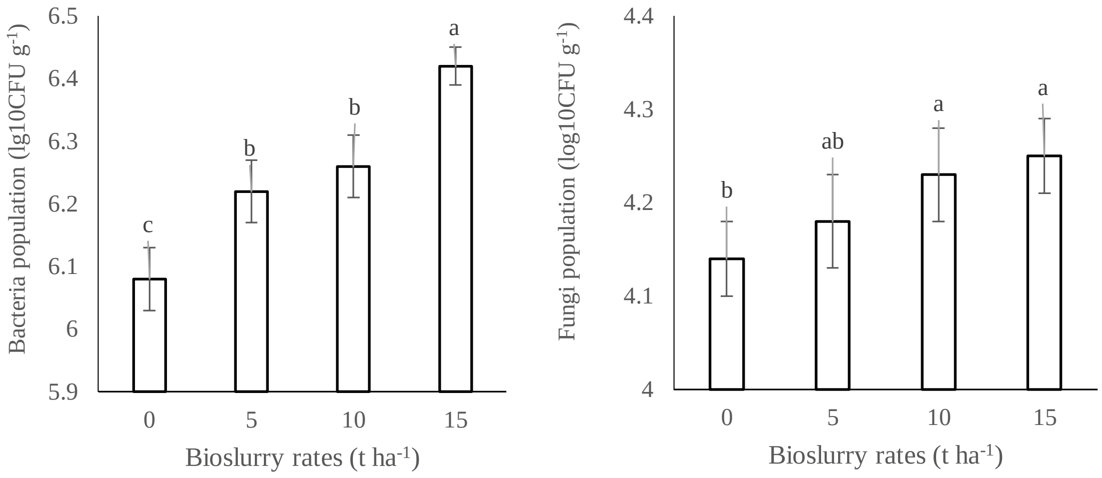


(a) (b)

Figure 4.21 Main effect of mineral N rates on (a) bacteria and (b) fungi populations in medium altitude site

Error bars represent standard error and different letters for same microbial group indicate significantly different values at $P < 0.05$.

In terraced Acrisols of high altitude site, for bioslurry, significantly ($P < 0.05$) higher bacteria population of 6.42 log_{10} CFU g^{-1} was found in plots treated with 15 t bioslurry ha^{-1}. Significantly ($P < 0.05$) higher fungi populations of 4.23 and 4.25 log_{10} CFU g^{-1} were observed in plots receiving 10 and 15 t bioslurry ha^{-1} (Figure 4.22).

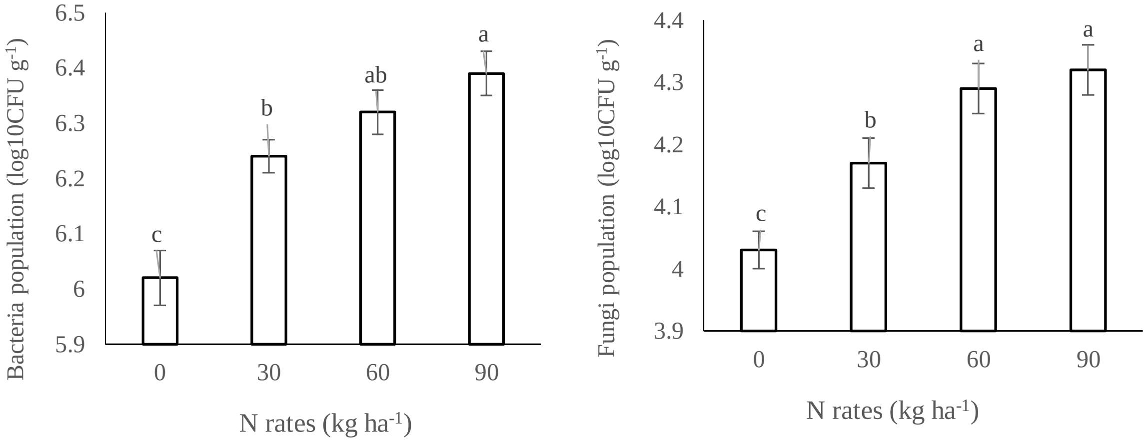


(a) (b)

Figure 4. 22 Main effect of bioslurry rates on (a) bacteria and (b) fungi populations in high altitude site

Error bars represent standard error and different letters for same microbial group indicate significantly different values at $P < 0.05$.

For mineral N, significantly ($P < 0.05$) higher bacteria population of 6.39 log_{10} CFU g^{-1} was recorded in plots treated with 90 kg N ha^{-1}. Higher fungi populations of 4.29 and 4.32 log_{10} CFU g^{-1} were observed in plots applied with 60 and 90 kg N ha^{-1}, respectively (Figure 4.23).



(a) (b)

Figure 4.23 Main effect of mineral N rates on (a) bacteria and (b) fungi populations in high altitude site

Error bars represent standard error and different letters for same microbial group indicate significantly different values at $P < 0.05$.

4.4 Effect of bioslurry and mineral nitrogen (N) on growth, N uptake and yields of maize in medium and high altitude areas

4.4.1 Emergence rate

Maize seedling emergence rate varied from 92.5 to 97.5% in terraced Lixisols of medium altitude site (Table 4.32) and from 91.2 to 98.1% in terraced Lixisols of high altitude site (Table 4.33). There was no significant ($P < 0.05$) interaction or main effects of bioslurry and mineral N on emergence rate in both study sites.

4.4.2 Maize height, collar diameter and number of leaves

In terraced Lixisols of medium altitude site, maize height increased with increasing levels of bioslurry and mineral N. At 60 DAS, significantly ($P <0.05$) taller plants of 206.3 – 214.7 cm height were obtained in plots with the combinations of 18:30, 6:90, 12:60, 18:60, 12:90 and 18:90 bioslurry (t ha^{-1}) : N (kg ha^{-1}) with increases of 49.1 – 55.1% over the control. At 90 DAS, significantly ($P < 0.05$) taller plants of 292.3 cm height were found in plots receiving the combination of 18:90 bioslurry (t ha^{-1}): N (kg ha^{-1}) with height increase of 53.9% over the control (Table 4.32).

In high altitude site, at 60 DAS, significantly ($P < 0.05$) taller plants of 191.3 cm height were observed in plots treated with the combinations of 15:60 bioslurry (t ha^{-1}): N (kg ha^{-1}) which increased plant height by 2.2 times over the control. At 90 DAS, significantly ($P < 0.05$) taller plants of 235.3 – 238.1 cm height were attained with the combinations of 5:90, 10:60, 15:60 and 15:90 bioslurry (t ha^{-1}): N (kg ha^{-1}) with height increase of 1.9 – 2 times over the control (Table 4.33).

In regards to stem collar diameter at medium altitude site, there was no significant interaction effect between bioslurry and mineral N while their main effects were significant ($P < 0.05$) (Table 4.32). Response to bioslurry rates was higher than the control with non-significant differences between bioslurry rates applied (Figure 4.24). For mineral N, significantly ($P < 0.05$) larger diameters were observed for 60 and 90 kg N ha^{-1} which increased diameters by 22.6% and 20.0% over the control, respectively, at both 60 and 90 DAS (Figure 4.25). In high altitude site, there was significant ($P < 0.05$) interaction effect between bioslurry and mineral N on stem collar diameter. At 60 DAS, largest diameters were obtained in plots receiving combinations of 5:90, 10:90, 15:30, 15:60 and 15:90 bioslurry (t ha^{-1}): N (kg ha^{-1}) with equal diameter increase of 1.9 times over the control. At 90 DAS, largest diameters were recorded for the combination of 10: 90 bioslurry (t ha^{-1}): N (kg ha^{-1}) with diameter increase of 1.8 times over the control (Table 4.33).

Table 4.32. Interaction effect between bioslurry and mineral N on emergence rate and growth parameters of maize for combined analysis of two cropping season's data A 2018 and B 2018 at medium altitude site

Bioslurry (t ha^{-1})	N (kg ha^{-1})	Emergence rate (%)	Plant height (cm)			Stem collar diameter (cm)			Number of leaves plant^{-1}		
			30 DAS	60 DAS	90 DAS	30 DAS	60 DAS	90 DAS	30 DAS	60 DAS	90 DAS
0	0	92.5 ± 2.0^{a}	54.6 ± 0.7$^{e''}$	138.4 ± 7.0^{f}	189.9 ± 5.9^{f}	1.0 ± 0.1^{a}	2.0 ± 0.1^{a}	2.4 ± 0.1^{a}	8.0 ± 0.3^{a}	12.8 ± 0.7^{a}	14.7 ± 0.5^{a}
	30	94.1 ± 2.3^{a}	64.6 ± 2.1^{d}	174.9 ± 10.0^{bcd}	213.3 ± 5.8^{e}	1.4 ± 0.1^{a}	2.5 ± 0.1^{a}	3.0 ± 0.1^{a}	8.2 ± 0.3^{a}	13.6 ± 0.7^{a}	14.9 ± 0.4^{a}
	60	93.5 ± 1.3^{a}	67.4 ± 2.0^{d}	174.0 ± 8.2^{bcd}	217.8 ± 6.1^{de}	1.4 ± 0.1^{a}	2.7 ± 0.1^{a}	3.0 ± 0.1^{a}	8.6 ± 0.3^{a}	13.7 ± 0.6^{a}	15.2 ± 0.3^{a}
	90	94.4 ± 1.1^{a}	67.2 ± 1.1^{d}	174.9 ± 5.5^{bcd}	218.3 ± 3.4^{de}	1.5 ± 0.1^{a}	2.7 ± 0.1^{a}	3.1 ± 0.1^{a}	8.7 ± 0.2^{a}	14.1 ± 0.6^{a}	15.2 ± 0.3^{a}
6	0	95.6 ± 2.1^{a}	62.5 ± 0.9^{d}	146.3 ± 4.1^{ef}	210.3 ± 2.8^{e}	1.3 ± 0.1^{a}	2.5 ± 0.1^{a}	2.8 ± 0.1^{a}	8.1 ± 0.3^{a}	12.7 ± 0.9^{a}	14.7 ± 0.4^{a}
	30	97.3 ± 1.4^{a}	80.8 ± 3.4^{c}	195.4 ± 7.5^{abc}	265.2 ± 1.8^{c}	1.6 ± 0.0^{a}	2.9 ± 0.1^{a}	3.2 ± 0.1^{a}	8.5 ± 0.2^{a}	13.5 ± 0.7^{a}	15.3 ± 0.4^{a}
	60	93.0 ± 2.7^{a}	86.5 ± 1.5^{ab}	200.7 ± 8.2^{ab}	273.8 ± 2.1^{bc}	1.7 ± 0.1^{a}	3.1 ± 0.1^{a}	3.5 ± 0.2^{a}	9.1 ± 0.3^{a}	13.9 ± 0.6^{a}	15.2 ± 0.3^{a}
	90	95.8 ± 2.0^{a}	89.3 ± 3.1^{a}	206.3 ± 10.0^{a}	273.1 ± 7.5^{bc}	1.8 ± 0.1^{a}	3.2 ± 0.2^{a}	3.6 ± 0.2^{a}	9.2 ± 0.2^{a}	14.0 ± 0.7^{a}	15.6 ± 0.3^{a}
12	0	98.3 ± 1.2^{a}	62.8 ± 0.9^{d}	170.0 ± 9.3^{cde}	231.3 ± 7.5^{d}	1.3 ± 0.1^{a}	2.5 ± 0.1^{a}	3.0 ± 0.2^{a}	7.4 ± 0.4^{a}	12.5 ± 0.6^{a}	14.5 ± 0.4^{a}
	30	94.9 ± 2.4^{a}	82.1 ± 2.3^{bc}	198.0 ± 7.4^{ab}	273.1 ± 2.2^{bc}	1.6 ± 0.1^{a}	2.9 ± 0.1^{a}	3.3 ± 0.2^{a}	8.6 ± 0.2^{a}	13.4 ± 0.5^{a}	14.9 ± 0.4^{a}
	60	96.5 ± 1.9^{a}	86.3 ± 2.1^{abc}	208.0 ± 6.8^{a}	287.4 ± 5.3^{ab}	1.7 ± 0.1^{a}	3.3 ± 0.2^{a}	3.7 ± 0.2^{a}	8.9 ± 0.1^{a}	13.9 ± 0.6^{a}	15.4 ± 0.4^{a}
	90	92.7 ± 1.9^{a}	87.2 ± 2.8^{ab}	211.2 ± 6.2^{a}	287.9 ± 4.1^{ab}	1.8 ± 0.1^{a}	3.2 ± 0.1^{a}	3.7 ± 0.1^{a}	8.7 ± 0.3^{a}	13.8 ± 0.6^{a}	15.6 ± 0.4^{a}
18	0	95.2 ± 1.8^{a}	63.6 ± 0.7^{d}	164.9 ± 14.7^{de}	230.5 ± 10.5^{d}	1.3 ± 0.1^{a}	2.6 ± 0.2^{a}	3.0 ± 0.2^{a}	7.7 ± 0.2^{a}	12.8 ± 0.8^{a}	14.8 ± 0.3^{a}
	30	97.5 ± 1.4^{a}	84.5 ± 1.9^{abc}	206.2 ± 10.7^{a}	277.8 ± 8.0^{abc}	1.6 ± 0.1^{a}	3.0 ± 0.2^{a}	3.5 ± 0.2^{a}	8.8 ± 0.4^{a}	13.7 ± 0.7^{a}	15.4 ± 0.2^{a}
	60	94.8 ± 1.7^{a}	84.8 ± 1.6^{abc}	210.6 ± 7.7a	287.5 ± 5.1^{ab}	1.7 ± 0.1^{a}	3.3 ± 0.2^{a}	3.7 ± 0.2^{a}	9.1 ± 0.3^{a}	14.1 ± 0.6^{a}	15.5 ± 0.5^{a}
	90	94.3 ± 1.3^{a}	89.3 ± 2.1^{a}	214.7 ± 6.0a	292.2 ± 3.1^{a}	1.8 ± 0.1^{a}	3.2 ± 0.1^{a}	3.6 ± 0.1^{a}	9.3 ± 0.2^{a}	14.0 ± 0.6^{a}	15.3 ± 0.5^{a}
Mean		**95.0**	**75.9**	**187.2**	**251.6**	**1.5**	**2.8**	**3.3**	**8.5**	**13.5**	**15.1**

DAS – days after sowing; ± values after the means represent means standard error; different letters indicate significantly different values at $P < 0.05$.

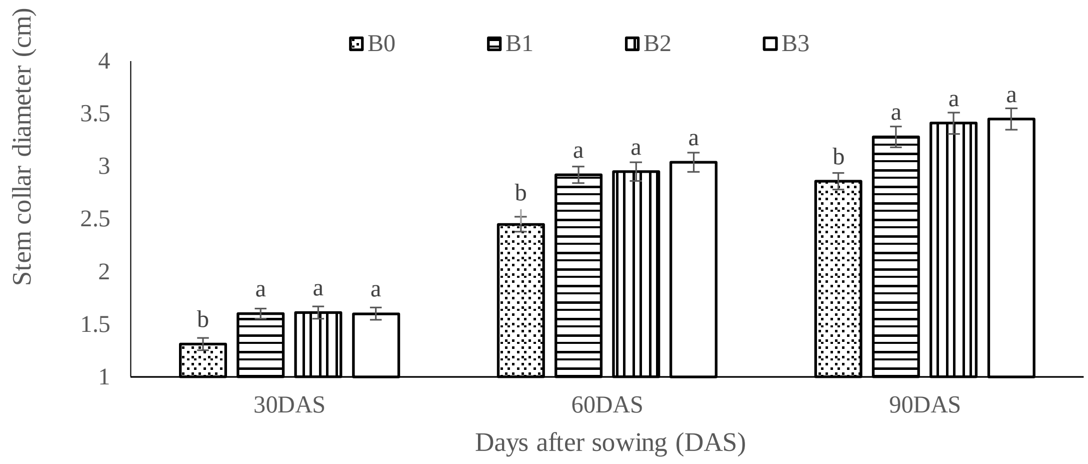


Figure 4.24 Main effect of bioslurry rates on stem collar diameter at medium altitude site

B0 – 0 t bioslurry ha^{-1}, B1 – 6 t bioslurry ha^{-1}, B2 – 12 t bioslurry ha^{-1}, B3 - 16 t bioslurry ha^{-1}

Error bars represent standard error and different letters for same DAS indicate significantly different values at $P < 0.05$.

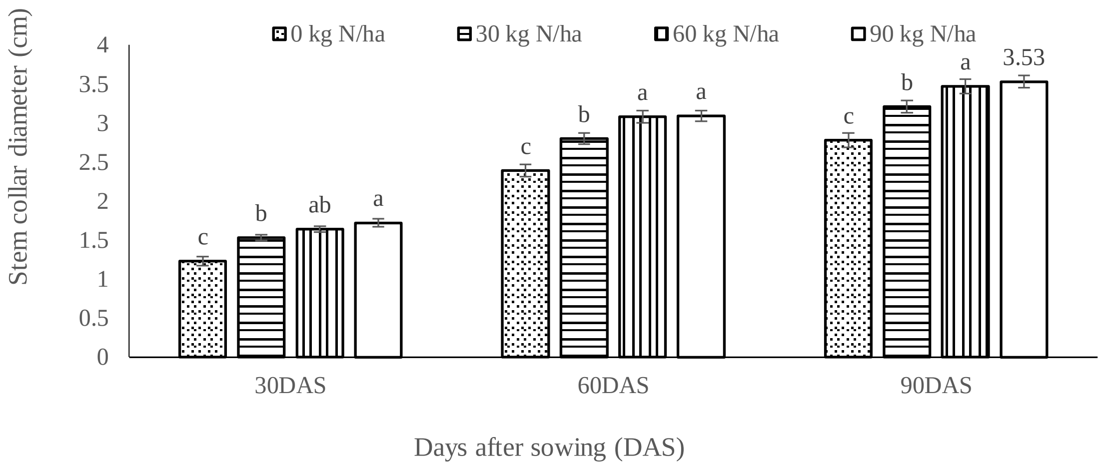


Figure 4.25. Main effect of mineral N rates on stem collar diameter at medium altitude site

Error bars represent standard error and different letters for same DAS indicate significantly different values at $P < 0.05$.

There was no significant interaction effect between bioslurry and mineral N on number of leaves plant^{-1} in both study areas (Tables 4.32 and 4.33). Their main effects were significant ($P < 0.05$); responses to bioslurry and mineral N rates were higher than the control with non-significant differences among rates applied at 30, 60 and 90 DAS.

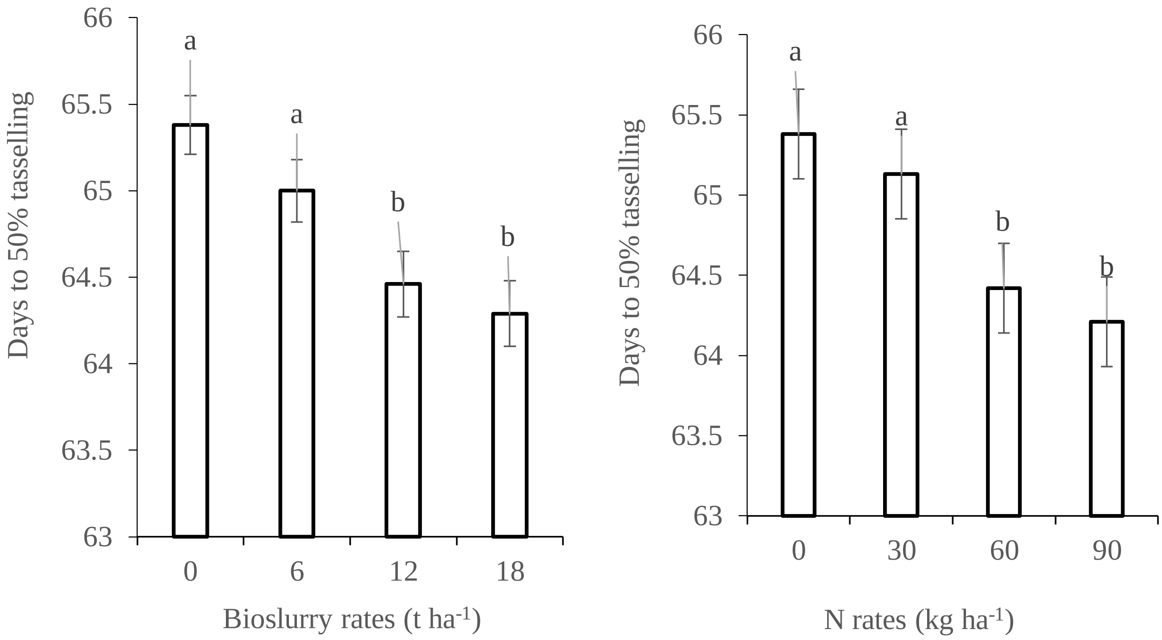
Table 4.33. Interaction effect between bioslurry and mineral N on emergence rate and growth parameters of maize in terraced Acrisols of high altitude area, combined analysis of two cropping season's data A 2018 and B 2018

Bioslurry ($t\ ha^{-1}$)	**N ($kg\ ha^{-1}$)**	**Emergence rate (%)**	**Plant height (cm)**			**Stem collar diameter (cm)**			**Number of leaves $plant^{-1}$**		
			30 DAS	60 DAS	90 DAS	30 DAS	60 DAS	90 DAS	30 DAS	60 DAS	90 DAS
0	0	91.2 ± 2.3^{a}	31.1 ± 2.7^{a}	85.7 ± 2.5^{f}	121.4 ± 6.6^{e}	0.7 ± 0.1^{e}	1.5 ± 0.1^{e}	1.9 ± 0.1^{g}	6.3 ± 0.4^{a}	10.4 ± 0.1^{a}	13.7 ± 0.3^{a}
	30	94.3 ± 2.2^{a}	40.8 ± 1.7^{a}	118.2 ± 4.2^{e}	180.5 ± 6.2^{d}	1.1 ± 0.1^{abc}	2.4 ± 0.1^{cd}	2.7 ± 0.2^{ef}	7.1 ± 0.2^{a}	11.7 ± 0.3^{a}	14.5 ± 0.2^{a}
	60	93.1 ± 2.7^{a}	45.8 ± 2.3^{a}	124.2 ± 1.4^{e}	195.0 ± 4.0^{cd}	1.0 ± 0.0^{bcd}	2.6 ± 0.0^{abcd}	2.9 ± 0.0^{cdef}	7.3 ± 0.1^{a}	11.9 ± 0.2^{a}	14.8 ± 0.2^{a}
	90	95.3 ± 2.2^{a}	46.2 ± 2.4^{a}	118.6 ± 0.9^{e}	189.7 ± 5.2^{cd}	0.9 ± 0.1^{d}	2.4 ± 0.1^{bcd}	2.8 ± 0.0^{def}	6.8 ± 0.2^{a}	11.3 ± 0.2^{a}	14.5 ± 0.3^{a}
5	0	92.9 ± 2.7^{a}	43.2 ± 1.9^{a}	119.8 ± 3.1^{e}	195.2 ± 4.5^{cd}	1.0 ± 0.1^{cd}	2.4 ± 0.1^{d}	2.6 ± 0.1^{f}	7.1 ± 0.1^{a}	11.3 ± 0.2^{a}	14.3 ± 0.3^{a}
	30	91.5 ± 3.0^{a}	57.5 ± 1.5^{a}	156.3 ± 2.9^{d}	216.9 ± 6.2^{b}	1.1 ± 0.0^{abc}	2.6 ± 0.1^{abcd}	2.9 ± 0.2^{def}	7.4 ± 0.2^{a}	12.0 ± 0.3^{a}	14.8 ± 0.2^{a}
	60	93.4 ± 2.9^{a}	61.2 ± 1.4^{a}	166.9 ± 6.5^{cd}	229.5 ± 6.7^{ab}	1.2 ± 0.1^{ab}	2.8 ± 0.1^{ab}	3.1 ± 0.1^{abcde}	7.3 ± 0.2^{a}	12.2 ± 0.3^{a}	14.9 ± 0.3^{a}
	90	95.9 ± 2.6^{a}	63.6 ± 2.4^{a}	175.8 ± 8.3^{abc}	237.4 ± 10.0^{a}	1.1 ± 0.1^{abc}	2.9 ± 0.1^{a}	3.3 ± 0.1^{ab}	7.5 ± 0.2^{a}	12.3 ± 0.4^{a}	15.0 ± 0.3^{a}
10	0	94.5 ± 2.4^{a}	50.2 ± 2.0^{a}	119.2 ± 4.6^{e}	198.6 ± 3.2^{c}	1.1 ± 0.1^{abc}	2.5 ± 0.2^{bcd}	2.7 ± 0.2^{ef}	7.1 ± 0.2^{a}	11.5 ± 0.3^{a}	14.8 ± 0.3^{a}
	30	95.9 ± 1.7^{a}	61.3 ± 2.5^{a}	175.1 ± 6.2^{abc}	232.0 ± 5.1^{ab}	1.2 ± 0.1^{a}	2.6 ± 0.1^{abcd}	3.0 ± 0.1^{bcdef}	7.7 ± 0.2^{a}	12.3 ± 0.3^{a}	15.1 ± 0.2^{a}
	60	95.2 ± 3.0^{a}	65.7 ± 2.3^{a}	182.1 ± 7.0^{abc}	235.3 ± 9.2^{a}	1.2 ± 0.1^{abc}	2.7 ± 0.2^{abc}	3.0 ± 0.2^{abcdef}	7.5 ± 0.2^{a}	12.5 ± 0.2^{a}	14.9 ± 0.3^{a}
	90	98.1 ± 1.2^{a}	64.8 ± 3.2^{a}	181.2 ± 4.6^{abc}	233.1 ± 5.4^{ab}	1.1 ± 0.1^{abc}	2.9 ± 0.1^{a}	3.4 ± 0.0^{a}	7.3 ± 0.2^{a}	12.9 ± 0.2^{a}	15.3 ± 0.3^{a}
15	0	92.7 ± 1.9^{a}	56.0 ± 1.9^{a}	129.2 ± 4.1^{e}	196.7 ± 3.2^{cd}	1.2 ± 0.1^{ab}	2.6 ± 0.1^{abcd}	3.0 ± 0.1^{bcdef}	7.2 ± 0.2^{a}	12.0 ± 0.3^{a}	14.8 ± 0.2^{a}
	30	97.3 ± 2.3^{a}	61.9 ± 1.9^{a}	182.5 ± 4.2^{abc}	232.2 ± 6.3^{ab}	1.2 ± 0.0^{a}	2.9 ± 0.1^{a}	3.3 ± 0.1^{abc}	7.7 ± 0.2^{a}	12.6 ± 0.3^{a}	15.1 ± 0.3^{a}
	60	97.4 ± 2.4^{a}	67.1 ± 2.3^{a}	191.3 ± 6.1^{a}	238.1 ± 6.3^{a}	1.2 ± 0.1^{ab}	2.8 ± 0.1^{a}	3.1 ± 0.1^{abcd}	7.5 ± 0.3^{a}	12.9 ± 0.3^{a}	15.1 ± 0.3^{a}
	90	97.1 ± 2.3^{a}	69.1 ± 1.8^{a}	185.2 ± 5.4^{ab}	236.9 ± 6.8^{a}	1.2 ± 0.1^{ab}	2.9 ± 0.1^{a}	3.2 ± 0.1^{abcd}	7.4 ± 0.3^{a}	12.9 ± 0.3^{a}	14.8 ± 0.3^{a}
Mean		**94.7**	**55.3**	**150.7**	**210.5**	**1.1**	**2.6**	**2.9**	**7.3**	**12.1**	**14.8**

DAS – days after sowing; ± values after the means represent means standard error; different letters indicate significantly different values at $P < 0.05$.

4.4.3 Days to 50% tasselling

There was no interaction effect between bioslurry and mineral N on number of days to 50% tasselling but their main effects were significant ($P < 0.05$) at both study areas (Tables 4.34 and 4.36). In medium altitude, for bioslurry, plants with less number of days to 50% tasselling were recorded in plots treated with bioslurry rates of 12 and 18 t ha^{-1} with decreases of 0.9 and 1.1 days to the control, respectively (Figure 4.26). For mineral N, plants with less number of days to 50% tasselling were observed in plots receiving 60 and 90 kg N ha^{-1} with decreases of 1 and 1.2 days to the control, respectively (Figure 4.26).

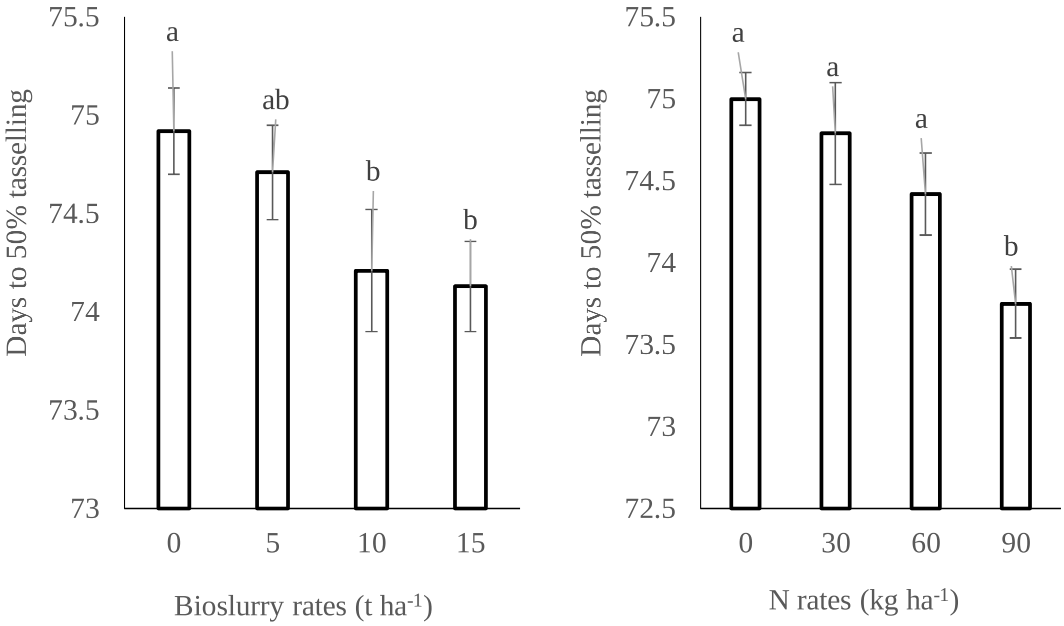


(a) **(b)**

Figure 4.26 Main effect of (a) bioslurry and (b) mineral N on number of days to 50% tasselling at medium altitude area

N – Nitrogen; Error bars represent standard error and different letters indicate significantly different values at $P < 0.05$.

In high altitude site, for bioslurry, plants with less number of days to 50% tasselling were found in plots receiving 10 and 15 t ha^{-1} with decreases of 0.7 and 0.8 days to the control, respectively (Figure 4.27). For mineral N, plants with less number of days to 50% tasselling were observed in plots receiving 90 kg N ha^{-1} with decrease of 1.2 days to the control (Figure 4.27).



(a) **(b)**

Figure 4.27 Main effect of (a) bioslurry and (b) mineral N on number of days to 50% tasselling at high altitude area

N – Nitrogen; Error bars represent standard error and different letters indicate significantly different values at $P < 0.05$.

4.4.4 Partitioning N update as affected by bioslurry and mineral N rates

In medium altitude site, the N concentration (%) and N uptake (kg ha^{-1}) in maize plants at 50% tasselling, stover and grain at physiological maturity increased with increasing levels of bioslurry and mineral N (Table 4.34). At 50% tasselling, significantly ($P < 0.05$) higher N uptake of 207.94 kg ha^{-1} was found in plots treated with the combination of 18:90 bioslurry (t ha^{-1}): mineral N (kg ha^{-1}) which increased the N uptake by 4 times over the control (Table 4.35). At physiological maturity, significantly ($P < 0.05$) higher N uptake in stover; 263.41 and 266.21 kg ha^{-1}, were recorded for combinations of 18:90 and 18:60 bioslurry (t ha^{-1}): mineral N (kg ha^{-1}) with N uptake increases of 5.6 and 5.5 times over the control, respectively. For grain N uptake, significantly ($P < 0.05$) higher N uptake of 138.31, 139.04 and 139.28 kg ha^{-1} were attained for combinations of 18:90, 12:90 and 18:60 bioslurry (t ha^{-1}): mineral N (kg ha^{-1}) with an equal N uptake increase of 5 times over the control (Table 4.35).

Table 4.34 Interaction effect between bioslurry and mineral N on days to 50% tasselling and N concentration (%) in plant, stover and grain for combined analysis of two cropping season's data of A 2018 and B 2018 in medium altitude area

Bioslurry ($t\ ha^{-1}$)	N ($kg\ ha^{-1}$)	Days to 50% tasselling	Concentration of N in plant at 50% tasselling (%)	Concentration of N in stover at harvest (%)	Concentration of N in grain (%)
0	0	65.8 ± 0.2^{a}	2.18 ± 0.03^{d}	1.07 ± 0.02^{a}	1.13 ± 0.09^{h}
	30	65.7 ± 0.2^{a}	2.64 ± 0.07^{bc}	1.17 ± 0.03^{a}	1.29 ± 0.05^{g}
	60	64.8 ± 0.4^{a}	2.59 ± 0.10^{bc}	1.25 ± 0.03^{a}	1.48 ± 0.02^{de}
	90	65.2 ± 0.4^{a}	2.59 ± 0.07^{bc}	1.33 ± 0.04^{a}	1.59 ± 0.04^{cd}
6	0	65.2 ± 0.3^{a}	2.67 ± 0.14^{bc}	1.20 ± 0.03^{a}	1.35 ± 0.04^{fg}
	30	65.8 ± 0.2^{a}	2.82 ± 0.12^{bc}	1.26 ± 0.04^{a}	1.48 ± 0.03^{de}
	60	64.8 ± 0.3^{a}	2.70 ± 0.11^{bc}	1.31 ± 0.06^{a}	1.55 ± 0.03^{cde}
	90	64.2 ± 0.3^{a}	2.96 ± 0.17^{ab}	1.38 ± 0.04^{a}	1.59 ± 0.01^{cd}
12	0	65.2 ± 0.3^{a}	2.53 ± 0.17^{d}	1.19 ± 0.04^{a}	1.45 ± 0.06^{ef}
	30	64.5 ± 0.3^{a}	2.66 ± 0.16^{bc}	1.32 ± 0.04^{a}	1.58 ± 0.04^{cde}
	60	64.3 ± 0.4^{a}	3.31 ± 0.21^{a}	1.45 ± 0.06^{a}	1.66 ± 0.03^{abc}
	90	63.8 ± 0.3^{a}	3.27 ± 0.12^{a}	1.39 ± 0.03^{a}	1.74 ± 0.04^{ab}
18	0	65.3 ± 0.3^{a}	2.63 ± 0.08^{bc}	1.33 ± 0.07^{a}	1.54 ± 0.05^{cde}
	30	64.5 ± 0.2^{a}	2.81 ± 0.12^{abcd}	1.34 ± 0.04^{a}	1.63 ± 0.03^{bc}
	60	63.7 ± 0.2^{a}	3.25 ± 0.12^{a}	1.44 ± 0.04^{a}	1.77 ± 0.05^{a}
	90	63.7 ± 0.2^{a}	3.34 ± 0.12^{a}	1.44 ± 0.04^{a}	1.74 ± 0.02^{ab}
Mean		**64.8**	**2.81**	**1.30**	**1.54**
n		**96**	**96**	**96**	**96**
CV (%)		**1.2**	**10.86**	**7.32**	**5.69**

N – Nitrogen; n – Number of observations; CV - Coefficient of variation; ± values after the means represent the means standard error; Different letters in the same column indicate significantly different values at $P < 0.05$.

Table 4.35 Interaction effect between bioslurry and mineral N on N uptake (kg ha^{-1}) for combined analysis of two cropping season's data of A 2018 and B 2018 in medium altitude area

Bioslurry (t ha^{-1})	N (kg ha^{-1})	N uptake in plant at 50% tasselling (kg ha^{-1})	N uptake in stover at harvest (kg ha^{-1})	N uptake in grain (kg ha^{-1})
0	0	51.61 ± 5.79^{j}	47.75 ± 6.38^{e}	26.92 ± 3.20^{i}
	30	74.75 ± 3.84^{hij}	93.58 ± 10.77^{d}	40.86 ± 4.46^{hi}
	60	99.57 ± 3.23^{efgh}	98.38 ± 7.80^{d}	53.74 ± 4.57^{gh}
	90	105.81 ± 2.81^{defg}	120.91 ± 10.76^{d}	72.10 ± 3.22^{f}
6	0	63.83 ± 7.97^{ij}	116.13 ± 12.68^{d}	59.48 ± 5.22^{fg}
	30	109.53 ± 7.88^{def}	172.89 ± 12.46^{c}	91.10 ± 4.15^{e}
	60	131.90 ± 7.34^{d}	222.97 ± 23.52^{ab}	106.57 ± 5.26^{cd}
	90	159.89 ± 7.86^{c}	222.39 ± 27.51^{ab}	107.22 ± 3.46^{cd}
12	0	79.27 ± 10.57^{ghij}	102.05 ± 12.25^{d}	59.85 ± 4.49^{fg}
	30	118.07 ± 12.26^{def}	200.16 ± 11.48^{bc}	95.81 ± 10.43^{de}
	60	181.31 ± 17.33^{abc}	247.04 ± 21.37^{ab}	129.37 ± 4.41^{ab}
	90	191.64 ± 12.31^{ab}	220.07 ± 13.53^{ab}	139.04 ± 5.91^{a}
18	0	88.92 ± 14.88^{fghi}	124.26 ± 17.91^{d}	62.62 ± 7.06^{fg}
	30	125.60 ± 10.37^{de}	213.40 ± 21.86^{bc}	116.91 ± 3.21^{bc}
	60	178.03 ± 11.10^{bc}	266.21 ± 19.80^{a}	139.28 ± 3.55^{a}
	90	207.94 ± 3.81^{a}	263.41 ± 13.04^{a}	138.31 ± 2.62^{a}
Mean		**122.98**	**170.72**	**89.95**
n		**96**	**96**	**96**
CV (%)		**15.19**	**17.73**	**10.17**

N – Nitrogen; n – Number of observations; CV - Coefficient of variation; ± values after the means represent the means standard error; Different letters in the same column indicate significantly different values at $P < 0.05$.

Similarly, in high altitude site, the N concentration (%) and N uptake (kg ha^{-1}) in maize plants at 50% tasselling, stover and grain at physiological maturity increased with increasing rates of bioslurry and mineral N (Table 4.36).

Table 4.36 Interaction effect between bioslurry and mineral N on days to 50% tasselling and N concentration (%) in plant, stover and grain for combined analysis of two cropping season's data of A 2018 and B 2018 in high altitude area

Bioslurry ($t\ ha^{-1}$)	N ($kg\ ha^{-1}$)	Days to 50% tasselling	Concentration of N in plant at 50% tasselling (%)	Concentration of N in stover at harvest (%)	Concentration of N in grain (%)
0	0	75.3 ± 0.3[a]	1.92 ± 0.03[f']	1.03 ± 0.03[a]	1.17 ± 0.06[g]
	30	75.3 ± 0.2[a]	2.23 ± 0.04[e]	1.13 ± 0.02[a]	1.30 ± 0.04[f]
	60	75.0 ± 0.5[a]	2.38 ± 0.04[de]	1.26 ± 0.02[a]	1.45 ± 0.02[e]
	90	74.0 ± 0.5[a]	2.43 ± 0.02[cd]	1.30 ± 0.03[a]	1.58 ± 0.03[abc]
5	0	75.3 ± 0.3[a]	2.23 ± 0.03[e]	1.22 ± 0.03[a]	1.36 ± 0.04[f]
	30	75.3 ± 0.3[a]	2.32 ± 0.05[de]	1.27 ± 0.04[a]	1.48 ± 0.02[de]
	60	74.7 ± 0.3[a]	2.40 ± 0.04[de]	1.30 ± 0.02[a]	1.55 ± 0.02[bcde]
	90	73.5 ± 0.5[a]	2.43 ± 0.03[cd]	1.32 ± 0.02[a]	1.58 ± 5.44[abc]
10	0	74.5 ± 0.3[a]	2.61 ± 0.05[b]	1.26 ± 0.06[a]	1.46 ± 0.06[e]
	30	74.8 ± 1.1[a]	2.62 ± 0.04[b]	1.28 ± 0.02[a]	1.58 ± 0.03[abc]
	60	73.7 ± 0.4[a]	2.71 ± 0.07[ab]	1.40 ± 0.03[a]	1.61 ± 0.02[abc]
	90	73.8 ± 0.4[a]	2.83 ± 0.06[a]	1.43 ± 0.03[a]	1.67 ± 0.03[a]
15	0	74.8 ± 0.2[a]	2.38 ± 0.11[de]	1.26 ± 0.02[a]	1.53 ± 0.04[cde]
	30	73.7 ± 0.3[a]	2.58 ± 0.10[bc]	1.32 ± 0.03[a]	1.65 ± 0.03[ab]
	60	74.3 ± 0.7[a]	2.82 ± 0.06[a]	1.39 ± 0.03[a]	1.64 ± 0.03[ab]
	90	73.7 ± 0.4[a]	2.84 ± 0.06[a]	1.39 ± 0.02[a]	1.66 ± 0.04[a]
Mean		**74.5**	**2.48**	**1.28**	**1.52**
n		**96**	**96**	**96**	**96**
CV (%)		**1.5**	**5.10**	**5.30**	**5.77**

N – Nitrogen; n – Number of observations; CV - Coefficient of variation; ± values after the means represent the means standard error; Different letters in the same column indicate significantly different values at P < 0.05.

At 50% tasselling, significantly (P < 0.05) higher N uptake of 178.10 and 178.78 kg ha^{-1} were found in plots treated with combinations of 15:90 and 15:60 bioslurry ($t\ ha^{-1}$): mineral N ($kg\ ha^{-1}$) with an equal N uptake increase of 4.6 times over the control (Table 4.37).

Table 4.37 Interaction effect between bioslurry and mineral N on N uptake (kg ha^{-1}) for combined analysis of two cropping season's data of A 2018 and B 2018 in high altitude area

Bioslurry (t ha^{-1})	N (kg ha^{-1})	N uptake in plant at 50% tasselling (kg ha^{-1})	N uptake in stover at harvest (kg ha^{-1})	N uptake in grain (kg ha^{-1})
0	0	39.10 ± 3.20^{h}	31.92 ± 2.73^{f}	26.24 ± 1.29^{h}
	30	65.89 ± 2.40^{g}	67.73 ± 2.91^{e}	44.52 ± 3.12^{fg}
	60	99.85 ± 1.90d^{def}	95.95 ± 5.84^{bcde}	59.68 ± 3.85^{de}
	90	108.26 ± 2.71^{cde}	109.47 ± 7.93^{bcd}	65.41 ± 3.36^{d}
5	0	64.22 ± 6.67^{g}	71.91 ± 8.84^{de}	36.25 ± 2.63^{gh}
	30	93.32 ± 8.70^{ef}	92.27 ± 8.33^{cde}	66.76 ± 2.32^{d}
	60	113.25 ± 6.79^{cde}	111.81 ± 10.87^{cd}	84.96 ± 4.21^{bc}
	90	120.16 ± 11.85^{cd}	129.91 ± 11.42^{bc}	93.99 ± 5.34^{b}
10	0	80.73 ± 7.84^{fg}	85.82 ± 9.95^{de}	43.03 ± 2.86^{fg}
	30	112.69 ± 11.92^{cde}	101.86 ± 13.23^{bcde}	81.54 ± 4.34^{c}
	60	159.83 ± 4.80^{ab}	195.57 ± 17.55^{a}	111.56 ± 4.54^{a}
	90	157.38 ± 7.78^{b}	174.96 ± 14.58^{a}	119.10 ± 4.18^{a}
15	0	82.56 ± 5.51^{fg}	96.85 ± 11.83^{bcde}	49.54 ± 3.75^{ef}
	30	129.43 ± 6.06^{c}	136.24 ± 19.94^{b}	89.30 ± 4.36^{bc}
	60	178.78 ± 9.40^{a}	201.35 ± 18.54^{a}	115.77 ± 4.96^{a}
	90	178.10 ± 9.14^{a}	179.06 ± 16.16^{a}	120.82 ± 4.49^{a}
Mean		**111.47**	**117.67**	**75.53**
n		**96**	**96**	**96**
CV (%)		**14.46**	**22.98**	**12.12**

N – Nitrogen; n – Number of observations; CV - Coefficient of variation; ± values after the means represent the means standard error; Different letters in the same column indicate significantly different values at P < 0.05.

At physiological maturity, significantly (P < 0.05) higher N uptake in stover; 174.96, 179.06, 195.57 and 201.35 kg ha^{-1}, were recorded in plots receiving combinations of 10:90, 15:90, 10:60 and 15:60 bioslurry (t ha^{-1}): mineral N (kg ha^{-1}) which increased N uptake by 5.5, 5.6, 6.1 and 6.3 times over the control, respectively. For grain N uptake, significantly ($P < 0.05$) higher N uptake; 111.56, 115.77, 119.10 and 120.82, were obtained in plots treated with 10:60, 15:60, 10:90 and 15:90 bioslurry (t ha^{-1}): mineral N (kg ha^{-1}) with N uptake increases of 4.3, 4.4, 4.5 and 4.6 times over the control respectively (Table 4.37).

4.4.5 Yield and yield components

Number of cobs plant^{-1}: there was significant ($P < 0.05$) interaction effect between bioslurry and mineral N on number of cobs plant^{-1} in both study sites. In medium altitude site, significantly ($P < 0.05$) higher number of cobs plant^{-1} (1.3 cobs) was recorded in plots treated with combination of 18:60 bioslurry (t ha^{-1}): mineral N (kg ha^{-1}) with increase of 30% over the control (Table 4.38). In high altitude site, similar increase of number of cobs plant^{-1} by 30% over the control was also observed in plots receiving combinations of 15:90, 10:90 and 10:60 bioslurry (t ha^{-1}): mineral N (kg ha^{-1}) (Table 4.39).

Grain yield: there was significant ($P < 0.05$) interaction effect between bioslurry and mineral N on grain yield in both study sites. In medium altitude, significantly ($P < 0.05$) higher grain yields of 7.8, 7.9 and 8.0 t ha^{-1} were attained with combinations of 12:60, 18:60, 12:90 and 18:90 bioslurry (t ha^{-1}): mineral N (kg ha^{-1}) with equal grain yield increase of 3.3 times over the control (Table 4.38). In high altitude, significantly ($P < 0.05$) higher grain yields of 6.9, 7.1 and 7.3 t ha^{-1} were recorded for 10:60, 15:60, 10:90 and 15:90 bioslurry (t ha^{-1}): mineral N (kg ha^{-1}) combinations, with grain yield increases of 3.0, 3.1 and 3.2 times over the control, respectively (Table 4.39).

Hundred grain weight: in medium altitude site, significantly ($P < 0.05$) higher hundred grain weight of 40.9 g was obtained in plots treated with combinations of 18:60 and 18:90 bioslurry (t ha^{-1}): mineral N (kg ha^{-1}) with weight increase of 41.5% over the control (Table 4.38). In high altitude, there was no significant interaction effect between bioslurry and mineral N on hundred grain weight, but their main effects were significant ($P < 0.05$) (Table 4.39). Responses to bioslurry and mineral N application rates were higher than the control, with non-significant differences between rates applied.

Above-ground biomass yield: in medium altitude, significantly ($P < 0.05$) higher above-ground biomass yields of 26.2 and 26.3 t ha^{-1} were obtained for combinations of 18:90 and 18:60 bioslurry (t ha^{-1}): mineral N (kg ha^{-1}) with biomass increase of 3.4 times over the control (Table 4.38).

Table 4.38 Interaction effect between bioslurry and mineral N on yield and yield components for combined analysis of two cropping season's data of A and B 2018 at medium altitude area

Bioslurry (t ha^{-1})	N (kg ha^{-1})	Number of cobs plant^{-1}	Grain yield (t ha^{-1})	AGB (t ha^{-1})	Harvest index (%)	100 grain weight (g)
0	0	1.0 ± 0.0^{f}	2.4 ± 0.2^{h}	7.6 ± 0.6^{e}	31.5 ± 1.6^{a}	28.9 ± 0.3^{h}
	30	1.0 ± 0.0^{f}	3.1 ± 0.3^{g}	12.6 ± 1.0^{d}	25.5 ± 2.3^{a}	31.0 ± 1.1^{gh}
	60	1.0 ± 0.0^{f}	3.6 ± 0.3^{fg}	13.0 ± 1.0^{d}	29.1 ± 2.8^{a}	32.0 ± 1.1^{fg}
	90	1.0 ± 0.0^{ef}	4.5 ± 0.1^{e}	15.4 ± 1.5^{d}	30.6 ± 2.8^{a}	33.2 ± 0.8^{efg}
6	0	1.0 ± 0.0^{f}	4.4 ± 0.3^{ef}	14.0 ± 1.2^{d}	31.7 ± 1.3^{a}	35.5 ± 0.8^{de}
	30	1.1 ± 0.0^{cdef}	6.2 ± 0.3^{cd}	20.0 ± 1.4^{c}	31.4 ± 1.7^{a}	37.4 ± 0.9^{cd}
	60	1.2 ± 0.0^{bc}	6.9 ± 0.3^{bc}	23.8 ± 2.4^{abc}	29.8 ± 2.1^{a}	38.0 ± 1.1^{bcd}
	90	1.1 ± 0.0^{bcde}	6.8 ± 0.3^{bcd}	22.7 ± 1.8^{abc}	30.4 ± 2.0^{a}	38.7 ± 0.9^{abc}
12	0	1.0 ± 0.0^{ef}	4.1 ± 0.2^{ef}	12.6 ± 1.1^{d}	33.4 ± 2.7^{a}	34.0 ± 0.3^{ef}
	30	1.1 ± 0.1^{bcd}	6.0 ± 0.6^{d}	21.3 ± 1.6^{bc}	28.2 ± 1.6^{a}	37.6 ± 1.1^{cd}
	60	1.2 ± 0.1^{bc}	7.8 ± 0.2^{a}	24.7 ± 0.9^{ab}	31.8 ± 1.5^{a}	39.8 ± 0.7^{abc}
	90	1.2 ± 0.1^{abc}	8.0 ± 0.3^{a}	23.9 ± 1.4^{abc}	33.6 ± 1.7^{a}	40.6 ± 0.8^{ab}
18	0	1.0 ± 0.0^{ef}	4.0 ± 0.3^{ef}	13.3 ± 1.4^{d}	30.7 ± 1.4^{a}	32.8 ± 0.9^{fg}
	30	1.1 ± 0.1^{bcd}	7.2 ± 0.2^{ab}	23.2 ± 1.8^{abc}	31.7 ± 1.8^{a}	38.6 ± 1.0^{abc}
	60	1.3 ± 0.1^{a}	7.9 ± 0.2^{a}	26.3 ± 1.2^{a}	30.2 ± 1.2^{a}	40.9 ± 0.8^{a}
	90	1.3 ± 0.0^{ab}	8.0 ± 0.2^{a}	26.2 ± 0.9^{a}	30.5 ± 0.9^{a}	40.9 ± 0.8^{a}
Mean		**1.1**	**5.7**	**18.8**	**30.6**	**36.2**
n		**96**	**96**	**96**	**96**	**96**
CV (%)		**7.5**	**9.6**	**14.5**	**13.0**	**5.2**

AGB – Above ground biomass; Different letters in the same column indicate significantly different values at $P < 0.05$; n – Number of observations / treatments; CV - Coefficient of variation; ± Values after the means represent the means standard error.

In high altitude site, significantly ($P < 0.05$) higher above-ground biomass yields of 22.4, 23.0, 23.2 and 24.3 t ha^{-1} were recorded for combinations of 10:90, 10:60, 15:90 and 15:60 bioslurry (t ha^{-1}): mineral N (kg ha^{-1}) with biomass increases of 3.3, 3.4, 3.4 and 3.6, respectively (Table 4.39).

Table 4.39 Interaction effect between bioslurry and mineral N on yield and yield components for combined analysis of two cropping season's data of A 2018 and B 2018 at high altitude area

Bioslurry ($t\ ha^{-1}$)	N ($kg\ ha^{-1}$)	Number of cobs $plant^{-1}$	Grain yield ($t\ ha^{-1}$)	AGB ($t\ ha^{-1}$)	Harvest index (%)	100 grain weight (g)
0	0	1.0 ± 0.0^{d}	2.3 ± 0.1g	6.8 ± 0.5^{h}	33.9 ± 2.3^{ab}	27.5 ± 1.8^{a}
	30	1.0 ± 0.0^{d}	3.4 ± 0.2^{e}	11.1 ± 0.3^{fg}	30.6 ± 1.3^{abc}	30.4 ± 1.2^{a}
	60	1.1 ± 0.1^{cd}	4.1 ± 0.3^{d}	13.9 ± 0.7^{def}	29.5 ± 1.2^{abc}	31.3 ± 1.1^{a}
	90	1.1 ± 0.1^{cd}	4.2 ± 0.2^{d}	14.8 ± 0.7^{cde}	28.2 ± 0.7^{bc}	32.2 ± 1.1^{a}
5	0	1.0 ± 0.0d	2.7 ± 0.2fg	10.2 ± 1.0^{g}	26.9 ± 2.2^{c}	30.3 ± 1.3^{a}
	30	1.1 ± 0.1^{cd}	4.5 ± 0.1d	13.9 ± 0.9^{def}	33.0 ± 1.9^{ab}	32.1 ± 1.9^{a}
	60	1.1 ± 0.0^{cd}	5.5 ± 0.2^{bc}	16.4 ± 1.1^{bcd}	33.9 ± 1.9^{ab}	32.3 ± 1.6^{a}
	90	1.1 ± 0.1^{bc}	5.93 ± 0.3^{b}	18.8 ± 1.2^{b}	31.7 ± 1.4^{abc}	34.7 ± 0.5^{a}
10	0	1.0 ± 0.0^{d}	2.9 ± 0.1ef	11.1 ± 0.9^{fg}	27.1 ± 2.0^{c}	31.6 ± 1.0^{a}
	30	1.1 ± 0.0^{cd}	5.2 ± 0.2^{c}	15.0 ± 1.2^{cde}	35.1 ± 2.1^{a}	30.1 ± 2.2^{a}
	60	1.3 ± 0.0^{a}	6.9 ± 0.2^{a}	23.1 ± 1.6^{a}	30.6 ± 1.9^{abc}	32.7 ± 1.4^{a}
	90	1.3 ± 0.0^{a}	7.1 ± 0.1^{a}	22.4 ± 1.2^{a}	32.1 ± 1.6^{abc}	35.4 ± 1.3^{a}
15	0	1.0 ± 0.0^{d}	3.3 ± 0.2^{ef}	12.6 ± 1.2^{efg}	26.4 ± 1.6^{c}	31.4 ± 1.6^{a}
	30	1.1 ± 0.1^{cd}	5.4 ± 0.3^{bc}	18.1 ± 2.0^{bc}	31.4 ± 2.5^{abc}	36.1 ± 1.3^{a}
	60	1.2 ± 0.1^{ab}	7.1 ± 0.3^{a}	24.3 ± 1.4^{a}	29.4 ± 1.8^{abc}	34.8 ± 1.9^{a}
	90	1.3 ± 0.0^{a}	7.3 ± 0.2^{a}	23.2 ± 1.0^{a}	31.5 ± 0.9^{abc}	32.9 ± 1.3^{a}
Mean		**1.1**	**4.9**	**16.0**	**30.7**	**32.2**
n		**96**	**96**	**96**	**96**	**96**
CV (%)		**8.9**	**10.2**	**16.1**	**13.0**	**8.8**

AGB – Above ground biomass; Different letters in the same column indicate significantly different values at $P < 0.05$; n – Number of observations / treatments; CV - Coefficient of variation; ± Values after the means represent the means standard error.

Harvest index: in medium altitude site, there was no significant interaction effect of bioslurry and mineral N rates nor their main effects were significant (Table 4.38). In high altitude site, significantly ($P < 0.05$) higher harvest index of 35.1% was recorded in plots treated with the combination of 10:30 bioslurry (t ha^{-1}): mineral N (kg ha^{-1}) with increase of 3.5% over the control (Table 4.39).

4.4.6 Effects of cropping seasons on growth, N uptake and yields

Maize growth, N uptake and yields were influenced by cropping seasons. Significantly ($P < 0.05$) higher plants, larger stem collar diameter and higher number of leaves were observed in season A 2018 compared to season B 2018 at both medium and high altitude sites separately and for pooled sites (Tables 4.40 and 4.41).

Table 4.40 Seasonal effect on maize growth and nitrogen uptake for medium and high altitude sites separately and pooled

Site location (altitude)	Season	Plant height at 90 DAS (cm)	Stem diameter at 90 DAS (cm)	Number of leaves $plant^{-1}$ 90 DAS (cm)	Number of days to 50% tasselling	N uptake at tasselling (kg ha^{-1})
Medium	A 2018	258.9 ± 5.0^{a}	3.4 ± 0.1^{a}	15.8 ± 0.1^{a}	64.8 ± 0.1^{a}	134.7 ± 7.7^{a}
	B 2018	244.3 ± 5.2^{b}	3.1 ± 0.1^{b}	14.5 ± 0.1^{b}	64.7 ± 0.2^{a}	111.3 ± 6.8^{b}
Mean		**251.6**	**3.3**	**15.1**	**64.8**	**123.0**
n		**96**	**96**	**96**	**96**	**96**
CV (%)		**3.7**	**9.5**	**3.7**	**1.2**	**15.2**
High	A 2018	215.7 ± 5.3^{a}	3.0 ± 0.1^{a}	15.2 ± 0.1^{a}	74.6 ± 0.2^{a}	114.2 ±6.9^{a}
	B 2018	205.4± 4.2^{b}	2.9 ± 0.1^{a}	14.4 ± 0.1^{b}	74.4 ± 0.2^{a}	108.7 ± 5.5^{a}
Mean		**210.5**	**2.9**	**14.8**	**74.5**	**111.5**
n		**96**	**96**	**96**	**96**	**96**
CV (%)		**7.0**	**10.4**	**3.4**	**1.5**	**14.5**
PSL	A 2018	237.3 ± 4.3^{a}	3.2 ± 0.1^{a}	15.5 ± 0.1^{a}	69.7 ± 0.5^{a}	124.5 ± 5.3^{a}
PSL	B 2018	224.9 ± 3.9^{b}	3.0 ± 0.0^{b}	14.4 ± 0.1^{b}	69.6 ± 0.5^{a}	110.0 ± 4.4^{b}
Mean		**231.1**	**3.1**	**14.9**	**69.6**	**117.2**
n		**192**	**192**	**192**	**192**	**192**
CV (%)		**5.4**	**10.1**	**3.6**	**1.4**	**14.9**

Different letters in the same column indicate significantly different values at $P < 0.05$;
DAS – days after sowing; n – Number of observations; CV - Coefficient of variation;
± values after the means represent the means standard error; PSL – pooled site location.

In regards to N uptake, significantly ($P < 0.05$) higher N uptake in plants at 50% tasselling, and N uptake in stover and grain at physiological maturity were also obtained in season A 2018. For yield components, significantly ($P < 0.05$) higher grain yield, hundred grain weight and above-ground biomass yield were similarly recorded in season A 2018. The number of days to 50% tasselling was not significantly different for both seasons A 2018 and B 2018 in both sites separately and for combined sites (Table 4.40). There was no significant interaction effect on maize growth, N uptake and yield parameters between cropping seasons, sites location, and bioslurry and mineral N rates.

Table 4.41 Seasonal effect on maize yields and nitrogen uptake for medium and high altitude sites separately and pooled

Site location	Season	Number of cobs plant^{-1}	Above-ground biomass (t ha^{-1})	Grain yield (t ha^{-1})	N uptake in stover (kg ha^{-1})	N uptake in grain (kg ha^{-1})
Medium	A 2018	1.1 ± 0.0^{a}	19.6 ± 1.0^{a}	5.9 ± 0.3^{a}	185.1 ± 12.0^{a}	96.2 ± 5.3^{a}
altitude	B 2018	1.1 ± 0.0^{b}	17.9 ± 0.9^{b}	5.5 ± 0.3^{b}	156.4 ± 9.8^{b}	83.7 ± 5.6^{b}
Mean		**1.1**	**18.8**	**5.7**	**170.7**	**90.0**
n		**96**	**96**	**96**	**96**	**96**
CV (%)		**7.5**	**14.5**	**9.6**	**17.7**	**10.2**
High	A 2018	1.1 ± 0.0^{a}	16.5 ± 0.9^{a}	5.0 ± 0.3^{a}	121.0 ± 8.9^{a}	78.1 ± 4.6^{a}
altitude	B 2018	1.1 ± 0.0^{a}	15.5 ± 0.8^{b}	4.7 ± 0.3^{b}	114.4 ± 6.9^{b}	72.9 ± 4.5^{b}
Mean		**1.1**	**16.0**	**4.9**	**117.7**	**75.5**
n		**96**	**96**	**96**	**96**	**96**
CV (%)		**8.9**	**16.1**	**10.2**	**23.0**	**12.1**
PSL	A 2018	1.1 ± 0.0^{a}	18.1 ± 0.7^{a}	5.5 ± 0.2^{a}	153.0 ± 8.1^{a}	87.2 ± 3.6^{a}
PSL	B 2018	1.1 ± 0.0^{a}	16.7 ± 0.6^{b}	5.1 ± 0.2^{b}	135.4 ± 6.4^{b}	78.3 ± 3.6^{b}
Mean		**1.1**	**17.4**	**5.3**	**144.2**	**82.7**
n		**192**	**192**	**192**	**192**	**192**
CV (%)		**8.3**	**15.4**	**10.2**	**20.5**	**11.4**

Different letters in the same column indicate significantly different values at $P < 0.05$;
DAS – days after sowing; n – Number of observations; CV - Coefficient of variation;
± values after the means represent the means standard error; PSL – pooled site location;

4.4.7 Effects of sites location on growth, N uptake and yields

Maize growth, N uptake and yields were influenced by location. Significantly ($P < 0.05$) taller plants, larger stem collar diameter and higher number of leaves at 90 DAS, and less number of days to 50% tasselling were observed in terraced Lixisols of medium altitude site for both seasons A 2018 and B 2018 separately and for pooled seasons (Tables 4.42 and 4.43).

Table 4.42 Sites location effect on maize growth, nitrogen uptake and yields for seasons A and B 2018 separately and pooled

Season	**Site location (altitude)**	**Plant height at 90 DAS (cm)**	**Stem diameter at 90 DAS (cm)**	**Number of leaves 90 DAS (cm)**	**Number of days to 50% tasselling**	**N uptake at tasselling (kg ha^{-1})**
A 2018	Medium	258.9 ± 5.0^{a}	3.4 ± 0.1^{a}	15.8 ± 0.1^{a}	64.8 ± 0.1^{b}	134.7 ± 7.7^{a}
	High	215.7 ± 5.3^{b}	3.0 ± 0.1^{b}	15.2 ± 0.1^{b}	74.6 ± 0.2^{a}	114.2 ± 6.9^{b}
Mean		**237.3**	**3.2**	**15.5**	**69.7**	**124.5**
n		**96**	**96**	**96**	**96**	**96**
CV (%)		**6.2**	**10.3**	**3.5**	**1.4**	**15.2**
B 2018	Medium	244.3 ± 5.2^{a}	3.1 ± 0.1^{a}	14.5 ± 0.1^{a}	64.7 ± 0.2^{b}	111.3 ± 6.8^{a}
	High	205.4± 4.2^{b}	2.9 ± 0.1^{b}	14.4 ± 0.1^{a}	74.4 ± 0.2^{a}	108.7 ± 5.5^{a}
Mean		**224.9**	**3.0**	**14.4**	**69.6**	**110.0**
n		**96**	**96**	**96**	**96**	**96**
CV (%)		**4.3**	**8.6**	**3.4**	**1.4**	**14.7**
PS	Medium	251.6 ± 3.6^{a}	3.3 ± 0.1^{a}	15.1 ± 0.1^{a}	64.8 ± 0.1^{b}	123.0 ± 5.3^{a}
PS	High	210.5 ± 3.4^{b}	2.9 ± 0.0^{b}	14.8 ± 0.1^{b}	74.5 ± 0.1^{a}	111.5 ± 4.4^{b}
Mean		**231.1**	**3.1**	**14.9**	**69.6**	**117.2**
n		**192**	**192**	**192**	**192**	**192**
CV (%)		**5.4**	**10.1**	**3.6**	**1.4**	**14.9**

Different letters in the same column indicate significantly different values at $P < 0.05$;
DAS – days after sowing; n – Number of observations; CV - Coefficient of variation;
± values after the means represent the means standard error; PS – pooled seasons;
A 2018 – season from September 2017 to February 2018; B 2018 - season from March 2018 to August 2018.

Similarly, higher N uptake in plants at tasselling, and N uptake in stover and grain at physiological maturity of maize were obtained in medium altitude site. Significantly (P < 0.05) higher grain yield, hundred grain weight and above-ground biomass were similarly recorded in medium altitude site. The number of cobs was significantly (P < 0.05) higher in high altitude site for season B 2018, and non-significant differences observed for season A 2018 and for pooled seasons (Tables 4.42 and 4.43).

Table 4.43 Sites location effect on maize growth, nitrogen uptake and yields for seasons A and B 2018 separately and pooled

Season	Site location (altitude)	Number of cobs plant^{-1}	Above-ground biomass (t ha^{-1})	Grain yield (t ha^{-1})	N uptake in stover (kg ha^{-1})	N uptake in grain (kg ha^{-1})
A 2018	Medium	1.1 ± 0.0^{a}	19.6 ± 1.0^{a}	5.9 ± 0.3^{a}	185.1 ± 12.0^{a}	96.2 ± 5.3^{a}
	High	1.1 ± 0.0^{a}	16.5 ± 0.9^{b}	5.0 ± 0.3^{b}	121.0 ± 8.9^{b}	78.2 ± 4.6^{b}
Mean		**1.1**	**18.1**	**5.5**	**153.0**	**87.2**
n		**96**	**96**	**96**	**96**	**96**
CV (%)		**9.1**	**15.8**	**10.1**	**21.4**	**11.1**
B 2018	Medium	1.1 ± 0.0^{b}	17.9 ± 0.9^{a}	5.5 ± 0.3^{a}	156.4 ± 9.8^{a}	83.7 ± 5.6^{a}
	High	1.1 ± 0.0^{a}	15.5 ± 0.8^{b}	4.7 ± 0.3^{b}	114.4 ± 6.9^{b}	72.9 ± 4.5^{b}
Mean		**1.1**	**16.7**	**5.1**	**135.4**	**78.3**
n		**96**	**96**	**96**	**96**	**96**
CV (%)		**7.6**	**14.8**	**10.1**	**18.6**	**11.6**
PS	Medium	1.1 ± 0.0^{a}	18.8 ± 0.7^{a}	5.7 ± 0.2^{a}	170.7 ± 7.9^{a}	90.0 ± 3.9^{a}
PS	High	1.1 ± 0.0^{a}	15.3 ± 1.0^{b}	4.9 ± 0.2^{b}	117.7 ± 5.6^{b}	75.5 ± 3.2^{b}
Mean		**1.1**	**17.4**	**5.3**	**144.2**	**82.7**
n		**192**	**192**	**192**	**192**	**192**
CV (%)		**8.3**	**15.4**	**10.2**	**20.5**	**11.4**

Different letters in the same column indicate significantly different values at P < 0.05; DAS – days after sowing; n – Number of observations; CV - Coefficient of variation; ± values after the means represent the means standard error; PS – pooled seasons; A 2018 – season from September 2017 to February 2018; B 2018 - season from March 2018 to August 2018.

4.4.8 Relationship between growth, N uptake and yield parameters as affected by bioslurry and mineral N

Correlation analysis indicated that plant height, stem collar diameter, number of leaves plant^{-1}, number of cobs plant^{-1}, above-ground biomass, hundred grain weight, grain yield, N uptake in plant at 50% tasselling, N uptake in stover and grain at physiological maturity of maize were significantly ($P < 0.05$) and positively correlated in both study sites (Tables 4.44 and 4.45). A negative correlation was observed between these parameters and days to 50% tasselling (Tables 4.44 and 4.45).

4.4.9 Estimating optimum rates of bioslurry and mineral N fertilizer

The results on modeling for optimum fertilizer (bioslurry, mineral N) rates and responses of maize grain yield on the fertilizer application are shown in Table 4.46 and Figures 4.28 and 4.29. The zero-solutions of the equations were located at the optimum rates of 14.3 t ha^{-1} of bioslurry and 75.2 kg ha^{-1} of mineral N with respective maximum grain yields of 6.9 and 6.6 t ha^{-1} in terraced Lixisols of medium altitude site. In terraced Acrisols of high altitude, the coefficient of determination (R^2) was not significant for bioslurry and therefore the optimum fertilizer rate was not estimated. For mineral N, the optimum rate was 78.4 kg N ha^{-1} with maximum grain yield of 5.8 t ha^{-1}.

Table 4. 44 Pearson correlation coefficients for growth, N uptake and yield parameters in medium altitude site

Variable	Plant height 90 DAS	Stem diameter 90 DAS	Number of leaves 90 DAS	Days to 50% tasselling	Number of cobs plant^{-1}	Above-ground biomass	Hundred grain weight	Grain yield	N uptake at 50% tasselling	N uptake in stover	N uptake in grain
Plant height 90 DAS	1.000										
Stem diameter 90 DAS	0.753***	1.000									
Number of leaves 90 DAS	0.449***	0.535***	1.000								
Days to 50% tasselling	-0.493***	-0.457***	-0.154ns	1.000							
Number of cobs plant^{-1}	0.668***	0.556***	0.353***	-0.495***	1.000						
Above-ground biomass	0.866***	0.749***	0.470***	-0.546***	0.665***	1.000					
Hundred grain weight	0.832***	0.747***	0.377***	-0.573***	0.688***	0.889***	1.000				
Gain yield	0.893***	0.737***	0.424***	-0.535***	0.732***	0.915***	0.886***	1.000			
N uptake at tasselling	0.809***	0.714***	0.412***	-0.583***	0.620***	0.742***	0.739***	0.809***	1.000		
N uptake in stover	0.859***	0.728***	0.473***	-0.520***	0.658***	0.961***	0.853***	0.884***	0.782***	1.000	
N uptake in grain	0.904***	0.755***	0.458***	-0.563***	0.753***	0.906***	0.877***	0.985***	0.859***	0.892***	1.000

ns = Non-significant; * Significant at P < 0.05; ** Significant at P < 0.01; *** Significant at P < 0.001;

DAS – Days after sowing.

Table 4.45 Pearson correlation coefficients for growth, N uptake and yield parameters in high altitude site

Variable	Plant height 90 DAS	Stem diameter 90 DAS	Number of leaves 90 DAS	Days to 50% tasselling	Number of cobs plant^{-1}	Above-ground biomass	Hundred grain weight	Grain yield	N uptake at 50% tasselling	N uptake in stover	N uptake in grain
Plant height 90 DAS	1.000										
Stem diameter 90 DAS	0.756***	1.000									
Number of leaves 90 DAS	0.576***	0.568***	1.000								
Days to 50% tasselling	-0.378***	-0.383***	-0.161ns	1.000							
Number of cobs plant^{-1}	0.456***	0.337***	0.253*	-0.343***	1.000						
Above-ground biomass	0.743***	0.636***	0.400***	-0.398***	0.637***	1.000					
Hundred grain weight	0.546***	0.579***	0.370***	-0.237*	0.251*	0.540***	1.000				
Gain yield	0.745***	0.578***	0.382***	-0.396***	0.700***	0.910***	0.453***	1.000			
N uptake at tasselling	0.719***	0.601***	0.388***	-0.387***	0.645***	0.840***	0.439***	0.866***	1.000		
N uptake in stover	0.679***	0.574***	0.354***	-0.357***	0.607***	0.973***	0.501***	0.833***	0.804***	1.000	
N uptake in grain	0.750***	0.592***	0.394***	-0.392***	0.695***	0.807***	0.448***	0.991***	0.878***	0.841***	1.000

ns = Non-significant; * Significant at P < 0.05; ** Significant at P < 0.01; *** Significant at P < 0.001;

DAS – Days after sowing.

Table 4.46 Modeling for optimum fertilizer (bioslurry, mineral N) rates and corresponding grain yields

Site	Fertilizer	Interc β_0	ReCoe β_1	ReCoe β_2	Quadratic Equation	R^2	Optimum fertilizer rate	Predicted grain yield
Medium altitude	**Bioslurry**	3.51	0.47	-0.0162	$Y = 3.51 + 0.47x - 0.0162x^2$	0.44***	14.3 t ha^{-1}	6.9 t ha^{-1}
	Mineral N	3.73	0.08	-0.0005	$Y = 3.73 + 0.08x - 0.0005x^2$	0.37*	75.2 kg ha^{-1}	6.6 t ha^{-1}
High altitude	**Bioslurry**	3.46	0.30	-0.0095	$Y = 3.46 + 0.30x - 0.0095x^2$	0.26ns	NA	NA
	Mineral N	2.75	0.08	-0.0005	$Y = 2.75 + 0.08x - 0.0005x^2$	0.59***	78.4 kg ha^{-1}	5.8 t ha^{-1}

* Significant at P= 0.05; *** Significant at P = 0.001;

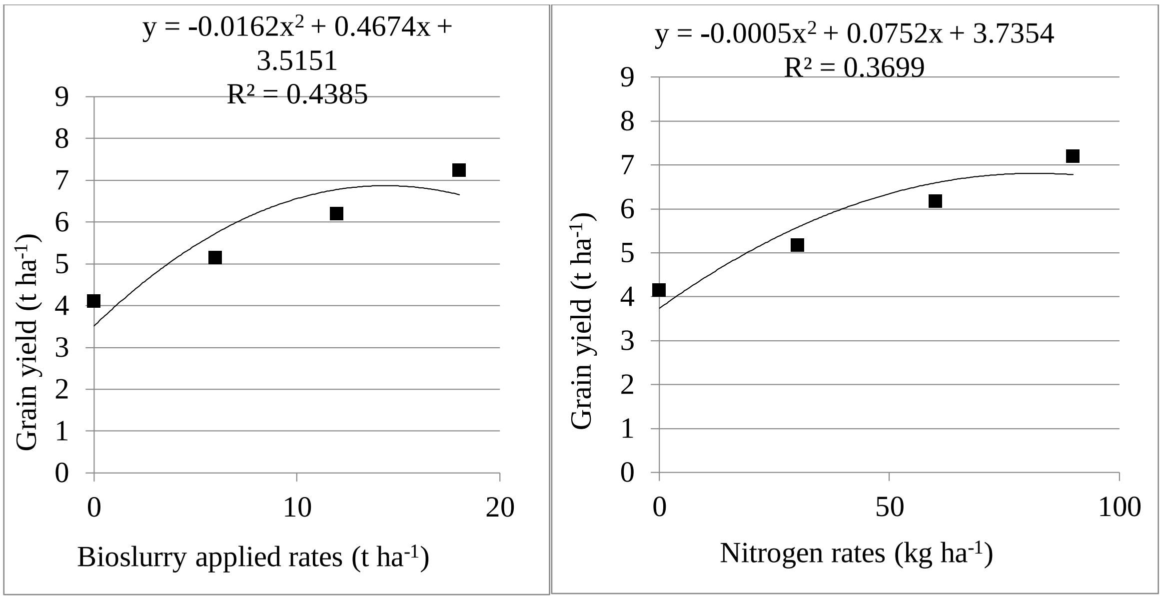
ns - not significant; NA - not applied;

Interc - Intercept with β_0 the intercept coefficient;

ReCoe - Regression coefficient with β_1 the linear terms and β_2 the squared terms;

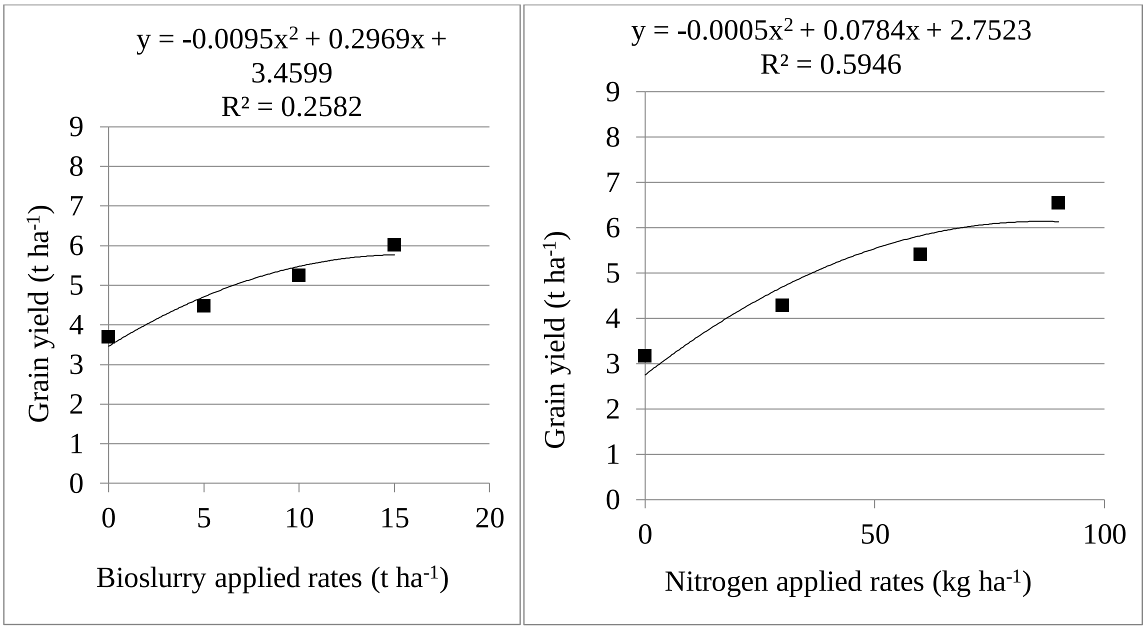
x - Independent variable (bioslurry, mineral N);

R^2 - coefficient of determination.



(a) *(b)*

Figure 4. 28 Effect of increasing applied rates of (a) bioslurry and (b) mineral N on grain yield at medium altitude area



(a) *(b)*

Figure 4.29 Effect of increasing applied rates of (a) bioslurry and (b) mineral N on grain yield at high altitude area

CHAPTER FIVE
DISCUSSION

5.1 Soil physical, chemical and biological properties across slope positions and profile depths in terraced and non-terraced lands of medium and high altitudes

5.1.1 Soil texture

Results of this study showed that the percentage of silt was relatively higher in terraced than in non-terraced soils while the percentage of clay was relatively higher in non-terraced land than in terraced soil, in medium altitude site. This indicated that land terracing led to slight changes in silt and clay distribution but no changes in the sand fraction. These results are in line with findings of Ramos *et al.* (2007) who reported changes in the fine particle size distribution of soils that contained more than 60% of coarse particles.

Along slope position of both terraced and non-terraced lands, clay contents were higher in top slope (dystric Regosols / dystric Leptosols) than middle and bottom slopes [haplic (humic) Ferralsols / haplic Lixisols], in medium altitude site. In high altitude, soils of top and middle slopes (humic Alisols / humic Acrisols) had higher contents of sand than those in bottom slope (humic Acrisols / humic (Ferralic) Cambisols) for both terraced and non-terraced lands. The observed changes in particle size fractions can be attributed to modification of slope characteristics by human or natural causes (Nelson, 2013).

Across profile depths, clay contents were relatively higher in deeper soil than in sub-soil and surface soil. This increase of clay with depth is probably indicative of illuviation of clay from the surface soils to the lower layers of the profile, resulting from the high amount of rainfall received in the highlands. Coltorti *et al.* (2019) reported that moderate clay illuviation in buried soils in the Ethiopian highlands was an indication of climatic amelioration and phases of slope stability.

5.1.2 Bulk density

Along slope position, relatively higher bulk density was found in middle and bottom slope soils [haplic (humic) Ferralsols / haplic Lixisols] in medium altitude, and also in high altitude [humic Acrisols / humic (Ferralic) Cambisols]. This might be due to lower organic matter content in middle and bottom slopes compared to top slope. Across profile depth, bulk density increased with the depth. This might be due to soil disturbance in the shallower layers caused by soil fauna and tillage which increase soil porosity. The deeper soil layers are relatively free from these disturbances and are also subject to the overburden of soil and increase in finer particles, hence their greater bulk density. Soil bulk density often increases with soil profile depth (Soltanpour and Jourgholami, 2013) due to decline in organic matter content and porosity and increased compaction (Chaudhari *et al.,* 2013).

5.1.3 Soil water holding capacity

Results indicated that water availability was high in both study sites, according to the ranking by Moore (2001). Land terracing slightly decreased TAWC by 9% and 6% at medium and high altitude sites, respectively. These results show similar trend with findings from north eastern Spain where terracing decreased water retention capacity by up to 45% (Ramos *et al.*, 2007). Dorren and Rey (2004), however, reported that terracing contributes to increasing the soil moisture content through improved infiltration. This was true in this study at pF0 where more water was stored in the terraced than non-terraced soils due to the higher pore space. At field capacity (pF2.0) and permanent wilting point (pF4.2), water retention capacity decreased due to terracing at the high altitude site. The soils had high sand content (65.3%).

5.1.4 Saturated hydraulic conductivity

Saturated hydraulic conductivity was higher in terraced than non-terraced soils. This indicated that soil disturbance by terracing work improved soil permeability due to increasing soil porosity by 45.5% and 36.1% in medium and high altitude sites, respectively. Ramos *et al.* (2007) in north eastern Spain also reported increases of hydraulic conductivity due to terracing work. Across the profile depth, surface soils were more permeable than sub-soils. This was due to increased infiltration of water in surface soils due to increased soil pore spaces created by soil fauna and tillage and organic matter from manure applied in surface soils (Melman *et al*., 2019; Wang *et. al.,* 2012).

5.1.5 Soil pH

Soils in the study areas were acidic, due to leaching of bases resulting from excessive rainfall amounts received in the highlands and limited application of lime (Agegnehu *et al.,* 2019). Land terracing did not affect soil pH. Similar results were reported by Amare *et al.* (2013) who also did not find any changes in pH due to terracing. Soils in bottom slopes were relatively less acidic (higher pH values) than those in middle and top slopes. This was due to relatively higher contents of basic cations Ca^{2+} and Mg^{2+} in bottom slope soils.

5.1.6 Soil cation exchange capacity and exchangeable bases

Cation exchange capacity (CEC) in the study areas were rated weak, according to the classification by Hazelton and Murphy (2007). This was as a result of low clay and organic matter contents in soil in addition to land use which consisted of continued cultivation in the study sites with low nutrients replishment. Clay and organic matter are the main factors that influence CEC in the soil (Adugna and Abegaz, 2015). Soils with a higher clay fraction tend to have a higher CEC. Terracing effect on CEC and exchangeable K^+, Mg^{2+} and Ca^{2+} was non-significant. Along slope positions, significantly ($P < 0.05$) higher CEC and exchangeable K^+, Mg^{2+} and Ca^{2+} were found in bottom slopes. Across profile depth, higher contents were found in deeper soils. Higher CEC and exchangeable K^+, Mg^{2+} and Ca^{2+} levels found in bottom slopes and deeper layers might be attributed to high clay content due to eluviation and illuviation processes. These results agree with findings of Lawal *et al.* (2014) who also reported higher contents in exchangeable bases at deeper layers of lower slopes.

5.1.7 Soil organic carbon (SOC)

A slightly higher SOC was found in non-terraced than terraced land, in medium altitude. A higher clay content in non-terraced land than terraced land may have protected organic matter from decomposition (Manson, 2018). The reduction in soil organic matter was however less than that of 50% reported on terraced lands in north eastern Spain (Ramos *et al*., 2007). This was due to low population of decomposers due to soil acidity. Along slope positions, higher SOC contents were found in top slopes in both medium and high altitudes. This may be attributed to higher clay content and lower mineralization due to lower population of decomposers (bacteria and fungi) in the top slopes compared to middle and bottom slopes. Across profile depth, higher SOC contents were found in surface layers than in sub and deeper layers. This might be attributed to greater concentration of organic matter in surface layers. A similar trend was reported by Eze (2015) and Lawal *et al.* (2014).

5.1.8 Total nitrogen

Total nitrogen contents in soil were low and ratios of carbon to nitrogen (C/N) indicated that mineralization was normal to low, according to the classification by Hazelton and Murphy (2007) and Landon (1991). Terracing did not have any effect on the total N content. Along slope positions, higher total N contents were found in top slopes, while across profile depth, higher total N contents were found in surface soils. These may be attributed to the higher contents of organic matter in top slopes and surface soils. These results agree with findings of Lawal *et al.* (2014) who also reported higher total N in surface soils.

5.1.9 Available phosphorus

Terracing did not affect soil available P content. However, differences in available P were found along slope positions. Higher available P contents were found in middle slope of medium and in bottom slopes of high altitudes. These might due to land use with application of FYM in addition to the P generated by the parent materials. Across soil depths, higher P contents were found in surface soils. This may be due to higher SOM in the surface soils.

5.1.10 Bacteria population

Bacteria population was low (i.e., 2.39 - 4.03 x 10^6 CFU g^{-1} in medium altitude site and 1.66 – 2.72 x 10^6 CFU g^{-1} in high altitude site) compared to 10^8 – 10^9 CFU g^{-1} estimated in 0 - 15 cm soil depth (Bahattarai *et al.*, 2015). Vieira and Nahas (2005) also reported that bacterial counts in different soils ranged from 4 x 10^6 to 2 x 10^9 g^{-1} dry soil. The lower population was due to low SOM content and acidity of soils in the study areas. The abundance and composition of bacterial community are strongly related to soil pH and various physico-chemical properties of soil (Laldinthar and Dkhar, 2015; Magdoff and ES, 2009). Bacteria tend to do better in neutral than acid soils (Magdoff and ES, 2009). Higher bacteria population was observed in terraced than non-terraced lands in medium altitude. This may due to the improved soil physical properties and enhanced microclimate in terraced lands. These include pore spaces, moisture content, adequate aeration and temperature. Microorganism population in soil is influenced by soil porosity; the more the pore spaces, the higher is the count of microbes (Bahattarai *et al.*, 2015; Magdoff and ES, 2009).

5.1.11 Fungi population

Fungi population values were low (i.e. 1.45 - 2.77 x 10^4 CFU g^{-1} in medium altitude site and 1.55 - 2.38 x 10^4 CFU g^{-1} in high altitude) compared to 10^5 – 10^6 CFU g^{-1} estimated in 0 - 15 cm soil depth (Bahattarai *et al.*, 2015). This may be attributed to low soil organic matter and nutrient content. Naturally, fungi growth tends to be promoted in natural undisturbed ecosystems (Magdoff and ES, 2009; Paul, 2007) and in high organically fertilized soils (Swer *et al.*, 2011). Higher fungi population was observed in terraced than non-terraced lands, in medium altitude. This might be attributed to higher aeration of soil (Bahattarai*et al.*, 2015).

5.2 Effect of nitrogen and phosphorus rates on growth and yield of maize (*Zea mays* L.) in terraced medium and high altitude areas

5.2.1 Maize height, collar diameter and number of leaves

Results of this study showed significant increases in maize height and collar diameter with combinations 120:80, 120:120, 180:80 and 180:80 N: P_2O_5 kg ha^{-1} rates in both terraced Lixisols of medium altitude and terraced Acrisols of high altitude areas. Response of number of leaves $plant^{-1}$ was higher with fertilizer application over the control but with no significant differences observed between rates applied. The growth increases with fertilizer use may be attributed to higher nitrogen and phosphorus assimilation by maize. Nitrogen and phosphorus are critical macronutrients for optimum plant growth and development (Reddy *et al*., 2018; Wang *et al.*, 2008). Nitrogen and phosphorus uptake influences plant growth characteristics through increased photosynthesis capacity, protein synthesis, sugar and starch utilization, nucleus formation and cell division (Reddy *et al.*, 2018; Om *et al.*, 2014; Masood *et al.*, 2011; Roy *et al.*, 2006). These results are in line with findings of Khan *et al.* (2014) who reported highest response of maize plant height to combined application of 150:150 N:P kg·ha^{-1}. Other authors also reported that N and P alone or in combination increased plant height and diameter (Getnet and Dugasa, 2019; Reddy *et al.*, 2018; Sapkota *et al.* , 2017; Khan *et al.*, 2014; Bakht *et al.*, 2006 and Khan *et al.*, 2005). Belfield and Brown (2008) reported that nitrogen determines the number of leaves that plant produces.

5.2.2 Days to 50% tasselling

The phenology of maize was influenced by nitrogen and phosphorus supply; early tasselled plants were observed in combinations of 120:120 N: P_2O_5 kg ha^{-1} in the medium altitude area. The nitrogen and phosphorus assimilated were adequate and contributed to increased health and energy levels in plants and enhanced tasselling (Jassal *et al.*, 2017; Kaur, 2016). The rates of 120 and 180 kg N ha^{-1} decreased the days to 50% tasselling by three days compared to the control. The reduction in days to 50% tasselling are as result of rapid growth related to the N and P supply which was not found in the control. This result is in line with findings of Jassal *et al.* (2017) and Kaur (2016) who reported that days to 50% tasselling decreased as N supply increased and Dawadi and Sah (2012) who reported similar results for number of days to 90% tasselling.

5.2.3 Yield and yield components

Different rates of nitrogen and phosphorus fertilizers significantly improved maize yield attributes. Yield parameters tended to increase as rates of N and P increased. This was evident in grain yield, above-ground biomass, number of cobs plant^{-1} and hundred grain weight. Combinations of 120:80, 120:120, 180:80 and 180:120 N: P_2O_5 kg ha^{-1} recorded higher grain and above-ground biomass yields. The increases in grain and biomass yields might be attributed to efficient absorption and utilization of the required plant nutrients resulting to increase of grain yield (Reddy *et al.*, 2018). These results agree with findings of Taye *et al.* (2015) who reported higher performance with combination of 184 kg N ha^{-1} and 92 kg P_2O_5 ha^{-1}, Khan *et al.* (2014) who reported maximum grain yield with combination of 150 kg N ha^{-1} and 100 kg P_2O_5 ha^{-1} and Getnet and Dugasa (2019) who reported highest grain yield with combination of N (120 kg ha^{-1}) and P (60 kg ha^{-1}).

Nitrogen improved vegetative phase and influenced grain yield due to the favourable effect of N levels on root systems (Wang *et al.*, 2008) leading to better nutrient acquisition. About two-thirds of the N absorbed by the plant ends up in the kernels at maturity (Belfield and Brown, 2008). Nitrogen determines the number of seeds per cob and therefore yield potential (Belfield and Brown, 2008). Hundred grain weight tended to increase as N supply increased and higher performance was given by the rates of 120 and 180 kg N ha^{-1}. This is in line with findings of Taye *et al.* (2015) and Om *et al.* (2014). Number of cobs plant^{-1} was not significantly influenced by N supply. This result is in agreement with findings of Om *et al.* (2014). Nitrogen supply improved vegetative growth and in turn higher production of dry matter. These results are in line with findings of Reddy *et al.* (2018) and Om *et al.*, (2014) who reported an increase of stover yield resulting from increase of N supply.

Phosphorus supply improved plant energy in vegetative and reproductive phases of the crop. The rates of 80 and 120 kg P_2O_5 ha^{-1} highly influenced yield parameters, i.e. grain yield, biomass above-ground, number of cobs plant^{-1} and hundred grain weight. In medium altitude site, the rate of 40 kg P_2O_5 ha^{-1} had good performance on grain yield and biomass above-ground which was closely following that of 80 and 120 kg P_2O_5 ha^{-1} and higher than the control response. This indicated that rates varying from 40 to 80 kg P_2O_5 ha^{-1} would be adequate for improved yield parameters in terraced Lixisols of medium altitude. Phosphorus plays a major role in the energy of plants as a constituent of adenosinetriphosphate (ATP). Phosphorus improves utilization of sugar and starch, photosynthesis, nucleus formation and cell division (Masood *et al.*, 2011; Roy *et al.*, 2006) which lead to enhanced plant growth and yield. Grain yield is also directly related to complex phenomenon of phosphorus utilization in plant metabolism (Reddy *et al.*, 2018). These results are in line with findings of Getnet and Dugasa (2019), Reddy *et al.* (2018), Taye *et al.* (2015), Khan *et al.* (2014), Masood *et al. (*2011) and Wasonga *et al.* (2008).

Grain yield obtained with application of above rates of nitrogen and phosphorus were much higher (more than two times) than the grain yield currently produced on farm level in the study areas; i.e.1.74 t ha^{-1} in season A 2015 (NISR, 2016), 1.5 and 1.6 t ha^{-1} in seasons A 2018 and A 2019, respectively (NISR, 2019).

5.2.4 Effects of cropping seasons on maize growth and yields

Maize growth and yields were influenced by cropping seasons. Plant height, stem collar diameter, above-ground biomass and grain yields were significantly higher in cropping season A 2018 compared to season B 2017 for both medium and high altitude sites separately and for pooled sites. This might be attributed to favourable climatic conditions including rainfall received over a long period in season A 2018, i.e. from September 2017 to January 2018 compared to season B 2017 (March to May 2018). Maize growth and yield positively responded to higher moisture that facilitated easier and higher nutrient uptake resulting in higher growth and yield. These results are similar to those reported by Mallarino *et al.* (2011) who attributed higher growth to adequate moisture and associated higher nutrient uptake.

5.2.5 Effects of sites location on growth and yield components

Maize growth and yields were influenced by the environments of the site. Plant height, collar diameter, biomass and grain yields were significantly higher in terraced Lixisols of medium altitude site than in terraced Acrisols of high altitude site for both seasons B 2017 and A 2018 separately and for pooled seasons. This may be attributed to the suitability of soil physical and chemical conditions for maize production, including pH levels which were less acidic in Lixisols of the medium altitude site than in Acrisols of high altitude. The increase of soil acidity reduces assimilability of nutrients by crop. Maize plant can be successfully grown on soils with pH ranging from 5 to 8 with optimum level ranging from 6 to 7 (Mallarino *et al.*, 2011). The soil texture may also have had a role in the differences found. The higher sand content of the high altitude soils could have resulted in higher leaching of nutrients due to their higher permeability.

5.2.6 Relationship between growth and yield parameters

Plant height, stem collar diameter, number of leaves plant^{-1}, number of cobs plant^{-1}, above-ground biomass, hundred grain weight and grain yield were significantly and positively correlated. Positive correlation coefficient among traits shows that the changes of any two variables are in the same direction; i.e. high value of one variable is associated with high value of other and vice versa (Raut *et al.,* 2017). This indicates that any one of these traits could be used to select for the other.

A negative correlation was observed between yields and number of days to 50% tasselling. This indicated that selection for early tasseling is desirable to increase yield. Similarly, increase of N rates decreased number of days to 50% tasselling with increase of yields. Raut *et al.* (2017) and Kumar *et al.* (2011) reported similar results for this trait.

5.2.7 Estimating optimum rates of nitrogen and phosphorus fertilizers

Although the best performing nitrogen and phosphorus fertilizer rates were 120 and 180 kg N ha^{-1} and 80 and 120 kg P_2O_5 ha^{-1}, the zero-solutions of the derivatives of the projection equations of grain yields as a function of increasing rates of N and P fertilizers indicated that the optimum rates were 176.6 kg N ha^{-1} and 96.2 kg P_2O_5 ha^{-1} in terraced Lixisols of medium altitude site. In terraced Acrisols of the high altitude site, the coefficient of determination (R^2) was not significant for both N and P and therefore the optimum fertilizer rates were not estimated. This indicated that the applied rates of N and P were low and did not reach the optimum.

The current fertilizer recommendations for maize production of 10 t ha^{-1} of FYM, 250 kg ha^{-1} of $NPK_{17.17.17}$ or 100 kg ha^{-1} of DAP applied at sowing and 50 to 100 kg ha^{-1} of urea at 45 days after sowing (MINAGRI, 2009; Kelly and Murekezi, 2000); equivalent to 10 t FYM ha^{-1}, 41 - 88.5 kg N ha^{-1} and 42.5 - 46 kg P_2O_5ha^{-1} are less than the required N and P_2O_5 rates as indicated in this study.

The fertilizer effect function model (quadratic model) is a promising tool for evaluating the optimum fertilizer recommendation rates, which is supported by experimental database for grain yield and different fertilizer application levels (Jiang *et al.,* 2020). It has been used by other workers (Lucas *et al.*, 2019; Ferreira *et al.*, 2019, Poffenbarger *et al.*, 2017).

5.3 Effect of bioslurry and mineral N on soil physical, chemical and biological properties in terraced medium and high altitude areas

5.3.1 Soil physical properties

The applied bioslurry and mineral N did not significantly affect the bulk density and moisture content of terraced soil for the evaluated cropping seasons under maize cultivation. This was not unexpected as the residual effects of bioslurry application may not be manifested after only one or two cropping seasons (Shahbaz *et al.*, 2014). A long-term observation period is required.

5.3.2 Soil chemical properties

Results of this study indicated that application of bioslurry at different rates influenced on SOC, total N and available P in terraced Acrisols of high altitude site, and SOC and total N in terraced Lixisols of medium altitude. Relatively higher levels were given by higher rates of bioslurry applied; 15 and 18 t ha^{-1} in high and medium altitudes sites, respectively. This may be attributed to bioslurry contribution to soil organic matter by relatively higher organic C and total N. Decomposition and mineralization release more available P. These results are in agreement with findings of Khan *et al.* (2015), Shahbaz *et al.* (2014) and Tuyishime (2012) who reported slight improvements in soil organic matter and nutrients due to application of bioslurry after a cropping season. However, the application of bioslurry did not influence CEC, exchangeable K^+, Ca^{2+} and Mg^{2+} during the season.

5.3.3 Soil biological properties

Bacteria and fungi populations were influenced by the application of bioslurry and mineral N, in both study areas. Higher populations were observed in plots treated with bioslurry rates of 12-18 t ha^{-1} and 10-15 t ha^{-1} in medium and high altitudes, respectively, as well as 60-90 kg mineral N ha^{-1} in both sites. This may be due to higher provision of nutrients by the fertilizers. Nitrogen fertilization affects soil biological traits and bacterial communities across different soil types (Yu *et al.*, 2019). Fungi growth also tends to be promoted in soils fertilized with high amounts of organic matter (Swer *et al.*, 2011).

5.4 Effect of bioslurry and mineral N on maize growth, N uptake and yields in terraced medium and high altitude regions

5.4.1 Emergence rate as affected by bioslurry and mineral N rates

Results of this study in both terraced Lixisols of medium and Acrisols of high altitude areas showed that application of bioslurry and mineral N at different rates did not significantly influence maize emergence rate. This could be related to the fact that the moisture levels were conducive and thus emergence was optimal. Emergence rate of above 91% was obtained in both study sites due to favourable moisture conditions during sowing and germination period. Emergence rate is influenced by soil moisture, oxygen, temperature and seed internal factors such as maturity (Shaban, 2013; Achakzai, 2009).

5.4.2 Maize height, collar diameter and number of leaves as affected by bioslurry and mineral N rates

Maize growth was significantly influenced by bioslurry and mineral N supply. Plant height and stem collar diameter tended to increase as rates of bioslurry and mineral N increased. Higher performance on plant height and stem collar diameter was recorded with combinations of 18:90, 12:90, 18:60 and 12:60 bioslurry (t ha^{-1}): N (kg ha^{-1}) in terraced Lixisols of medium altitude site and 15:90, 15:60, 10:90, 10:60 and 5:90 bioslurry (t ha^{-1}): N (kg ha^{-1}) in high altitude site. This might be attributed to the adequate levels of N resulting from applied mineral N and supplemented by N released from bioslurry. Bioslurry decomposes by slowly releasing N profitable by plant during the whole vegetative growth period. It is estimated that, for the cropping season, half of N contained in bioslurry is released and availed to plants. In addition to N supply, bioslurry increased assimilation of mineral N and other nutrients by improving soil physical conditions including structure, aeration and water-holding capacity (Tuyishime, 2012), beneficial microorganisms and diversifying nutrients (Shahbaz *et al.*, 2014). The improved assimilation of N improves root system and results in better plant height and stem collar diameter. Nitrogen is an integral part of proteins, increases the photosynthetic capacity, rapidly converts the synthesized carbohydrates to proteins and protoplasm, and therefore allows the plant to grow faster (Reddy *et al.*, 2018; Om *et al.*, 2014). These results are in agreement with findings of Islam *et al.* (2010) who reported increase of maize plant height and stem circumference with increase in bioslurry N rates up to 70 kg N ha^{-1}. Many other researchers reported the increase of plant growth as N supply increased (Getnet and Dugasa, 2019; Reddy *et al.*, 2018; Sapkota *et al.* , 2017; Khan *et al.*, 2014; Bakht *et al.*, 2006 and Khan *et al.*, 2005). Number of leaves plant^{-1} was influenced by bioslurry and mineral N supply with similar response for all rates applied. The increase in number of leaves upon N application has also been reported by other researchers (Belfield and Brown, 2008).

5.4.3 Days to 50% tasselling as affected by bioslurry and mineral N rates

The phenology of maize was influenced by bioslurry and mineral N supply. Number of days to 50% tasselling was slightly reduced with application of bioslurry and mineral N. This may be due to improved nutrient availability for plots receiving bioslurry and N fertilizer which subsequently enhanced tasselling process (Jassal *et al.*, 2017; Kaur, 2016). The number of days to 50% tasselling tended to decrease with increase in bioslurry and mineral N rates. This result is in agreement with findings of Jassal *et al.* (2017) and Kaur (2016). They reported that number of days to 50% tasselling decreased as N supply increased. Dawadi and Sah (2012) reported similar results for number of days to 90% tasselling.

5.4.4 Partitioning N uptake as affected by bioslurry and mineral N rates

Nitrogen from bioslurry and mineral N applied was assimilated by maize. At 50% maize tasselling, relatively higher uptake was recorded with higher applied rates of mineral N (60 and 90 kg ha^{-1}) combined with higher applied rates of bioslurry (12 and 18 t ha^{-1} in medium altitude, and 10 and 15 t ha^{-1} in high altitude). The N uptake of 191.30 kg ha^{-1} was given by the combination of 18 t bioslurry ha^{-1} and 90 kg N ha^{-1} in medium altitude site, and N uptake of 194.39 kg ha^{-1} was given by the combination of 15 t bioslurry ha^{-1} and 90 kg N ha^{-1} in high altitude. Crop N uptake depends on soil mineral N availability and distribution, and it is predominantly taken up in the forms of NO_3 and NH_4^+ (Gastal and Lemaire, 2002). Soil organic N can also be mineralized and taken up by crop and may represent a significant proportion of total N absorption under particular ecological situations like acidic soils and low temperature environments (Gastal and Lemaire, 2002). If N supply is optimum, N uptake depends on root system distribution. In field conditions where N supply is limited, plants can increase their root size to assimilate more soluble N from the soil (Wang *et al.*, 2008). During vegetative growth maize can accumulate N in excess of what is required for biomass accumulation (Nasielski *et al.*, 2019). The maximum N content in maize crop coincides with the greatest period of dry matter accumulation during its vegetative growth. This is the period from V10 (tenth leaf) to V14 (fourteenth leaf) of maize vegetative growth stages; maize requires the availability of 3.5 kg N day^{-1} ha^{-1} (Bender *et al.*, 2013).

At physiological maturity of maize, N concentrations in stover were relatively less than those recorded in grain, and both were less than that recorded in plant at 50% tasselling. This points to the N mobility in crop. Nitrogen possesses mobility characteristics allowing it to be utilized in one tissue, then later transported (remobilized) and used in another (Bender *et al*, 2013). The N remobilization process occurs preferentially from stem and older leaves sustaining the upper leaf (Ciampitti and Vyn, 2013), and a large percentage of total N uptake is stored in maize grain at maturity (Bender *et al.*, 2013). Relatively higher N concentration and N uptake in stover and grain were given by higher applied rates of bioslurry (12 and 18 t ha^{-1} in medium altitude, and 10 and 15 t ha^{-1} in high altitude) combined with higher applied rates of mineral N (60 and 90 kg ha^{-1}). This might be attributed to higher N adsorbed from both organic and inorganic fertilizers with higher levels compared to other treatments having less rates and the control. The differences among treatments observed in N concentration and N uptake in stover and grain could be related to N availability to crops and release patterns by the bioslurry organic residues. The higher N concentration in stover (1.25, 1.23%) observed in Lixisols of medium altitude and Acrisols of high altitude were relatively less than that of 2.6% reported by Tuyishime (2012) with application 150 kg ha^{-1} of urea and 20 t ha^{-1} of bioslurry in andosols of Northern Rwanda. However, they are in line with findings of Setiyono *et al.* (2010) on irrigated maize in Nebraska and South East Asia. The results on grain N concentration (%) and uptake (kg ha^{-1}) are in line with findings of Tenorio *et al.* (2018), Setiyono *et al.* (2010) and other researchers who reported increased grain N concentration and uptake with increase of N fertilizer applications.

5.4.5 Maize yields as affected by bioslurry and mineral N rates

Bioslurry and mineral N at different rates significantly increased maize grain and above-ground biomass yields. Best performances were given by the combinations of 12:60, 18:60, 12:90 and 18:90 bioslurry (t ha^{-1}): N (kg ha^{-1}) in medium altitude site, and 10:60, 15:60, 10:90 and 15:90 bioslurry (t ha^{-1}): N (kg ha^{-1}) in high altitude.

Total above-ground biomass increased with increase of N supply. Relatively higher total above-ground biomass yields were given by higher rates of mineral N (60 and 90 kg ha^{-1}) combined with higher rates of bioslurry (12 and 18 t ha^{-1} in medium altitude, and 10 and 15 t ha^{-1} in high altitude). Nitrogen from fertilizer and decomposed bioslurry was assimilated by maize resulting in increased vegetative growth and biomass accumulation (Nasielski *et al*, 2019). The results are in agreement with findings of Reddy *et al.* (2018) and Om *et al.* (2014) who reported an increase in stover yield resulting from increase in N supply.

Higher grain yields were given by higher applied rates of mineral N (60 and 90 kg ha^{-1}) combined with higher applied rates of bioslurry (12 and 18 t ha^{-1} in medium altitude, and 10 and 15 t ha^{-1} in high altitude). This might be attributed to the supply of N from both inorganic and organic fertilizer sources and improved assimilation of N by bioslurry through improvement of soil quality and diversification of nutrients. About two-thirds of the N absorbed by the plant ends up in the kernels at maturity; it determines the number of seeds per cob and therefore yield potential (Belfield and Brown, 2008). The results are in agreement with findings of Tuyishime (2012) who reported higher maize grain yield given by the combination of urea at 50 kg N ha^{-1} and bioslurry at 10 t ha^{-1} in northern Rwanda. Khan *et al.* (2015) and Warnars and Oppenoorth (2014) also reported improvement in maize yields with application of bioslurry. Other authors reported that yield improvement is usually greater when organic inputs and inorganic fertilizers are applied together (Mugwe *et. al.*, 2019; Fairhurst, 2012). The combination of organic and inorganic fertilizers results in improvement of agronomic efficiency of the nutrients compared to the same amount of nutrients applied through either source alone (Vanlauwe *et al.,* 2001), and sustains crop yield without affecting soil fertility (Islam *et al.,* 2013).

5.4.6 Influence of cropping seasons on growth, N uptake and yields

Maize height, collar diameter, N uptake, above-ground biomass and grain yields were significantly higher in cropping season A 2018 compared to season B 2018 for both medium and high altitude sites separately and for pooled sites. This might be attributed to favourable climatic conditions in season A as discussed in section 5.2.4.

5.4.7 Influence of sites location on growth, N uptake and yield components

Maize height, collar diameter, N uptake, above-ground biomass and grain yields were higher in terraced Lixisols of medium altitude site than in terraced Acrisols of high altitude, for both seasons A 2018 and B 2018 separately and for pooled seasons. This might be attributed to suitability of soil physical and chemical conditions for maize production as discussed in section 5.2.5.

5.4.8 Relationship between growth, N uptake and yield parameters as affected by bioslurry and mineral N

Maize grain yield was significantly and positively correlated with plant height, stem collar diameter, number of leaves plant^{-1}, number of cobs plant^{-1}, above-ground biomass, hundred grain weight and N uptake. Yield reflects the result of complex traits of growth and yield components (Raut *et al.*, 2017). Thus, the improvement of growth through bioslurry and mineral N application resulted in increase of grain yield. Garba (2015) reported the positive and significant correlation due to nitrogen fertilizer application. A negative correlation was observed between grain yields and number of days to 50% tasselling, indicating that selection for early tasseling is desirable to increase yield. Similar result was reported by Raut *et al.* (2017) and Kumar *et al.* (2011). The increase of bioslurry and mineral N rates decreased number of days to 50% tasselling indicating enhanced growth rate and correspondingly resulting to increase of yields.

5.4.9 Estimating optimum rates of bioslurry and mineral N fertilizer

The zero-solutions of the derivatives of the projection equations of grain yield as a function of increasing rates of bioslurry and mineral N indicated that optimum rates were 14.3 t ha^{-1} of bioslurry and 75.2 kg ha^{-1} of mineral N with respective maximum grain yields of 6.9 and 6.6 t ha^{-1} in terraced Lixisols of medium altitude, i.e. the rates of 138.7 kg N ha^{-1} from bioslurry (0.97% N) and 75.2 kg N ha^{-1} from urea (46% N). In terraced Acrisols of high altitude, 78.4 kg N ha^{-1} of mineral N was estimated with maximum grain yield of 5.8 t ha^{-1}. However, for bioslurry, the coefficient of determination (R^2) was not significant and therefore the optimum rate was not estimated. This indicated that the rates of bioslurry applied did not reach the optimum.

The optimum N rates were higher in terraced Acrisols of high altitude site with lower grain yields compared to those in terraced Lixisols of medium altitude. This may be attributed to higher nutrient loss by leaching in the terraced Acrisols. Soils in the high altitude area had higher sand (65%) and received excessive amount of rainfall; 1200 – 1500 mm (Gicumbi District, 2013), compared to 950 – 1000 mm received in the medium altitude area (Rwamagana District, 2013) on soils with less sand fraction (52.5%).

The current fertilizer recommendations used for maize production in both terraced and non-terraced lands are 10 t ha^{-1} of FYM, 250 kg ha^{-1} of $NPK_{17.17.17}$ or 100 kg ha^{-1} of DAP applied at sowing and 50 to 100 kg ha^{-1} of urea at 45 days after sowing (MINAGRI, 2009;

Kelly and Murekezi, 2000). They are equivalent to 10 t FYM ha^{-1}, 41 - 88.5 kg N ha^{-1} and 42.5 - 46 kg P_2O_5 ha^{-1}. It can be seen that these current applied N rates are less than the required N rates, as indicated in this study at both areas.

CHAPTER SIX
CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

Land terracing is carried out in hilly and mountainous terrains of Rwanda to prevent soil erosion, increase soil fertility and crop yields. Fertilizer recommendations for maize in the country are based on studies done in non-terraced lands and therefore not appropriate in terraced lands.

The following conclusions are drawn from the study on four-year old terraced and non-terraced lands in medium and high altitude regions of Rwanda;

i) Land terracing causes slight changes in the clay and silt fractions of soil but does not alter texture. The predominant texture in the study areas remained sandy clay loam. Terracing increases soil permeability, aeration and water infiltration, and decreases soil organic matter in surface layers.

ii) Nitrogen rates of 120 - 180 kg ha^{-1} combined with 80 - 120 kg P_2O_5 ha^{-1} increases maize yields in terraced Lixisols and Acrisols. Optimum rates for maximum yields, determined by quadratic polynomial regression analysis, were 176.6 kg N ha^{-1} and 96.2 kg P_2O_5 ha^{-1} in terraced Lixisols of medium altitude.

iii) Bioslurry and mineral N do not significantly manifest effects on soil properties in short cropping periods. Slight increases in SOC, total N, available P, and populations of bacteria and fungi occurred with increases in bioslurry rates in the two cropping seasons of the study.

iv) Application of 120 -180 kg bioslurry N ha^{-1} combined with 60 - 90 kg mineral N ha^{-1} increases maize growth, N uptake and yields in terraced Lixisols and Acrisols. Optimum rates, determined by quadratic polynomial regression analysis, were 14.3 t bioslurry ha^{-1} (i.e 139 kg bioslurry N ha^{-1}) and 75.2 kg mineral N ha^{-1} in terraced Lixisols of medium altitude.

6.2 Recommendations

This study recommends the following:

i) Soil water and fertility management in terraced lands should consider changes in soil properties that occur upon terracing.

ii) Nitrogen and phosphorus inorganic fertilizers should be applied at the of 176.6 kg N ha^{-1} and 96.2 kg P_2O_5 ha^{-1} for maize production in terraced Lixisols of medium altitude and other regions with similar characteristics.

iii) Bio-slurry should be applied at the rate of 14.3 t ha^{-1} (i.e 139 kg bio-slurry N ha^{-1}) and 75.2 kg mineral N ha^{-1} for maize production in terraced Lixisols of medium altitude and other regions with similar characteristics.

This study recommends the following areas of further research:

i) Long term effects of terracing on soil properties. The study only dealt with four year old terraces and the results may be different for older terraces.

ii) Optimal rates of nitrogen and phosphorus fertilizers, and bioslurry for maximum maize yields in terraced Acrisols of high altitude area.

iii) Fertility management of terrace soils, using bioslurry, N and P fertilizers, under different crops.

iv) Production of higher quality bioslurry in order to reduce amounts required to meet crop nutrient needs (i.e. nitrogen).

v) Economic study on the profitability of maize production in terraced lands with application of bioslurry and mineral fertilizers.

REFERENCES

Achakzai, A. K. (2009). Effect of water stress on imbibition , germination and seedling growth of maize cultivars. *Sarhad Journal of Agriculture*, 25: 165 – 172.

Adugna, A. and Abegaz, A. (2015). Effects of soil depth on the dynamics of selected soil properties among the highlands resources of Northeast Wollega , Ethiopia : are these sign of degradation ? *Soil Earth*, 1: 2011 – 2035.

Agegnehu, G., Yirga, C. and Erkossa, T. (2019). *Soil Acidity Management.* Ethiopian Institute of Agricultural Research (EIAR). Addis Ababa.

Amare, T., Terefe, A., Selassie, Y. G., Yitaferu, B., Wolfgramm, B. and Hurni, H. (2013). Soil Properties and Crop Yields along the Terraces and Toposequece of Anjeni Watershed, Central Highlands of Ethiopia. *Journal of Agricultural Science,* 5: 134 – 144.

Bahattarai, A., Bhattarai, B. and Pandey, S. (2015). Variation of Soil Microbial Population in Different Soil Horizons. *Journal of Microbiology and Experimentation,* 2: 2 – 5.

Bakht, J., Ahmad, S., Tariq, M., Akber, H. and Shafi, M. (2006). Response of maize to planting methods and fertilizer N. *Journal of Agricultural and Biological Science,* 1: 8 – 14.

Banami, A. and Ofen, A. (1984). *Irrigation engineering: sprinkler, trickle, surface irrigation; principles, design and agricultural practices.* Irrigation Engineering Scientific Publications. Haifa, Israel.

Beauregard, M. S., Atul-Nayyar, H. C. and St-Arnaud, M. (2010). Long-Term Phosphorus Fertilization Impacts Soil Fungal and Bacterial Diversity but not AM Fungal Community in Alfalfa. *Microbial Ecology,* 59: 379–389.

Belfield, S. and Brown, C. (2008). *Field Crop Manual : Maize. A Guide to Upland Production in Cambodia.* NSW Department of Primary Industries.

Bender, R. R., Haegele, J. W., Ruffo, M. L. and Below, F. E. (2013). Modern Corn Hybrids ' Nutrient Uptake Patterns. *Better Crops,* 97: 7 – 10.

Bunemann, E. K. (2003). *Phosphorus dynamics in a Ferralsol under maize-fallow rotations: The role of the soil microbial biomass.* PhD Thesis, Swiss Federal: Swiss Federal Institute of Technology Zurich. 162 pp.

Cassman, K. G. and Plant, R.E. (1992). A model to predict crop response to applied fertilizer nutrients in heterogeneous fields. *Fertilizer research,* 31: 151–163.

Chahal, P. S. and Jhala, A. J. (2016). Factors affecting germination and emergence of glyphosate-resistant hybrid corn (*Zea mays* L .) and its progeny. *Canadian Journal of*

Plant Science, 96: 613 – 620.

Chaudhari, P. R., Ahire, D. V., Ahire, V. D., Chkravarty, M. and Maity, S. (2013). Soil Bulk Density as related to Soil Texture, Organic Matter Content and available total Nutrients of Coimbatore Soil, *International Journal of Scientific and Research Publications,* 3(2): 1 – 8.

Chen, N. (2015). Re: How can I assess the new formula about N use efficiency?. Retrieved from: ttps://www.researchgate.net/post/How_can_I_assess_the_new_formula_about_N_use_efficiency/55a7753a6307d906748b45f8/citation/download. Accessed 21/06/2020.

Chianu, J. N., Chianu, J. N. and Mairura, F. (2012). Mineral fertilizers in the farming systems of sub-Saharan Africa . A review. *Agronomy for Sustainable Development,* 32: 545 – 566.

Ciampitti, I. A. and Vyn, T. J. (2013). Grain nitrogen source changes over time in maize: A review. *Crop Science*, 53: 366 – 377.

Coltorti, M., Pieruccini, P., Arthur, K. J. W., Arthur, J. and Curtis, M. (2019). Geomorphology, soils and palaeosols of the Chencha area (Gamo Gofa, south western Ethiopian Highlands). *Journal of Africa Earth Sciences*, 151: 225 – 240.

Davis, S. C., Parton, W. J., Dohleman, F. G., Candice, M., Grosso, S. D., Kent, A. D., Delucia, E. H. (2010). Comparative Biogeochemical Cycles of Bioenergy Crops Reveal Nitrogen-Fixation and Low Greenhouse Gas Emissions in a Miscanthus × giganteus Agro-Ecosystem. *Ecosystems,* 13:144 –156.

Dawadi, D. and Sah, S. K. (2012). Growth and Yield of Hybrid Maize (*Zea mays* L .) in Relation to Planting Density and Nitrogen Levels during Winter Season in Nepal. *Tropical Agricultural Research,* 23: 218 – 227.

Dorren, L. and Rey, F. (2004). A review of the effect of terracing on erosion. In: Briefing Papers of the second SCAPE workshop in Cinque Terre, Italy, 13-15 April 2004. pp 97 – 108.

Driessen, P., Deckers, J. and Spaargaren, O. (2001). Lecture Notes on the major Soils of the world. World Soil Resources Reports 94. Rome: FAO.

Eze, P. N. (2015). Spatial variability and classification of soils on a Legon hill catena in the Accra Plains , Ghana. *Journal of Soil Science and Environmental Management,* 6: 204 – 214.

Fairhurst, T. (2012). *Handbook for Integrated Soil Fertility Management.* Africa Soil Health Consortium. CABI, Nairobi.

FAO. (2019). FAO in Rwanda: Rwanda at a glance. Retreived from http://www.fao.org/rwanda/fao-in-rwanda/rwanda-at-a-glance/en/.Accessed 05/08/2019.

FAO. (2000). Manual on integrated soil management and conservation practices. FAO Land and Water Bulletin 8. Rome, FAO.

Ferreira, Curvelo, C.R.S., Pereira, A.I.A and Tomazele, A.A.S. (2018). Nitrogen Fertilization Combined with Biostimulant in Second-Crop Maize Luiz Leonardo. *International Journal of Agriculture Innovations and Research,* 6: 2319-1473.

Foundation, M. G., Setiyono, T. D., Walters, D. T., Cassman, K. G., Witt, C. and Dobermann, A. (2010). Estimating maize nutrient uptake requirements Field Crops Research Estimating maize nutrient uptake requirements. *Field Crops Research*, 118, 158 – 168.

García-Orenes, F., Morugán-Coronado, A., Zornoza, R. and Scow, K. (2013). Changes in Soil Microbial Community Structure Influenced by Agricultural Management Practices in a Mediterranean Agro-Ecosystem. *PLOS ONE,* 8: 1 – 9.

Gastal, F. and Lemaire, G. (2002). N uptake and distribution in crops : An agronomical and ecophysiological perspective. *Journal of Experimental Botany*, 53: 789 – 799.

Garba, Y. (2015). Correlation Analysis of Growth and Yield Components of Maize (*Zea mays* L.) Under Striga Hermonthica Infestation. *Production Agriculture and Technology*, 11: 101-107.

Getnet, B. E. and Dugasa, T. (2019). Response of Maize Yield and Yield Related Components to Different Levels of Nitrogen and Phosphorus Fertilizers. *Acta Scientific Agriculture,* 3: 3 – 8.

Gicumbi District. (2013). Gicumbi District Development Plan (2013 - 2018). Gicumbi District, (Ed.). Kigali, Rwanda.

Gomez, K. A. and Gomez, A. A. (1984). *Statistical Procedures for Agricultural Research (Vol. 6)*. John Willey and Sons, Inc.

Habiyakare, T. and Zhou, N. Q. (2015). Water Resources Conflict Management of Nyabarongo River and Kagera River Watershed in Africa. *Journal of Water Resource and Protection,* 7: 889 - 896.

Hazelton, P. and Murphy, B. (2007). Interpreting Soil Test Results: What do all the Numbers mean? (N. D. of N. Resources, Ed.). Australia: CSIRO Publishing.

Islam, M. A., Begum, M. A. and Jahangir, M. M. (2013). Effect of integrated approach of plant nutrients on yield and yield attributes of different crops in wheat-sesame-T. Aman cropping pattern. *International Journal of Agricultural Research, Innovation and Technology*, 3: 66 – 71.

Islam, R., Mohammad, S., Rahman, E. and Rahman, M. (2010). The effects of biogas slurry on the production and quality of maize fodder. *Turkish Journal of Agriculture and Forestry*, 34: 91 – 99.

Islam, M. S. (2006). Use of Bioslurry as Organic Fertilizer in Bangladesh Agriculture. In: International Workshop on the Use of Bioslurry Domestic Biogas Programmes, Bangkok, Thailand. pp. 27 – 28.

Jassal, R. K., Kang, J. S., Singh, H. and Singh, T. (2017). Growth , Phenology and Seed Yield of Fodder Maize in Relation to Different Planting Methods and Nitrogen Levels. *International Journal of Current Microbiology and Applied Sciences*, 6: 1723 – 1735.

Jéan du Plessis. (2003). Maize production. Department of Agriculture, Republic of Aouth Africa. Retrieved from http://www.arc.agric.za/arc-gci/Fact%20Sheets%20Library/Maize%20Production.pdf. Accessed 03/08/2016.

Johnson, T. R. and Case, C. L. (2007). *Laboratory Experiments in Microbiology* (8^{th} ed.). Pearson.

Jury, W. A., Gardner, W. R. and Gardner, W. H. (1991). *Soil physics (5^{th} ed.).* New York: John Wiley and Sons.

Kagabo, D. (2014). Radical Terraces: Rwanda - Amaterasi y'indinganire. (WOCAT, Ed.). Kigali - Rwanda.

Karki A. B. (2006). Country Report on the Use of Bioslurry in Nepal. Nepal: SNV.

Kaur, A. (2016). *Effect of different planting methods and nitrogen levels on the growth, yield and quality of kharif maize* (*Zea mays* L.). Thesis. Punjab Agricultural University, Ludhiana.

Kelly, V. and Murekezi, A. (2000). Fertilizer Response and Profitability in Rwanda. A Synthesis of Findings from MINAGRI Studies Conducted by The Food Security Research Project (FSRP) and the FAO Soil Fertility Initiative. FSRP/MINAGRI, Kigali.

Khan, A., Jan, A., Bashir, S. and Noor, M. (2005). Short Communication Effect of nitrogen and seed sizes on maize crop I. *Journal of Agriculture and Social Sciences*, 1: 380 - 381.

Khan, F., Khan, S., Fahad, S., Faisal, S., Hussain, S., Ali, S. and Ali, A. (2014). Effect of Different Levels of Nitrogen and Phosphorus on the Phenology and Yield of Maize Varieties. *American Journal of Plant Sciences*, 4: 2582 – 2590.

Khan, S. A., Malav, L. C., Kumar, S., Malav, M. K. and Gupta, N. (2015). Resource Utilization of Biogas Slurry for Better Yield and Nutritional Quality of Baby Corn. In: *Advances in Environmental and Agricultural Science*. Indian Agricultural Research Institute (IARI), New Delhi. pp. 382 – 394.

Klute, A. and Dirksen, C. (1986). Hydraulic conductivity and diffusivity: Laboratory methods. In: A. Klute (Ed.), Methods of Soil Analysis, Part 1. Monograph 9. USA: American Society of Agronomy, Madison, WI.

Kroetsch, D. and Wang, C. (2006). Particle Size Distribution. In: M. R. Carter, E. G. Gregorich and Canadian Society of Soil Science (Eds.). *Soil Sampling and Methods of Analysis (2nd ed.).* Taylor and Francis Group, LLC. pp 713 – 725.

Kumar, T. S., Reddy, D. M., Reddy, K. H. and Sudhakar, P.(2011). Targeting of traits through assessment of interrelationship and path analysis between yield and yield components for grain yield improvement in single cross hybrids of maize (*Zea mays* L.).

Laldinthar, R. and Dkhar, M.S. (2015). Relationship between Soil Bacterial Population and Various Physico-Chemical Properties at Two Broadleaved Forest Stands of Meghalaya Differing in Altitudes. *Transcriptomics*, 3: 1 - 7.

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

Lawal, B. A., Tsado, P. A., Eze, P. C., Idefoh, K. K., Zaki, A. A. and Kolawole, S. (2014). Effect of Slope Positions on some Properties of Soils under a Tectona grandis Plantation in Minna, Southern Guinea Savanna of Nigeria. *International Journal of Research in Agriculture and Forestry*, 1: 37 – 43.

Lelei, J. J. and Onwonga, R. N. (2014). Response of microbial populations, soil available P and yield of Lupin (*Lupinus albus* L cv. Amiga) to application of Minjingu phosphate rock - A green house study. *International Journal of Current Microbiology and Applied Sciences*, 3: 671 – 684.

Lucas, F.T., Borges, B.M.M.N and Coutinho, E.L.M. (2019). Nitrogen Fertilizer Management for Maize Production under Tropical Climate. *Agronomy Journal*, 111:1–7.

Magdoff, F. and ES, H. V. (2009). *Building SoilS Better Crops, Sustainable Soil Management. F. Magdoff and H. V. ES (Eds.) (3rd edn.)*. Sustainable Agriculture Research and Education (SARE) Program, USA.

Mallarino, P. A., Pagani, A. and Sawyer, J. E. (2011). Corn and soybean response to soil pH level and liming. In: 2011 Integrated Crop Management Conference. Iowa: Iowa State University. pp. 93 – 102.

Manjula, V. N. and Yichang, S. (2006). Methods for Plant Analysis. A Guide for Conducting

Plant Analysis in Missouri. Misouri - Columbia: University of Missouri.

Manson, A. (2018). Soil organic matter. Research and Technology Bulletin 20017-18/06. Department of Agriculture and Rural Development. Kwazulu-Natal.

Masood, T., Gul, R., Munsif, F., Jalal, F., Hussain, Z., Noreen, N., Khan, H. (2011). Effect of different phosphorus levels on the yield and yield components of maize. *Sarhad Journal of Agriculture*, 27: 167 – 170.

Melman,D.A., Kelly, C., Schneekloth, J., Calderón, F. and Fonte, S. (2019). Tillage and residue management drive rapid changes in soil macrofauna communities and soil properties in a semiarid cropping system of Eastern Colorado. *Applied Soil Ecology,* 143: 98-106.

Mesfin, A. (2016). A Field Guideline on Bench Terrace Design and Construction. Ministry of Agriculture and Natural Resources Natural Resource Management Directorate. Ethiopia.

Meyers, L. S., Gamst, G. and Guarino, A. J. (2009). Data Analysis Usingh SAS Enterprise Guide. Cambridge.

MINAGRI. (2009). Farmar's diary 2008-2009. Kigali, Rwanda.

MININFRA. (2014). Energy, Biogas. Kigali, Rwanda.

Moore, G. (2001). A soil guide: A handbook for understanding and managing agricultural soils. Bulletin 4343. Western Astralia: CSIRO Publishing.

Morgan, R. P. C. (2009). Soil Erosion and Conservation (3rd ed.). Blackwell.

Morugán-Coronado, A., García-Orenes, F. and Cerdà, A. (2015). Changes in soil microbial activity and physicochemical properties in agricultural soils in Eastern Spain. *Spanish Journal of Soil Science,* 5: 201 – 213.

Mugwe, J., Ngetich, F. and Otieno, E. O. (2019). *Integrated Soil Fertility Management in Sub-Saharan Africa: Evolving Paradigms Toward Integration*. Springer Nature Switzerland AG 2019. W. Leal Filho et al. (eds.), Zero Hunger. https://doi.org/10.1007/978-3-319-69626-3_71-1.

Nájera, F., Tapia, Y., Baginsky, C., Figueroa, V., Cabeza, R. and Salazar, O. (2015). Evaluation of soil fertility and fertilisation practices for irrigated maize (*Zea mays* L.) under Mediterranean conditions in central Chile. *Journal of Soil Science and Plant Nutrition*, 15: 84 – 97.

Nasielski, J., Earl, H. and Deen, B. (2019). Luxury Vegetative Nitrogen Uptake in Maize Buffers Grain Yield Under Post-silking Water and Nitrogen Stress: A Mechanistic Understanding. *Frontiers in Plant Science*, 10: 1 – 14.

Nelson S.A. (2013). Slope stability, Triggering events, Mass movement Hazards. Retrieved from http://www.tulane.edu/~sanelson/Natural_Disasters/slopestability.htm. Accessed 02/08/2019.

NISR. (2019). Seasonal Agricultural Survey, Season A 2019 Report. Kigali - Rwanda: National Institute of Statistics of Rwanda.

NISR. (2018). Seasonal Agricultural Survey, 2018 Annual Report. Kigali - Rwanda: National Institute of Statistics of Rwanda.

NISR. (2016). Seasonal Agricultural Survey, 2015 Annual Report. Kigali - Rwanda: National Institute of Statistics of Rwanda.

Okalebo, J., Gathua, K. W. and Woomer, P. L. (2002). *Laboratory methods of soil and plant analysis: A working manual* (2nd ed.). Kenya.

Om, H., Singh, S. P., Singh, J. K., Ansari, M. A., Meena, R. L. and Yadav, B. (2014). Short Communication. Productivity, Nitrogen balance and economics of winter maize (*Zea mays* L.) as influenced by QPM cultivars and nitrogen level Productivity. *Indian Journal of Agricultural Sciences*, 84: 130 – 132.

Onasanya, O., Aiyelari, O. and Oikeh, S. O. (2009). Growth and Yield Response of Maize (*Zea mays* L .) to Different Rates of Nitrogen and Phosphorus Fertilizers in Southern Nigeria. *World Journal of Agricultural Sciences*, 5: 400 – 407.

Pal, S. K. (2013). Soil sampling and methods of analysis. Pitam Pura, New Delhi - 110 088: New India Publishing Agency (NIPA).

Paul, E. A. (2007). *Soil Microbiology, Ecology and Biochemistry*. (E. A. Paul, Ed.) (3rd ed.). Oxford: Elsevier.

Peters J., Combs, S., Hoskins B., Jarman J., Kovar J., Watson M., Wolf A. and Wolf A. (2003). Recommended Methods of Manure Analysis (A3769). University of Wisconsin.

Poffenbarger, H.J., Barker, D.W., Helmers, M.J., Miguez, F.E., Olk, D.C., Sawyer, J.E., .. (2017). Maximum soil organic carbon storage in Midwest U.S. cropping systems when crops are optimally nitrogen-fertilized. *PLoS ONE,* 12(3): e0172293. doi:10.1371/journal.pone.0172293.

Posthumus, H. and Stroosnijder, L. (2010). To terrace or not: the short-term impact of bench terraces on soil properties and crop response in the Peruvian Andes. *Environment, Development and Sustainability*, 12: 263 – 276.

RAB. (2013). Annual report 2012-2013. Rwanda Agriculture Board, (Ed.). Kigali, Rwanda.

Rakotojaona, L. (2013). Domestic biogas development in developing countries. Belgium: Open Ideas, ENEA Consulting.

Ramos, M. C., Cots-Folch, R. and Martínez-Casasnovas, J. A. (2007). Effects of land terracing on soil properties in the Priorat region in Northeastern Spain: A multivariate analysis. *Geoderma,* 142: 251 – 261.

Raut, S. K., Ghimire, S. K., Khare, R., Kuwar, C. B., Sapkota, M. and Kushwaha, U. K. S. (2017). Study of Yield and Yield Attributing Traits of Maize. *American Journal of Food Science and Health*, 3: 123-129.

Reddy, U. V. B., Reddy, G. P., Reddy, M. S. and Kavitha, P. (2018). Effect of Different Nitrogen and Phosphorus Levels on Growth and Yield of Maize during Kharif Season. *International Journal of Current Microbiology and Applied Sciences,* 7: 3548 – 3555.

Roy, R. N., Finck, A., Blair, G. J. and Tandon, H. L. S. (2006). Plant nutrition for food security; A guide for integrated nutrient management. FAO Fertilizer and plant nutrition bulletin (16th ed.). FAO, Rome.

Ruganzu, V., Rukangantambara, H., Fashaho, A., Shirimpumu, A., Nduwumuremyi, A. and Mutegi, J. (2015). Farmer Field School Facilitator's Module: Integrated Soil Fertility Management (ISFM). R. S. H. Consortium (Ed.). Kigali - Rwanda: RAB.

Rushemuka, P. N., Bock, L. and Mowo, J. G. (2014). Soil science and agricultural development in Rwanda: state of the art. A review. *Biotechnologie Agronomie Societe et Environnement,* 18: 142 – 154.

Rwamagana District. (2013). District Development Plan 2013/2014 - 2017/2018. (Rwamagana District, Ed.). Kigali, Rwanda.

Rwibasira, E. (2016). Effect of Crop Intensification Program on Maize Production in Nyagatare, Rwanda. *International Journal of Agricultural Extension and Rural Development Studies,* 3: 87 - 102.

Sapkota, A., Shrestha, R. K. and Chalise, D. (2017). Response of Maize to the Soil Application of Nitrogen and Phosphorous Fertilizers. *International Journal of Applied Science and Biotechnology,* 5: 537-541.

SAS. (2008). SAS/STAT® 9.2 *User's Guide.* SAS Institute Inc.,. Cary, NC., USA.

Shaban, M. (2013). Effect of water and temperature on seed germination and emergence as a seed hydrothermal time model. *International Journal of Advanced Biological and Biomedical Research,* 1: 1686 – 1691.

Shahbaz, M., Akhtar, M. J., Ahmed, W. and Wakeel, A. (2014). Integrated effect of different N-fertilizer rates and bioslurry application on growth and N-use efficiency of okra (*Hibiscus esculentus* L .). *Turkish Journal of Agriculture and Forestry,* 38: 311 – 319.

Setiyono T.D., Waltersa,D.T., Cassman, K.G., Wittb, C., Dobermann, A. (2010). Estimating maize nutrient uptake requirements. *Field Crops Research,*118: 158–168.

Swer, H., Dkhar, M. S. and Kayang, H. (2011). Fungal population and diversity in organically amended agricultural soils of Meghalaya, India. *Journal of Organic Systems,* 6, 3–12.

Taye, G., Tesfaye, K. and Debele, T. (2015). Effects of Nitrogen and Phosphorus Fertilizers on the Yield of Maize (*Zea mays* L.) at Nedjo, West Wollega, Ethiopia. *Journal of Natural Sciences Research,* 5, 197 – 203.

Tenorio, F. A. M., Eagle, A. J., McLellan, E. L., Cassman, K. G., Howard, R., Below, F. E., … Grassini, P. (2018). Assessing variation in maize grain nitrogen concentration and its implications for estimating nitrogen balance in the US North Central region. *Field Crops Research,* 240: 185-193.

Tuyishime, O. (2012). Effect of bioslurry and inorganic-N fertilizers on soil properties and improvement of maize productivity in Musanze District, Rwanda. Thesis, Kenyatta University.

Twagiramungu, F. (2006). Environmental profile of Rwanda. European commission and Republic of Rwanda, Kigali.

Vanlauwe, B., Wendt, J. and Diels, J. (2001). Combined application of organic matter and fertilizer. In: Tian, G., Ishida, F. and Keatinge, J.D.H.,(Ed.), *Sustaining soil fertility in West Africa.* Madison, WI, USA, Soil Science Society of America, Special Publication Number 58, 247 – 280.

Vanlauwe, B. and Zingore, S. (2011). Integrated soil fertility management: Operational definition and consequences for implementation and dissemination. *Better Crops,* 95: 4 – 7.

Verdoodt, A. and Van Ranst, E. (2003). Land Evaluation for Agricultural Production in the Tropics. A Large - Scale Land Suitability Classification for Rwanda. G. U. Laboratory of Soil Science, (Ed.). Ghent, Belgium.

Vieira, F.C.S. and Nahas, E. (2005). Comparison of microbial numbers in soils by using various culture media and temperatures. *Microbiological Research,* 160: 197 - 202.

Wallenius, K. (2011). *Microbiological characterisation of soils: Evaluation of some critical steps in data collection and experimental design*. Academic dissertation, University of Helsinki.

Wang, Z. R., Rui, Y. K., Shen, J. B. and Zhang, F. S. (2008). Effects of N fertilizer on root growth in Zea mays L. seedlings. *Spanish Journal of Agricultural Research,* 6: 677 – 682.

Wang, J.J., Li, X.Y., Zhu, A.N., Zhang, X.K., Zhang, H.W., Liang, W.J. (2012). Effects of tillage and residue management on soil microbial communities in North China. *Plant, soil and environment,* 58: 28–33.

Wang, G.L, Ye, Y.L, Chen, X. P. and Cui, Z.L. (2014). Determining the optimal nitrogen rate for summer maize in China by integrating agronomic, economic, and environmental aspects. *Biogeosciences,* 11: 3031–3041.

Waring, B. G., Averill, C. and Hawkes, C. V. (2013). Differences in fungal and bacterial physiology alter soil carbon and nitrogen cycling: Insights from meta-analysis and theoretical models. *Ecology Letters,* 16: 887 – 894.

Warman, P. R. and Termeer, W. C. (2005). Evaluation of sewage sludge, septic waste and sludge compost applications to corn and soils. *Bioresource Technology,* 96: 955 – 961.

Warnars, L. and Oppenoorth, H. (2014). *Bioslurry: A Supreme Fertiliser A study on bioslurry results and uses. K. Atkinson (Ed.). Hivos.*

Wasonga, C. J., Sigunga, D. O. and Musandu, A. O. (2008). Phosphorus requirements by maize varieties in different soil types of Western Kenya. *African Crop Science Journal,* 16: 161 – 173.

Jiang, W., Xing, Y., Wang, X., Liu, X., and Cui, Z. (2020). Developing a Sustainable Management Strategy for Quantitative Estimation of Optimum Nitrogen Fertilizer Recommendation Rates for Maize in Northeast China. *Sustainability* 2020, 12, 2607; doi:10.3390/su12072607.

Wheaton, R. Z. and Monke, E. J. (2001). Terracing as a ` Best Management Practice for Controlling Erosion and Protecting Water Quality. Purdue University.

Widomski, M. K. (2011). Terracing as a Measure of Soil Erosion Control and Its Effect on Improvement of Infiltration in Eroded Environment. Danilo Godone (Ed.). Soil Erosion Issues in Agriculture. InTech.

Yadav, O.P., Prasanna, B.M., Yadava, P., Jat, S.L., Kumar, D., Dhillon, B.S., Solanki, I.S. and Sandhu, J.S. (2016). Doubling maize (*Zea mays* L.) production of India by 2025 – Challenges and opportunities. *Indian Journal of Agricultural Sciences,* 86: 427 – 434.

Yu, H., Ling, N., Wang, T., Zhu, C., Wang, Y., Wang, S. and Gao, Q. (2019). Responses of soil biological traits and bacterial communities to nitrogen fertilization mediate maize yields across three soil types. *Soil and Tillage Research,* 185: 61-69.

Zebarth, B., Brown, W. and Karemangingo, C. (2006). Nitrogen Management for Corn : General Fertilizer Recommendations. Factsheet. Greenhouse Gas Mitigation Program for

Canadian Agriculture. Canada.

Zhu, Z. I. and Chen, D. L. (2002). Nitrogen fertilizer use in China – contributions to food production, impacts on the environment and best management strategies. *Nutrition Cycle in Agroecosystem*, 63: 117 – 127.

Zornoza, R., Guerrero, C., Mataix-solera, J., Scow, K. M., Arcenegui, V. and Mataix-beneyto, J. (2009). Changes in soil microbial community structure following the abandonment of agricultural terraces in mountainous areas of Eastern Spain. *Applied Soil Ecology,* 42: 315-323.

APPENDICES

Appendix 1. ANOVA table for sand in medium altitude area

The GLM Procedure

Dependent Variable: Sand

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	19	600.9969778	31.6314199	13.38	<.0001
Error	34	80.4068222	2.3649065		
Corrected Total	53	681.4038000			

R-Square	Coeff Var	Root MSE	Sand Mean
0.881998	2.931983	1.537825	52.45000

Source	DF	Type I SS	Mean Square	F Value	Pr > F
Rep	2	3.3080444	1.6540222	0.70	0.5039
Terracing	1	1.7785185	1.7785185	0.75	0.3919
Slope	2	506.3709000	253.1854500	107.06	<.0001
Depth	2	16.1934111	8.0967056	3.42	0.0442
Terracing*Slope	2	59.2335593	29.6167796	12.52	<.0001
Terracing*Depth	2	0.6491593	0.3245796	0.14	0.8722
Terracin*Slope*Depth	8	13.4633852	1.6829231	0.71	0.6795

Appendix 2. ANOVA table for sand in high altitude area

The GLM Procedure

Dependent Variable: Sand

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	19	860.9873574	45.3151241	14.03	<.0001
Error	34	109.8450519	3.2307368		
Corrected Total	53	970.8324093			

R-Square	Coeff Var	Root MSE	Sand Mean
0.886855	2.753463	1.797425	65.27870

Source	DF	Type I SS	Mean Square	F Value	Pr > F
Rep	2	0.7448148	0.3724074	0.12	0.8915
Terracing	1	3.7288167	3.7288167	1.15	0.2902
Slope	2	791.3612926	395.6806463	122.47	<.0001
Depth	2	7.3962815	3.6981407	1.14	0.3303
Terracing*Slope	2	44.9742111	22.4871056	6.96	0.0029
Terracing*Depth	2	0.4353778	0.2176889	0.07	0.9350
Terracin*Slope*Depth	8	12.3465630	1.5433204	0.48	0.8633

Appendix 3. ANOVA table of TAWC in medium altitude site

The GLM Procedure

Dependent Variable: TAWC

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	12	10048.22312	837.35193	4.13	0.0127
Error	11	2231.55155	202.86832		
Corrected Total	23	12279.77466			

R-Square	Coeff Var	Root MSE	TAWC Mean
0.818274	11.38715	14.24319	125.0813

Source	DF	Type I SS	Mean Square	F Value	Pr > F
Rep	1	781.699204	781.699204	3.85	0.0754
Terracing	1	1632.345204	1632.345204	8.05	0.0162
Slope	2	3024.659425	1512.329713	7.45	0.0090
Depth	1	224.420504	224.420504	1.11	0.3155
Terracing*Slope	2	1534.355008	767.177504	3.78	0.0562
Terracing*Depth	1	191.139704	191.139704	0.94	0.3526
Terracin*Slope*Depth	4	2659.604067	664.901017	3.28	0.0533

Appendix 4. ANOVA table of TAWC in high altitude area

The GLM Procedure

Dependent Variable: TAWC

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	12	26415.51350	2201.29279	23.36	<.0001
Error	11	1036.55070	94.23188		
Corrected Total	23	27452.06420			

R-Square	Coeff Var	Root MSE	TAWC Mean
0.962241	6.653856	9.707311	145.8900

Source	DF	Type I SS	Mean Square	F Value	Pr > F
Rep	1	13.14240	13.14240	0.14	0.7159
Terracing	1	534.49282	534.49282	5.67	0.0364
Slope	2	22924.95497	11462.47749	121.64	<.0001
Depth	1	2.36882	2.36882	0.03	0.8769
Terracing*Slope	2	843.86681	421.93340	4.48	0.0378
Terracing*Depth	1	0.02940	0.02940	0.00	0.9862
Terracin*Slope*Depth	4	2096.65828	524.16457	5.56	0.0107

Appendix 5. ANOVA table of SOC in medium altitude area

The GLM Procedure

Dependent Variable: SOC

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	19	3.32833519	0.17517554	6.62	<.0001
Error	34	0.89958519	0.02645839		
Corrected Total	53	4.22792037			

R-Square	Coeff Var	Root MSE	C Mean
0.787228	13.62019	0.162660	1.194259

Source	DF	Type I SS	Mean Square	F Value	Pr > F
Rep	2	0.20294815	0.10147407	3.84	0.0315
Terracing	1	1.24822407	1.24822407	47.18	<.0001
Slope	2	1.41640370	0.70820185	26.77	<.0001
Depth	2	0.38917037	0.19458519	7.35	0.0022
Terracing*Slope	2	0.01802593	0.00901296	0.34	0.7137
Terracing*Depth	2	0.00739259	0.00369630	0.14	0.8701
Terracin*Slope*Depth	8	0.04617037	0.00577130	0.22	0.9853

Appendix 6. ANOVA table of SOC in high altitude site

The GLM Procedure

Dependent Variable: SOC

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	19	24.53249444	1.29118392	19.43	<.0001
Error	34	2.25945556	0.06645458		
Corrected Total	53	26.79195000			

R-Square	Coeff Var	Root MSE	SOC Mean
0.915667	14.71672	0.257788	1.751667

Source	DF	Type I SS	Mean Square	F Value	Pr > F
Rep	2	1.21301111	0.60650556	9.13	0.0007
Terracing	1	0.13400185	0.13400185	2.02	0.1647
Slope	2	22.37250000	11.18625000	168.33	<.0001
Depth	2	0.51524444	0.25762222	3.88	0.0304
Terracing*Slope	2	0.03595926	0.01797963	0.27	0.7646
Terracing*Depth	2	0.00072593	0.00036296	0.01	0.9946
Terracin*Slope*Depth	8	0.26105185	0.03263148	0.49	0.8539

Appendix 7. ANOVA table for effect of N and P rates on grain yield in medium altitude

The GLM Procedure

Dependent Variable: Grain Yield

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	33	196.9948844	5.9695420	19.77	<.0001
Error	62	18.7192646	0.3019236		
Corrected Total	95	215.7141490			

R-Square	Coeff Var	Root MSE	GY Mean
0.913222	12.06120	0.549476	4.555729

Source	DF	Type I SS	Mean Square	F Value	Pr > F
Season	1	2.5123010	2.5123010	8.32	0.0054
Rep	2	0.9426021	0.4713010	1.56	0.2181
N	3	135.1365781	45.0455260	149.20	<.0001
P	3	48.3189615	16.1063205	53.35	<.0001
Season*N	3	0.0243115	0.0081038	0.03	0.9940
Season*P	3	1.9000115	0.6333372	2.10	0.1096
N*P	9	6.7604594	0.7511622	2.49	0.0170
Season*N*P	9	1.3996594	0.1555177	0.52	0.8582

Appendix 8. ANOVA table for effect of N and P rates on grain yield in high altitude

The GLM Procedure

Dependent Variable: Grain Yield

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	33	152.1965542	4.6120168	9.39	<.0001
Error	62	30.4633083	0.4913437		
Corrected Total	95	182.6598625			

R-Square	Coeff Var	Root MSE	GY Mean
0.833224	17.47211	0.700959	4.011875

Source	DF	Type I SS	Mean Square	F Value	Pr > F
Season	1	6.55215000	6.55215000	13.34	0.0005
Rep	2	0.40442500	0.20221250	0.41	0.6644
N	3	59.10241250	19.70080417	40.10	<.0001
P	3	63.69768750	21.23256250	43.21	<.0001
Season*N	3	2.67675000	0.89225000	1.82	0.1535
Season*P	3	1.57385833	0.52461944	1.07	0.3694
N*P	9	11.19822917	1.24424769	2.53	0.0153
Season*N*P	9	6.99104167	0.77678241	1.58	0.1409

Appendix 9. ANOVA table for effect of N and P rates on grain yield for combined analysis of locations and seasons

The GLM Procedure

Dependent Variable: Grain Yield

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	65	362.1184943	5.5710538	13.91	<.0001
Error	126	50.4528302	0.4004193		
Corrected Total	191	412.5713245			

R-Square	Coeff Var	Root MSE	GY Mean
0.877711	14.77162	0.632787	4.283802

Source	DF	Type I SS	Mean Square	F Value	Pr > F
Location	1	14.1973130	14.1973130	35.46	<.0001
Season	1	8.5894380	8.5894380	21.45	<.0001
Rep	2	0.0767698	0.0383849	0.10	0.9087
N	3	185.1114724	61.7038241	154.10	<.0001
P	3	110.4184141	36.8061380	91.92	<.0001
Location*N	3	9.1275182	3.0425061	7.60	0.0001
Location*P	3	1.5982349	0.5327450	1.33	0.2675
Season*N	3	1.4803766	0.4934589	1.23	0.3008
Season*P	3	1.3200349	0.4400116	1.10	0.3522
N*P	9	15.1661297	1.6851255	4.21	<.0001
Location*Season*N	4	1.6956979	0.4239245	1.06	0.3799
Location*Season*P	3	2.1538349	0.7179450	1.79	0.1519
Location*Season*N*P	27	11.1832599	0.4141948	1.03	0.4295

Appendix 10. ANOVA table of quadratic regression analysis for estimating optimum N rate on grain yield in medium altitude

The REG Procedure
Model: MODEL1
Dependent Variable: Grain Yield
Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	2	130841109	65420555	71.67	<.0001
Error	93	84888384	912778		
Corrected Total	95	215729493			

Root MSE	955.39433	R-Square	0.6065
Dependent Mean	4555.80208	Adj R-Sq	0.5980
Coeff Var	20.97094		

Parameter Estimates

Variable	DF	Parameter Estimate	Standard Error	t Value	Pr > |t|
Intercept	1	2714.38542	190.08106	14.28	<.0001
N	1	33.88212	5.08755	6.66	<.0001
SQN	1	-0.09587	0.02709	-3.54	0.0006

Appendix 11. ANOVA table for effect of bioslurry and mineral N rates on plant N uptake at tasseling in medium altitude site

The GLM Procedure

Dependent Variable: Nitrogen uptake at tasselling in medium altitude site

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	33	232101.7225	7033.3855	20.15	<.0001
Error	62	21643.9027	349.0952		
Corrected Total	95	253745.6253			

R-Square	Coeff Var	Root MSE	NUT Mean
0.914702	15.19294	18.68409	122.9788

Source	DF	Type I SS	Mean Square	F Value	Pr > F
Season	1	13159.2300	13159.2300	37.70	<.0001
Rep	2	2210.6045	1105.3023	3.17	0.0491
B	3	66450.8377	22150.2792	63.45	<.0001
N	3	130964.9310	43654.9770	125.05	<.0001
Season*B	3	4843.4563	1614.4854	4.62	0.0055
Season*N	3	943.8043	314.6014	0.90	0.4458
B*N	9	11687.2161	1298.5796	3.72	0.0009
Season*B*N	9	1841.6426	204.6270	0.59	0.8035

Appendix 12. ANOVA table for effect of bioslurry and mineral N rates on plant N uptake at tasseling in high altitude site

The GLM Procedure

Dependent Variable: Nitrogen uptake at tasselling in high altitude site

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	33	160071.4107	4850.6488	18.66	<.0001
Error	62	16112.8579	259.8848		
Corrected Total	95	176184.2686			

R-Square	Coeff Var	Root MSE	NUT Mean
0.908545	14.46187	16.12094	111.4721

Source	DF	Type I SS	Mean Square	F Value	Pr > F
Season	1	730.07570	730.07570	2.81	0.0988
Rep	2	620.11610	310.05805	1.19	0.3102
B	3	59941.87414	19980.62471	76.88	<.0001
N	3	88873.08620	29624.36207	113.99	<.0001
Season*B	3	2558.30170	852.76723	3.28	0.0266
Season*N	3	781.05775	260.35258	1.00	0.3981
B*N	9	4906.02301	545.11367	2.10	0.0431
Season*B*N	9	1660.87608	184.54179	0.71	0.6974

Appendix 13. ANOVA table for effect of bioslurry and mineral N rates on grain yield in medium altitude site

The GLM Procedure

Dependent Variable: Grain Yield in medium altitude site

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	33	347.2980771	10.5241842	35.58	<.0001
Error	62	18.3373188	0.2957632		
Corrected Total	95	365.6353958			

R-Square	Coeff Var	Root MSE	GY Mean
0.949848	9.589088	0.543841	5.671458

Source	DF	Type I SS	Mean Square	F Value	Pr > F
Season	1	4.8420167	4.8420167	16.37	0.0001
Rep	2	2.3630146	1.1815073	3.99	0.0233
B	3	169.7610208	56.5870069	191.33	<.0001
N	3	140.2447875	46.7482625	158.06	<.0001
Season*B	3	1.2195750	0.4065250	1.37	0.2589
Season*N	3	1.0310250	0.3436750	1.16	0.3315
B*N	9	19.1031875	2.1225764	7.18	<.0001
Season*B*N	9	8.7334500	0.9703833	3.28	0.0025

Appendix 14. ANOVA table for effect of bioslurry and mineral N rates on grain yield in high altitude site

The GLM Procedure

Dependent Variable: Grain Yield in high altitude site

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	33	264.1720229	8.0052128	32.55	<.0001
Error	62	15.2477771	0.2459319		
Corrected Total	95	279.4198000			

R-Square	Coeff Var	Root MSE	GY Mean
0.945431	10.21979	0.495915	4.852500

Source	DF	Type I SS	Mean Square	F Value	Pr > F
Season	1	1.9608167	1.9608167	7.97	0.0064
Rep	2	0.9265563	0.4632781	1.88	0.1606
B	3	76.6803917	25.5601306	103.93	<.0001
N	3	168.7531250	56.2510417	228.73	<.0001
Season*B	3	0.6163583	0.2054528	0.84	0.4796
Season*N	3	0.4987250	0.1662417	0.68	0.5700
B*N	9	12.9016167	1.4335130	5.83	<.0001
Season*B*N	9	1.8344333	0.2038259	0.83	0.5923

Appendix 15. ANOVA table for effect of bioslurry and mineral N rates on grain yield for combined analysis of locations and seasons

The GLM Procedure

Dependent Variable: Grain Yield for combined analysis of locations and seasons

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	65	641.1251010	9.8634631	34.40	<.0001
Error	126	36.1233469	0.2866932		
Corrected Total	191	677.2484479			

R-Square	Coeff Var	Root MSE	GY Mean
0.946662	10.17559	0.535437	5.261979

Source	DF	Type I SS	Mean Square	F Value	Pr > F
Location	1	32.1932521	32.1932521	112.29	<.0001
Season	1	6.4827000	6.4827000	22.61	<.0001
Rep	2	0.7513198	0.3756599	1.31	0.2734
B	3	232.4383521	77.4794507	270.25	<.0001
N	3	307.8679604	102.6226535	357.95	<.0001
Location*Season	1	0.3201333	0.3201333	1.12	0.2927
Location*B	3	14.0030604	4.6676868	16.28	<.0001
Location*N	3	1.1299521	0.3766507	1.31	0.2729
Season*B	3	0.3958042	0.1319347	0.46	0.7106
Season*N	3	0.5866125	0.1955375	0.68	0.5646
B*N	9	27.8615521	3.0957280	10.80	<.0001
Location*Season*B	3	1.4401292	0.4800431	1.67	0.1759
Location*Season*N	3	0.9431375	0.3143792	1.10	0.3532
Season*B*N	9	7.2073000	0.8008111	2.79	0.0051
Location*Season*B*N	18	7.5038354	0.4168797	1.45	0.1182

Appendix 16. ANOVA table for quadratic analysis to estimate optimum bioslurry rate in medium altitude site

The REG Procedure
Model: MODEL1
Dependent Variable: Grain Yield

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	2	164.64395	82.32198	38.09	<.0001
Error	93	200.99144	2.16120		
Corrected Total	95	365.63540			

Root MSE	1.47010	R-Square	0.4503
Dependent Mean	5.67146	Adj R-Sq	0.4385
Coeff Var	25.92105		

Parameter Estimates

Variable	DF	Parameter Estimate	Standard Error	t Value	Pr > |t|
Intercept	1	3.51408	0.29248	12.01	<.0001
B	1	0.46769	0.07828	5.97	<.0001
SQB	1	-0.01628	0.00417	-3.91	0.0002

Appendix 17. ANOVA table for quadratic analysis to estimate optimum bioslurry rate in medium altitude site

```
                              The REG Procedure
                                Model: MODEL1
                         Dependent Variable: Grain Yield

                             Analysis of Variance
                                    Sum of           Mean
Source                   DF        Squares         Square    F Value    Pr > F
Model                     2       76.51239       38.25620      17.53    <.0001
Error                    93      202.90741        2.18180
Corrected Total          95      279.41980

             Root MSE              1.47709    R-Square     0.2738
             Dependent Mean        4.85250    Adj R-Sq     0.2582
             Coeff Var            30.43981

                             Parameter Estimates
                                 Parameter       Standard
     Variable     DF              Estimate          Error    t Value    Pr > |t|
     Intercept     1               3.45963        0.29388      11.77      <.0001
     B             1               0.29713        0.09439       3.15      0.0022
     SQB           1              -0.00955        0.00603      -1.58      0.1167
```

Appendix 18. Standards of interpretation for bulk density (g/cm^3, or t/m^3)

Analysis	Rating		
	Low	Medium	High
Bulk density (g/cc)	< 0.9	0.9-1.5	>1.5

Source: Moore, 2001

Appendix 19. Standards of interpretation for total available water content

Analysis	Rating		
	Low	Medium	High
Available water (mm/m)	< 50	50-150	>150

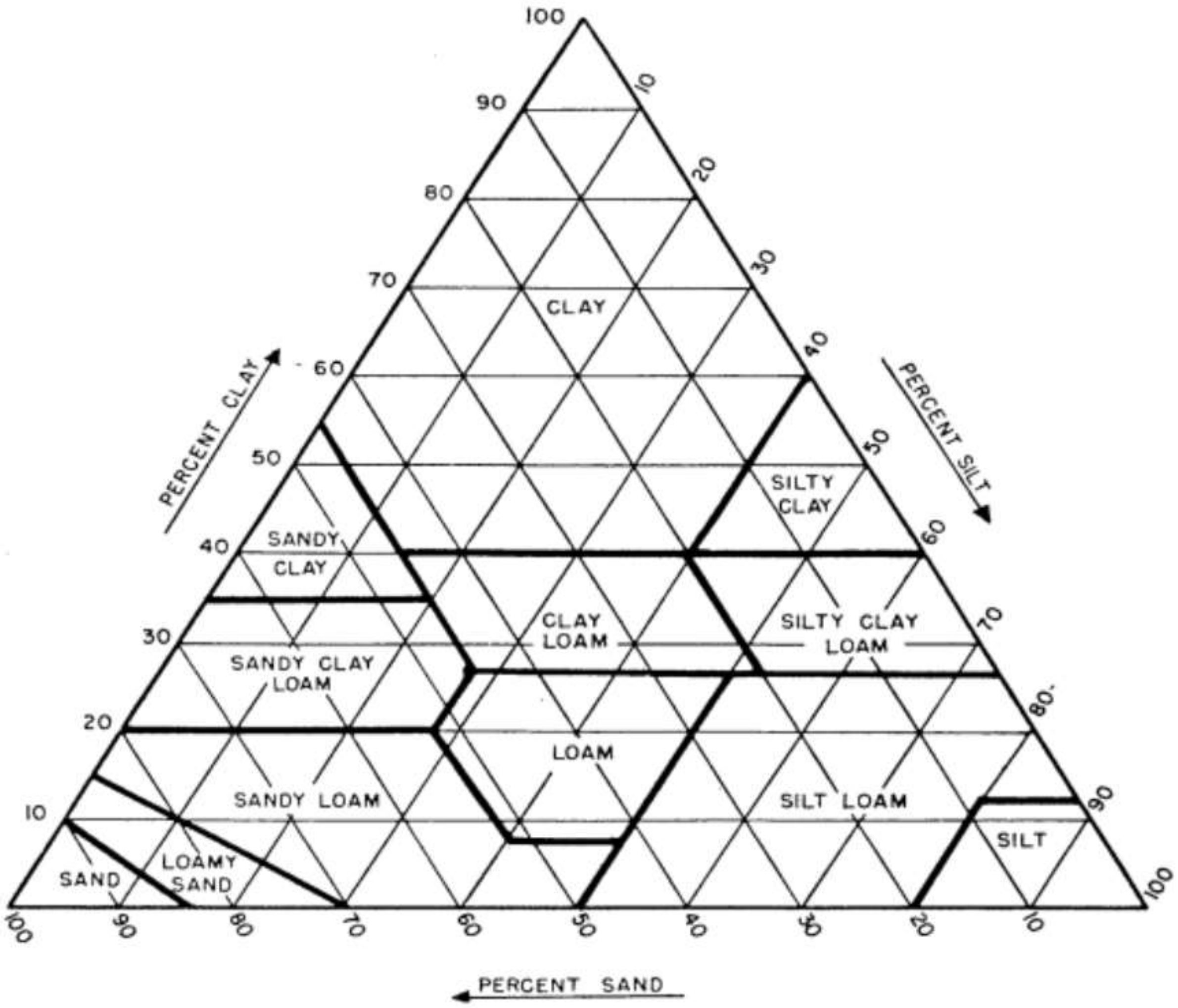
Source: Moore, 2001

Appendix 20. Standards of interpretation for permeability

Analysis	Rating		
	Slow	Moderate	Rapid
Permeability (Ks), mm/hr	< 5	5-130	>130

Source: Moore, 2001

Appendix 21. Textural triangle



Source: Gupta, 2004

Appendix 22. Standards of interpretation for pH

pH	Strongly acid	Very acid	Fairly acid	Slightly acid	Neutral	Slightly basic
pH eau	3.5 – 4.2	4.2 – 5.2	5.2 – 6.2	6.2 – 6.9	6.9 – 7.6	7.6 – 8.5
pH KCl	3.0 – 4.0	4.0 – 5.0	5.0 – 6.0	6.0 – 6.8	6.8 – 7.2	7.2 – 8.0

Source: Landon, 1991

Appendix 23. Standards of interpretation for soil chemical values

Analyze and unity	Mean values	Classification or qualification
CEC (cmol$_{(+)}$/kg de soil)	>40	Very high
	25-40	High
	15-25	Middle
	5-15	Weak
	<5	Very weak
% of bases saturation (ration in % of exhangeable bases and CEC)	>60	High
	20-60	Middle
	<20	weak
Exhangeable bases (cmol$_{(+)}$/kg of sol)		
Calcium	>10	High
	<4	Weak
Magnesium	>4	High
	<0.5	Weak
Potassium	>0.6	High
	<0.2	weak
Sodium	>1	High
	<1	Weak
Organic carbon in %	>10	High
	4-10	Middle
	<4	Weak
Total nitrogen (Kjeldahl) in %	>0.5	High
	0.2 – 0.5	Middle
	<0.2	Weak
Available phosphorus in ppm (for Bray method recommended for acidic soils)	>50	High
	50-15	Middle
	<15	Weak

Source: Landon, 1991

Appendix 24. Scientific contribution: paper published in Agricultural Science Digest

RESEARCH ARTICLE Agricultural Science Digest, Volume 39 Issue 3 (July-September 2019)

Variations in Soil Chemical Properties, Bacteria and Fungi Populations Along Slope Positions and Profile Depths in Terraced and Non-terraced Lands of Rwanda highlands

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Abstract
The objective of the current study was to evaluate the effect of terracing on soil chemical and biological properties in the Rwanda highlands. The study was done in March 2017. Composite soil samples were collected from the top, middle and bottom slopes of four-year-terraced and non-terraced lands, in three profile depths, in medium and high altitudes. Results showed that, levels of organic carbon (1.35, 1.04%) were significantly ($p < 0.05$) higher in non-terraced than terraced land, and populations of bacteria (3.59, 2.61 CFU*$10^6 g^{-1}$) and fungi (2.51, 1.57 CFU*$10^4 g^{-1}$) were significantly higher in terraced than non-terraced land, in the medium-altitude, with no significant differences observed in the high altitude. Soil pH, total N, available P, CEC, exchangeable K^+, Mg^{2+} and Ca^{2+} levels in terraced and non-terraced lands were not significantly different in both altitudes. Thus, soil characteristics and fertility of the study areas showed slight changes after four years of terracing.

Keywords: Cation exchange capacity, Exchangeable bases, Nitrogen, Organic carbon, Phosphorus

Appendix 25. Scientific contribution: paper published in South African Journal of Plant and Soil

South African Journal of Plant and Soil 2020: 01–10

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Effect of land terracing on soil physical properties across slope positions and profile depths in medium and high altitude regions of Rwanda

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Although land terracing is promoted as a management practice for effective soil conservation in hilly areas, construction of terraces causes changes in soil properties. This study evaluated the effect of land terracing on some soil physical properties across slope positions and profile depths in medium and high altitudes of eastern and north-eastern Rwanda. Soil samples were collected from top, middle and bottom slopes of four year-old terraced and non-terraced lands. Results showed that soil textures were mainly sandy clay loams. At medium altitude, silt (19.6, 18.6%) and hydraulic conductivity (237.9, 129.8 mm h^{-1}) were significantly (p < 0.05) higher in terraced than non-terraced land, while clay (29.2, 27.8%) and total available water content (TAWC) (222.2, 201.7 mm m^{-1}) were higher in non-terraced than terraced land. At the high altitude, hydraulic conductivity (194.3, 124.1 mm h^{-1}) was higher in terraced than non-terraced land, while soil bulk density (1.42, 1.35 g cm^{-3}) and TAWC (251.6, 235.3 mm m^{-1}) were higher in non-terraced than terraced land. Terracing increased silt content and hydraulic conductivity, and slightly decreased clay and water retention capacity. These changes are important in soil water and fertility management, and therefore need to be considered when using terraced lands.

Keywords: soil texture, soil water retention capacity, terracing

Appendix 26. Scientific contribution: paper published in Agricultural Science Digest

RESEARCH ARTICLE **Agricultural Science Digest, Volume Issue: ()**

Effects of Nitrogen and Phosphorus Fertilizer Rates on Maize (*Zea mays* L.) Growth and Yields in Terraced Lands of Medium and High Altitude Regions of Rwanda

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ABSTRACT

Depletion of nitrogen and phosphorus in terraced hilly areas of Rwanda has lowered maize (*Zea mays* L.) production. Trials were carried out in 2017 and 2018 in four-year-old-terraced Lixisols and Acrisols of medium and high altitudes to determine effect of nitrogen and phosphorus fertilizer application rates on maize yields. A factorial arrangement of four levels of nitrogen (0, 60, 120 and 180 kg N ha^{-1}) and phosphorus (0, 40, 80 and 120 kg P_2O_5 ha^{-1}) in a randomized complete block design with 3 replications, was used. Results showed that combinations of 120 - 180 kg N ha^{-1} and 80 - 120 kg P_2O_5 ha^{-1} resulted in significantly ($P < 0.05$) higher increases in plant height (45 – 60 % and 56 – 70 % over the control), stem collar diameter (63 – 74 % and 43 % over the control) and grain yields (3 times over the control; i.e. 6.40 – 6.46 t ha^{-1} and 6.02 - 6.12 t ha^{-1}) in medium and high altitude sites. The optimum fertilizer rates are 176.6 kg N ha^{-1} and 96.2 kg P_2O_5 ha^{-1} in terraced Lixisols of medium altitude area. Land use needs to adjust fertilizer application to these optimum rates for enhanced maize yields in this area and other regions with similar agro-ecological characteristics. Further studies on integrated effects of N and P fertilizers are recommended.

Key words: Acrisols, Grain yield, Lixisols, Nitrogen, Phosphorus

Appendix 27. Research permit

REPUBLIC OF KENYA

NATIONAL COMMISSION FOR SCIENCE,TECHNOLOGY & INNOVATION

Ref No: **453018**

Date of Issue: **06/November/2019**

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