PEDOLOGICAL CHARACTERIZATION AND SUITABILITY ASSESSMENT OF SOILS OF MATI MUBONDO FARM, KIGOMA TANZANIA FOR MAIZE AND BEANS PRODUCTION

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EXTENDED ABSTRACT

The study was carried out at MATI Mubondo Farm located at Kasulu district in Kigoma region, Tanzania to examine soil morphological, physico-chemical and biological properties, as well as carrying out soil classification, suitability assessment (potential and limitations) for maize and beans production, and nutrients recommendation. The reconnaissance field survey of 800 ha was conducted at the study area in late December 2019 to mid-January 2020. Six sampling units were identified based on soil variation and features such as color, slope, vegetation and agronomic practices. Six profiles namely MBD-P1, MBD-P2, MBD-P3, MBD-P4, MBD-P5 and MBD-P6 were excavated, studied and 20 soil samples were collected and analyzed. All profiles were very deep, highly weathered, well drained and clayey. Color ranged from very dusky red to dark reddish brown. Topsoil bulky density ranged from 1.20 to 1.47 gcm^{-3}. The surface soil pH ranged from 4.59 (very strong acid) to 5.6 (moderately acid) and subsoils pH ranged from 4.0 (extremely acid) to 5.45 (strongly acid). Topsoil OC ranged from 1.56 (medium) to 6.47 (high) and subsoil ranged from 0.35 (low) to 2.81 (medium) for subsoils. TN ranged from 0.13 (medium) to 0.31 (high) percent for topsoil and 0.04 (low) to 0.15 (medium) percent for the subsoil. Available P for all the profile was rated low (0.67-7.19 mg kg^{-1}) in topsoils and 0.34-8 mg kg^{-1} in subsoils. CEC (cmol(+) kg^{-1}) for the topsoils were 13 (medium) to 36 (high) and 5.2 (very low) to 22 (medium) for subsoils. BS of the top soil range from 10 (low) to 34 (medium) and subsoil range from 7.67 (low) to 41 (medium). Using the USDA Soil Taxonomy, soils were classified as *Typic Haplustox* (MBDP1), *Kanhaplic Rhondustalfs* (MBDP2), *Typic Kandiustox* (MBDP3 and MBDP4), *Typic Ustorthents* (MBDP5) and *Rhodic Kandiustox* (MBDP6) and corresponding to *Rhodic umbric Ferralsols (Clayic, Dystric)* (MBDP1), *Umbric Ferralsols (Clayic, Dystric)* (MBDP2), *Rhodic Umbric Ferralsols (Clayic, Dystric)* (MBDP3), *Rhodic Umbric Ferralsols (Clayic, Dystric* (MBDP4), *Rhodic*

Cambic Ferralsols (Clayic Dystric) (MBDP5) and *Umbric Ferralsols (Clayic, Dystric)* (MBDP6) in WRB. The quality of soils was rated marginally suitable (s2) and moderately suitable (s1) for both crops due to the identified limitations. The most limiting factors for the crop production being low pH, available phosphorus, total nitrogen and base saturation. The low pH of the soil might have attributed to the deterioration of other soil chemical properties in the farm. The study also generated the suitability map by kriging method where by top soil macronutrients, CEC, pH and % BS were used in geographic information system (GIS) environment. Nutrient recommendations were done for each soil unit by referring the soil test results. The buildup and maintenance approaches for nutrient recommendations were proposed. Soils were dominated by kaolinitic clay and sesquioxides and had low inherent fertility. Routine soil analysis, nutrient amendments, suitability of soils in quantitative terms and determination of nutrients available in grains and cobs of maize were recommended.

DECLARATION

I, Nicholaus Pius Mwakinyala, do hereby declare to the Senate of Sokoine University of Agriculture that this dissertation is my own original work done within the period of registration and that it has neither being submitted nor concurrently being submitted in any other institution.

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Dr. Boniface H. J. Massawe Date

(Supervisor)

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DEDICATION

I dedicate this work to my mother and father Getruda Jeremiah Kangalawe and Pius John Mwakinyala for laying the foundation of my education profile.

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LIST OF ABBREVIATION AND SYMBOLS

AAS	Atomic Adsorption Spectrophotometer
AEZ	Agro-ecological zone
BCSR	Basic Cation Saturation Ratio
BD	Bulk density
BS	Base Saturation
C	Carbon
Ca	Calcium
CEC	Cation Exchange Capacity
Cl	Chloride
Cmol	Cent mole
Cu	Copper
dS/m	deciSiemens per metre
DTPA	Diethylene Triamine Pentaacetic acid
EC	Electrical Conductivity
ESP	Exchangeable Sodium Percent
EW	Equivalent weight
FAO	Food and Agriculture Organization
Fe	Iron
FP	Flame Photometer
g	gram
GAP	Good agricultural practices
GPS	Global Positioning System
Ha	Hectare
IUSS	International Union Soil Sciences
K	Potassium

kg	kilogram
MATI	Ministry of Agriculture Training Institute
MBDP	Mubondo Profile
Mg	Magnesium
mg	milligram
Mn	Manganese
MOA	Ministry of Agriculture
N	Nitrogen
Na	Sodium
nd	not determined
no.	number
OC	Organic Carbon
OM	Organic Matter
P	Phosphorus
pH	Potential Hydrogen
RSG	Reference Soil Group
S	Sulphur
ST	Soil Taxonomy
t	Tonne
TEB	Total Exchangeable Base
TN	Total nitrogen
USDA	United State Department of Agriculture
WRB	World Reference Base
Zn	Zinc
ΔpH	Change in potential Hydrogen

CHAPTER ONE

1.0 INTRODUCTION

1.1 Background Information and Justification

Soil is one of the most important natural resources (de Melo *et al.,* 2001). The scientific study which provides information and knowledge on soil characteristics is known as pedological characterization (Alemayehu *et al*., 2014; Abera *et al.,* 2016; Mtama *et al*., 2018). The study involves collecting and delineating different soils in the area and gives clear understanding of soil genesis and pedogenic factors as put forward by Jenny (1941), namely; parent material, climate, organisms, topography and time (Kalala *et al*., 2017).

Soil morphology is the field observable attributes of the soil within the various soil horizons and the description of the kind and arrangement of the horizons (Jahn *et al.,* 2006). The observations are usually done on a soil profile, which is the vertical cross-sectional view of the soil (Balasubramanian, 2017).

Soil classification is the systematic arrangement of soils into groups or categories on the basis of their properties (chemical, physical and biological), which vary widely according to several soil forming factors (Msanya, 2003).

Soil classification is done for the purposes such as; theoretical or scientific, which emphasize the origin of soils and their relationships. As a result of the organization of ideas there is an overall advancement of soil science and also of practical importance, which are aimed at the application in agricultural or other technological uses of soils. The gathering of data on soils and the arrangement in an order allows discussion and communication about properties which link with the behavior of soils under specific use or management (De Bakker, 1970).

Spatial distribution of soils in an area is the natural phenomena whereby soil properties vary from one place to another under the influence of soil forming factors and soil management practices (Daniel *et al*., 2017). In pedological characterization, soil profiles are dug, described, horizons are identified and assigned symbols according to the observed physical properties, and soil samples of each horizon taken and prepared for laboratory analysis (Edmonds, 2006). Soil characterization data are important for soil classification, nutrients management planning, allocation and introduction of crops to the area (Msanya, 2003; Alemayehu *et al*., 2014).

MATI Mubondo Farm has been under extensive maize and beans production for many years. Recently, it has been noted that, there is a trend of decline of yields that might be caused by deterioration of soil physical and chemical properties (Ray *et al*., 2012), antagonistic effects of plant nutrients (Rietra *et al*., 2017), inappropriate nutrient recommendations (Bekunda *et al*., 2002), allelopathic effects between plants (Shah *et al*., 2018), pests and diseases affecting food crops causing significant losses to farmers and threatening food security (Donatelli *et al*., 2017).

1.2Problem Statement and Justification

Despite using fertilizers, yields for maize and beans are decreasing at Mubondo farm. The average current yields are 1.25 t ha^{-1} and 0.3 t ha^{-1} for maize and beans respectively while the potential yields if the farm is well managed is 5 t ha^{-1} and 2 t ha^{-1} for maize and beans respectively (Binagwa *et al*., 2016; Cameron *et al*., 2017). The poor performance of the crops may be due to deterioration of physical and chemical properties of soil as a result of inappropriate soil management.

MATI Mubondo farm has no detailed soil characterization analysis and suitability evaluation for cultivation of crops. Therefore, characterization of the soil of this farm is essential in order to be acquainted with the physical, chemical characteristics and their suitability (Taghizadeh-Mehrjardi *et al.*, 2020). Hence, there is a need for generation of site-specific information of the soils in order to come up with the source of problem and propose management strategies to improve crop production.

The information obtained will be used for decision making on suitable management practices such as nutrient recommendations, diversification of crops, facilitation on proper land use and for training purposes. Currently, the fertilizer rates used for maize and beans were adopted from the rates issued for the cotton in 1982, for only two nutrient elements which are nitrogen and potassium (Senkoro *et al.*, 2017).

1.3 Objectives of the Study

1.3.1General objective

The general objective of this study was to appraise the fertility status of the soils of MATI Mubondo farm for improved and sustainable production of maize and beans.

1.3.2 Specific objectives

The specific objectives of the proposed study were:

i. To characterize and classify soils of MATI Mubondo Farm
ii. To assess the suitability of soils for maize and beans production.
iii. To generate site and crop specific nutrients recommendations rates for maize and beans.

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CHAPTER TWO

2.0 LITERATURE REVIEW

2.1 Soil

Soil is a living, naturally occurring dynamic system at the interface of air (atmosphere) and rocks (lithosphere). It is a mixture of organic matter, minerals, gases, liquids and organisms (Stephen *et al*., 2017). The soil is living because it is capable of supporting the life of plants and other living organisms (micro and macro). Soil organisms are well known for their huge diversity and contribution to maintenance of soil fertility, though agricultural practices threaten biodiversity and long-term sustainability of agricultural production itself through conversion of natural habitats to croplands and use of agrochemicals (Saxena *et al.,* 2014).

Soil is the most essential constituents to satisfy the basic needs of human being as an important component of farming (Kekane *et al.*, 2015). Nowadays there is an increasing demand for information on soils as a means to increase production of food to feed the growing population (Merumba *et al.,* 2020). The knowledge on the land for agriculture and its suitability is important since it will help to guide investment opportunities and strategies for enhanced people’s livelihood (Kimaro and Hieronimo, 2014). The best utilization of soil depends on knowledge and the reason for application of that knowledge regarding the nature, properties, extent and location of the soil (Stephen *et al*., 2017).

2.2 Pedological Characterization

Pedology is the study of soils in their natural environment. It is important for applications of soils data in agriculture, agroforestry, environmental issues and land use planning (Brevik *et al.*, 2015). Pedological characterization is very important in providing valuable information on soil physio-chemical, mineralogical and biological characteristics, classification, soil fertility assessment and fertilizer recommendations (Uwingabire, 2016; Tenga *et al*., 2018). It gives clear understanding of soil genesis, morphology, spatial distribution in an area as well as their potential and limitations for crop production (Kalala *et al*., 2017). With increase in farming activities, plant nutrient depletion become prominent and interferes with the agricultural production (Uwingabire, 2016; Tenga *et al*., 2018).

Pedological characterization that its objective is to make an inventory of the soils of the area, have been done in some places in Tanzania such as the southern highland zone (Mtama *et al*., 2018) and Morogoro region (Kalala *et al.*, 2017). Additionally, other works have been done in Tanzania by Msanya (2003), Kaaya (2003), Kimaro (1999), Meliyo (1997), Massawe (2015), Shepherd (2010) and Walsh *et al.* (2020).

2.2.1 Soil genesis

Genesis (origin) of soil describes in details the formation of soil from rocks under the influence of pedogenic (soil forming) factors (Hartemink and Bockheim, 2013). Soil formation is a global biospheric process, and as a result of its manifestation a soil attains a number of characteristics, which are absent in soil forming rock and those distinguish soil from other components of the biosphere (Vladychenskiy, 2004). Soil forming process takes place due to the interaction of five major factors, according to Jenny (1941), which are time (T), climate (C), parent material (P), topography or relief (R), and organisms (O) as expressed in the following equation:

$$S = f(C, O, R, P, T\ldots) \quad (1)$$

Human activities that result in soil changes are considered a sixth factor, although they are not included in Jenny's equation because it just the activities of other organisms such as clearing forests, expanding agriculture, addition of manures, composts and inducing erosion (Bockheim and Hartemink, 2017). The relative influence of each factor varies from place to place, but the combination of all five factors normally determines the kind of soil developing in any given place (Jenny, 1983). According to Certin (2014), fire is also considered as a soil forming factor as par with the other factors showed in equation (1). From rocks to the formation of a soil, the processes involved are combined as follows:

$$\textbf{Rock and minerals} \xrightarrow{\textit{weathering processes}} \textbf{Parent material} \xrightarrow{\text{soil } \textit{forming factors}} \textbf{Soil}\ldots(2)$$

2.2.1.1 Climate

Climate is important factor in soil formation. It determines soil formation with moisture (atmospheric precipitation) and solar radiation (energy). Climate influences the soil development or formation through differences in mean annual, seasonal, and extremes in temperature and moisture. Temperature affects the rate of large number of chemical reactions which approximately doubles for every 10^0C rise (Jenny, 1983). Temperature and rainfall affect organic matter decomposition and microbial activities occurring in soil. These conditions determine the extent of processes taking place in the soil. Favorable hydrothermal (moisture and temperature) conditions have influence upon communities of flora and fauna, increasing their productivity which finally has effect on intensity of soil formation (Jenny, 1983; Vladychenskiy, 2004; Bockheim and Hartemink, 2017).

2.2.1.2 Parent material

A geological deposit over, and within which a soil develops is termed as soil parent material (Lawley, 2009). The parent material characteristics dictate the chemical, physical, mineralogical and composition of the resulting soil (Jenny, 1983; Vladychenskiy, 2004; Bockheim and Hartemink, 2017). Acid igneous rocks and sandstones weather to form coarse sandy soils with low base status characterized by kaolinitic clays, while most of the basic igneous rocks and sedimentary rocks normally weather to fine textured soil with high base status dominated by montmorillonitic clays (Urio *et al*., 1979). Rocks are primary parent materials, others like alluvial, aeolian and colluvial deposit are secondary (Jonathan and Brian, 2002).

2.2.1.3 Organisms

The function of organisms in the soil formation is extensive and diverse. Organisms are only source of organic substances which serves as a material for formation of soil humus. Plant roots break rocks when it grows, animal influence soil development by burrowing and pedoturbation (Bockheim and Hartemink, 2017). Another important function of organisms is based on the ability of living for selective absorption of elements, therefore determine the chemical composition of the soil (Jenny, 1983; Vladychenskiy, 2004).

2.2.1.4 Topography (Relief)

This refers the configuration of the land surface that includes slope, aspect, and position of site. The topographic designations employed in pedology are level or flat, undulating, rolling, hilly and mountains. Topography exerts action on soil formation by both directly, by influencing movement of soil masses along slope, erosion and deposition processes, and indirectly, redistributing heat and moisture (climate modifier) by its elements and thus forming original climatic condition (Vladychenskiy, 2004). On upland areas, there is a greater incidence of cloudiness and hence, less solar radiation and evapotranspiration a condition favoring the development of thicker organic horizons. Soils formed on slopes facing the sun are different from those on the opposite side, therefore influencing the nature and characteristics of the resulting soil profile. On steep slopes, soil profiles are usually young and not well developed because of lack of water entering the soil due to slope (Bockheim and Hartemink, 2017).

2.2.1.5 Time

Generally, the large the number of horizons and the greater their thickness and intensity the more mature is the soil (Jenny, 1983). All the five soil forming factors are interacting over time and cause a range of soil processes that result in diversity of soil properties (Bockheim and Hartemink, 2017). Therefore, the length of time required for a soil to develop horizons depends upon inter-related factors such as climate, nature of the parent material, organisms present in the area and relief (Schoonover and Crim, 2015).

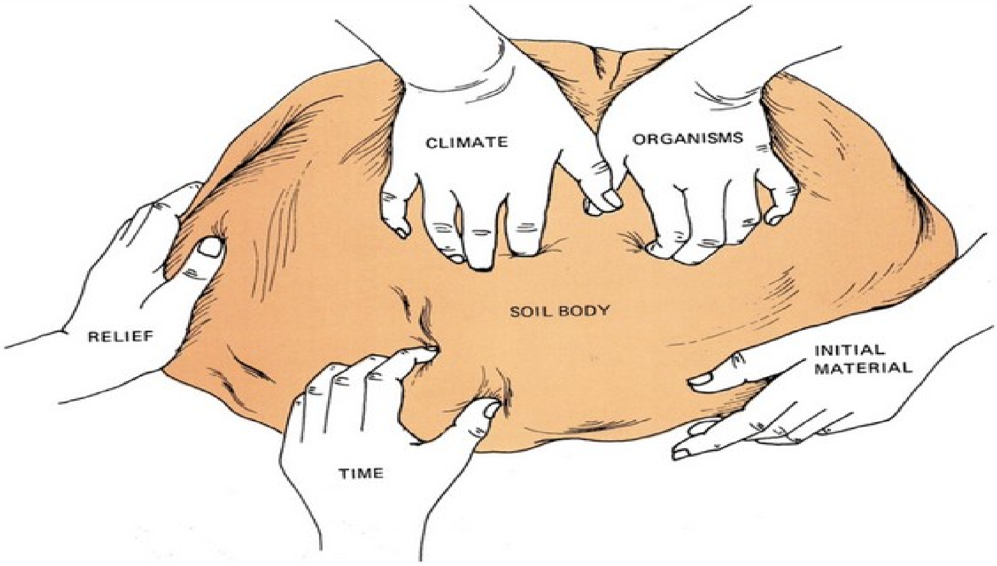

Figure 2.1: The five soil-forming factors

Source: Bockheim and Hartemink, 2017

2.2.2 Soil morphology

The branch of soil science that deals with the description, using standard terminologies, of *in situ* spatial organization and physical properties of soil is termed as soil morphology (Hillel and Hatfield, 2005). It is concerned with the field observable attributes of the soil typically done on a soil profile and the description of the kind and arrangement of the horizons (Holliday, 2016). The observable attributes generally described in the field are composition, form, soil structure, soil color and features such as mottling, distribution of roots and pores (Jahn *et al.*, 2006). Also, evidence of translocated materials such as carbonates, iron, manganese and clay, consistence and gilgai (Mermut *et al.*, 1996).

Soil profile

Soil morphology determination is usually done on a soil profile, which is the vertical cross-sectional view of the soil. When exposed, various soil horizons of soil become apparent. Soil horizons are zones within the soil (subdivisions of the soil profile) that parallel the land surface and have distinctive physical, chemical and biological properties (Holliday, 2016). Depending on the environment, soil profiles can have five major horizons designated as O, A, B, C, E and R, and sometimes suffixes are added for special features of horizons which are normally in small letter (example b for buried horizon). Each horizon differs from the other layer currently below or above it in physical and/or chemical ways (Holliday, 2016). Soil profile description forms the basis for understanding and communicating soil properties among soil scientists and other professionals (Edmonds, 1991).

2.2.3 Soil classification

Soil classification is the systematic arrangement of soils into groups or categories on the basis of their properties (chemical, physical and biological), which vary widely according to several soil forming factors (Msanya, 2003). It is an important component of pedology, which is the categorization of soils into groups at varying level of generalization according to their morphological, physical and chemical properties (Holliday, 2016).

Soil classification is done for the purposes of grouping soil with similar properties, to facilitate communication between scientists for comparison, exchange and extrapolation of soil information, results and experience on various applications, and improve scientific understanding of the genesis of soil by reflecting the relationship between soils and environment (Nikiforova, 2019). As a result of the organization of ideas, there is an overall advancement of soil science and also of practical importance, which are aimed at the application in agricultural and other technological uses of soils. The gathering of data on soils and the arrangement in an order allows discussion and communication about properties which link with the behavior of soils under specific use or management (Schoonover and Crim, 2015).

There are many soil classification systems in the world, some of which being national and others international in terms of their usage (Msanya, 2003). Some National systems enjoy International recognition and usage. These include United States Soil Classification System, *Office de la Recherche Scientifique et Technique Outre-Mer* (*ORSTOM-French*), Canadian Soil Classification System and Australian System of Soil classification.

In Tanzania, the two principal systems of soil classification in use today are the Soil System of Classification of the United States (Soil Taxonomy) (Soil Survey Staff, 2014) and the World Reference Base (WRB) for Soil Resources, developed by the Food and Agriculture Organization (FAO) of the United Nations (FAO, 2015).

Soil Taxonomy is the system of soil classification used for mapping and classifying soils by the National Cooperative Soil Survey (NCSS) in the United States and other countries (Ditzler and Hempel, 2016). Soil taxonomy is a hierarchical soil classification system with six categories; order, suborder, great group, subgroup, family, and series.

The WRB comprises of two levels; the first level having 32 soil Reference Soil Groups (RSGs) and the second level, for further differentiation a set of qualifiers is added to the to the name of the RSG. There are 185 qualifiers in total which are subdivided into principal qualifiers describing typical characteristics of RSG and supplementary qualifiers, describing additional characteristics. Principal qualifiers are ranked and given in an order of importance and placed before the name of the RSG, while supplementary qualifiers are not ranked and used in alphabetical order, and placed after the name of the RSG in brackets and separated from each other by commas (FAO, 2015).

2.2.4 Spatial distribution of soil

Spatial distribution of soils in an area is the natural phenomena whereby soil properties (chemical and physical) vary in space (from one place to another) and are influenced by soil forming factors and soil management practices (Rubinic *et al.,* 2017). Jenny (1941), cited by Wills (2005), emphasized the importance of human impact through cultivation on the five stated soil forming factors: climate, organisms, topography, parent material and time. Bockheim and Hartemink (2017) cites examples of cultivation practices which cause changes on individual soil properties such as bulky density and soil structure are burning, changing vegetation and erasing micro-relief. Soil structure influences plant growth factors such as water supply, aeration, availability of plant nutrients, heat, root penetration and microbial activities (Phogat *et al.,* 2015). The suitability of soils for agriculture depends mainly on the interrelationship between these factors (Rubinic *et al., 2017*). Additionally, it has been established that, cultivation increases bulky density (Wills, 2005), which in turn influence root growth, depending on soil texture and organic matter content (Tamm *et al*., 2016).

Land use change has a significant impact on soil properties and in some cases, it is considered to be among the main threats to soil quality. The productivity and sustainability of soil in an area depends on dynamic equilibrium among its physical, chemical and biological properties which are continuously influenced by various land uses (Nanganoa *et al.,* 2019; Zajícová and Chuman, 2019). Variation in soil properties in the field contributes to the variation in water retention, availability, transport, and storage of nutrients (Daniel *et al*., 2017).

2.3 Assessment of Soil Suitability for Maize and Beans

Soil suitability analysis bring about identification of the main limiting factors for the agricultural production and enables decision makers to develop crop managements to increase the soil productivity (Alemayehu *et al.*, 2016; Narayanaswamy *et al.*, 2017). To make soil resources productive and achieve optimal crop production, it is essential to commit the most suitable soil to a specific soil use (Sharififar, 2012). The assessment of soil is carried out to determine their suitability for specific uses in this case for maize and beans production. Assessing the suitability of soils for crop production, requirements for crops must be known within the context of limitations imposed by the soil and other features which do not form a part of the soil such as water logging, slope and erosion risk (Grealish *et al*., 2008). For most crops, soil characteristics have been identified for high, moderate, marginal and unsuitable levels. Soil suitability classifications are established by matching requirements for crops and soil qualities (Maniyunda and Gwari, 2014). Soil suitability can be assessed for present condition (Actual soil Suitability) or after improvement (Potential Soil Suitability) (Msanya *et al.,* 2001).

There are two kinds of land suitability evaluation approaches: qualitative and quantitative. A qualitative approach is a narrative statement of soil suitability for particular uses. Soil is grouped into a subjective way of small number of suitability classes based on experience and intuitive judgement such as highly suitable, moderately suitable, or not suitable (De la Rosa and Van Diepen, 2002). In the second approach, quantitative, assessment of soil suitability is given by numeric indicators, in such a way that quantitative expression of inputs and outputs are given (De la Rosa and Van Diepen, 2002; Kurtener, *et al.*, 2008).

2.4 Nutrient Recommendations

Recommendation means advice from a soil or crop specialist on amount, form and period to apply fertilizer to a soil to benefit growth of crop (s) (Yost *et al*., 2000). Nutrient recommendations refer to the way conclusions are drawn based on soil tests. In the farm and Kasulu District as whole, no detailed soil analysis has been done recently (Kasulu District Agricultural Officer, personal communication, 2019). The Nutrient recommendations in use were issued in 1982 as blanket recommendations (Samki and Harrop, 1984; Senkoro *et al.*, 2017). These nutrient recommendations for Tanzania were based on farming systems and agro-ecological zones. Western zone (Kigoma and Tabora regions) rates issued vary depending on the soil texture as 20-60 $kgNha^{-1}$ and 15-30 $kgPha^{-1}$. These rates were cotton based for two nutrient elements only nitrogen and phosphorus (Bekunda *et al*., 2002).

Although Maize (*Zea mays L*) and common beans (Phaseolus vulgaris L) are major crops in Kasulu district (Urassa and Magweiga, 2017; Kasulu District Agricultural Officer, personal communication, 2019), there are no current fertilizer recommendation rates. Hence, the average yield of maize is 1 - 1.5 t ha^{-1} compared to the optimum yield of 3.25 – 5 t ha^{-1} (Cameron *et al*., 2017). The average yield of beans is 0.1 – 0.5 t ha^{-1} compared to the optimum yield of 1.5– 2 t ha^{-1} (Binagwa *et al*., 2016). It is envisioned that use of appropriate recommendation rates of fertilizer will boost yield significantly in the farm and district in general.

However, the information about the soil which is essential for the requirements of the crops has to be known (Maniyunda and Gwari, 2014). Soil fertility specialist engaged in transferring agronomic technologies require well characterized data of the entire pedon (Kalala *et al*., 2017). The real time information of soil will help to recommend right fertilizer (s) to right crop (s), right rates and right time of application ending up with benefit from the fertilizer purchased (Senkoro *et al.,* 2017).

Maintaining soil quality to attainable crop yield requires application of adequate amount of fertilizers and minimizes the misuse of soil resources which is possible by knowing actual situation of soil physical, chemical and biological condition through observation, investigation and soil testing. Soil testing is an imperative tool for assessing the fertilizer requirement for sustainable production of crops and for sustaining soil fertility (Sultana *et al*., 2015). Improved management of soil resources and identification of the potential agricultural capability of soils is therefore needed to prevent soil degradation and maximize production (Abd-Elmabod *et al*., 2019).

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CHAPTER THREE

3.0 PEDOLOGICAL CHARACTERIZATION AND CLASSIFICATION OF THE SOILS OF MATI MUBONDO FARM, KIGOMA TANZANIA

3.1 Abstract

Pedological characterization covering an area of 800 ha was carried out at MATI Mubondo farm, Kasulu, Kigoma. The characteristics of the site were identified during the transect walk and used for determination of six sampling units. Six soil profile pits namely MBDP1, MBDP2, MBDP3, MBDP4, MBDP5 and MBDP6 were excavated, described and sampled for laboratory physico-chemical analysis. Topsoil bulky densities were determined and ranged from 1.20 to 1.47 gcm^{-3}. The profiles were deep, highly weathered and clayey. The surface soil pH ranged from 4.59 to 5.6 and subsoils from 4.0 to 5.45. Soil OC of the top soil ranged from 1.56 to 6.47 and subsoil ranged from 0.35 to 2.81. TN ranged from 0.13 to 0.31 percent for topsoil and 0.04 to 0.15 percent for the subsoil. Available P for all the profiles were rated low. CEC (cmol(+) kg^{-1}) for the topsoils were 13 to 36 and 5.2 to 22 for subsoils. BS of the top soils ranged from 10 to 34 and subsoil from 7.67 to 41. Using the USDA Soil Taxonomy, soils were classified as *Typic Haplustox* (MBDP1), *Kanhaplic Rhondustalfs* (MBDP2), *Typic Kandiustox* (MBDP3 and MBDP4), *Typic Ustorthents* (MBDP5) and *Rhodic Kandiustox* (MBDP6) and corresponding to *Rhodic umbric Ferralsols (Clayic, Dystric)* (MBDP1), *Umbric Ferralsols (Clayic, Dystric)* (MBDP2), *Rhodic Umbric Ferralsols (Clayic, Dystric* (MBDP3), *Rhodic Umbric Ferralsols (Clayic, Dystric)* (MBDP4*)*, *Rhodic Cambic Ferralsols (Clayic Dystric)* (MBDP5) *and Umbric Ferralsols (Clayic, Dystric)* (MBDP6) in WRB. Almost all the studied soils were clayey but well drained since it is dominated by kaolinitic clay which has the tendency of aggregating into strong grade of fine and very fine granular structure which exhibit the properties of

coarser soils. Soils were low in inherent fertility and nutrient reserve due to leaching. To sustain yields, application of fertilizers, limes and manures is needed.

Keywords: Pedological characterization, reconnaissance survey, soil profile, composite sample, soil classification.

3.2 Introduction

Agriculture is among major contributors to Tanzania's economy. Almost 65.5 percent of Tanzanians live in rural areas and nearly all of them are involved in the agricultural sector. However, agricultural productivity has been falling mainly due to population pressure, land degradation and climate change (Kimaro and Hieronimo, 2014). Land degradation is the temporary or permanent lowering of the productive capacity of land, due to soil fertility decline associated to deterioration in physical, chemical and biological soil properties (Moges and Gebregiorgis, 2013; Bado and Bationo, 2018).

Pedological characterization provides knowledge and information on soil characteristics i.e. physical, chemical and biological, and gives clear understanding on soil genesis, morphology, classification and spatial distribution of soil in an area (Kebeney *et al.*, 2014). Therefore, correct information generated show the potential of the soils and appropriate management practices required to bring positive changes in the agricultural sector (Msanya *et al*., 2001; Manda, 2002), and can be easily extrapolated to other areas with the same geographical setting (Kebeney *et al.*, 2014). Knowledge of characterized physical and chemical soil properties with other ecological conditions will assist in determining the correct types and amount of fertilizers to be applied for optimum crop production and maintenance of required soil fertility (Kebeney *et al.*, 2014). Also, pedological characterization help to identify problem soils i.e. soils which present special difficulties for agriculture because of one or more unfavorable soil properties such as saline soils, sandy soil, strongly acid soils, shallow soils or poorly drained soil (Beek *et al.,* 1980; Alemayehu *et al.,* 2016).

MATI Mubondo is among 14 Training Institutes of Agriculture under Ministry of Agriculture Tanzania. Their roles are training of extension workers, disseminating agricultural technologies and information to the surrounding communities with similar ecological conditions through demonstration plots of the crops. Therefore, pedological characterization was carried out to identify potentials and constraints of the farm for the production of maize and beans, since no scientific study to characterize and classify the soil in this area and surrounding has been done. The information obtained will be extrapolated to other areas with similar ecological setting.

3.3 Materials and Methods

3.3.1 Description of the study area

The study was conducted at MATI Mubondo farm, which is located 14 kilometers, South East of Kasulu township. The farm has an area of about 800 hectares. The vegetation of the area is mainly miombo woodland (*Brachystegia* spp). The farm is used for production of maize and beans as major crops (Urassa and Magweiga, 2017). Other crops grown in the area are sunflower, cassava, sweet potatoes, bananas and vegetables. Also, MATI Mubondo runs animal keeping and training activities. Average annual temperature, rainfall and humidity are 20.7°C, 1 184 mm and 72.3% respectively, elevation is 1240 m above mean sea level. The farm lies between longitudes 30.18588°E to 30.19249°E and latitudes 4.50777°S to 4.54282°S. The rainfall pattern is characterized as unimodal and rainfed agriculture is a dominant cultivation practice. Soil samples were taken from areas currently under cultivation, abandoned land overgrown with trees and shrubs and areas under fallow for the past years.

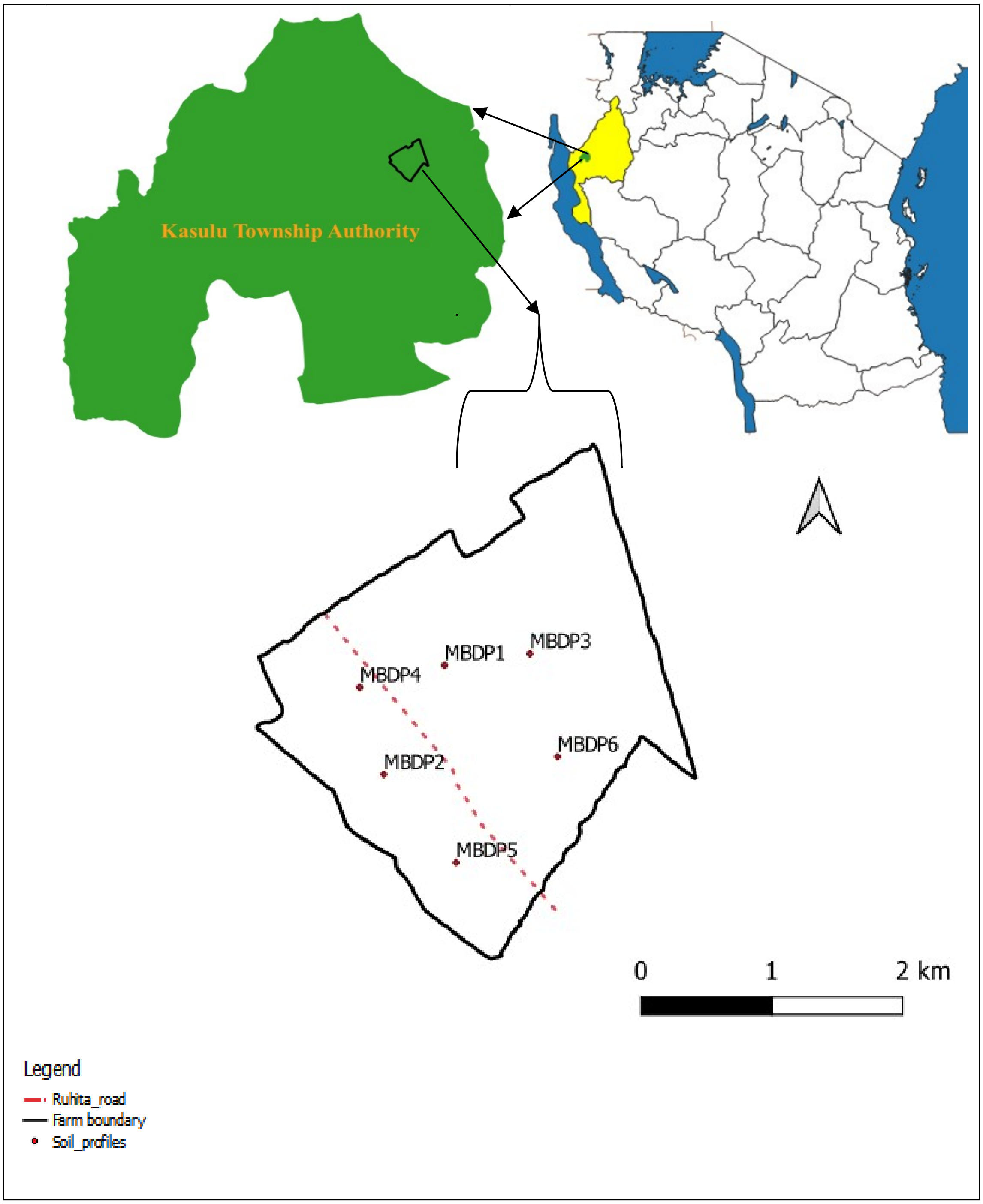

Figure 3.1: Location of MATI Mubondo farm

3.3.2Pedological characterization of the study area

3.3.2.1 Pre-field work

Tools and equipment for field survey were mobilized including GPS (GARMIN etrex 20), notebook, digital camera, soil auger, Guideline for soil profile description, Munsell soil-color chart, profile description forms, satellite image, marker pen, sampling bags (zipped), profile tape, hand hoe, panga, knife, core sampler, compass, water bottle, spade and measuring tape. Manpower also was mobilized i.e. the people who dug the soil profile pits and assisted the whole survey work. Base map was not used during the conduct of this study. Satellite image was used as aid to identify some parts of the area.

3.3.2.2 Field work

The reconnaissance field survey was carried out between late December 2019 and mid-January 2020, and the key characteristics of the site were recorded. It involved augering and description along the transect on the farm, to gain understanding of the soils of the area and taking note on soil variation features such as soil color, soil texture, slope, vegetation, landform, morphological characteristics and agronomic practices. Six soil units (sampling units) were determined in areas under cultivation, forest and abandoned land. The boundaries of the farm were georeferenced and coordinates were taken using GPS. The coordinates of the boundaries were used to generate the map of the study area.

3.3.2.2.1 Soil sampling and preparation

Six soil profile pits namely; MBDP1, MBDP2, MBDP3, MBDP4, MBDP5 and MBDP6 (20 horizons) were opened in the six sampling units, geo-referenced using GPS, and described using guideline for soil profile description (FAO, 2006). Soil samples were collected and labeled according to the name assigned to the horizon and width example, MBDP1: Ah (0-15cm) and A/B (15-26/34cm) etc. Six undisturbed topsoil samples (one from each sampling unit) were taken by core sampler.

3.3.2.2.2 Laboratory soil analysis

Undisturbed soil samples collected using core samplers were used for bulk density determination after oven drying (105 °C) for 48 hours. Disturbed soil samples (20 samples) were air dried, ground and sieved through 2 mm mesh sizes prior to analysis (Gupta *et al.*, 2012; Alemayehu *et al.,* 2014). Air drying, was the means of soil sample preservation before analysis since it reduces the rate of possible reactions in the disturbed soil sample (Tan, 2005). Grinding and sieving operations ensure a homogeneous mixture for analysis (Gupta *et al.,* 2012). The selected physical and chemical properties of the soils in the laboratory were determined, including particle size analysis that done by hydrometer method (Bouyoucos, 1935), whereby the samples were treated with 5% sodium hexametaphosphate (Calgon) to break and replace Ca^{++}, Al^{3+}, Fe^{3+}, and other cations that bind clay and silt particles into aggregates with Na^{+} which results into smaller soil separates. The soil particles were dispersed into individual primary particles of sand, silt and clay, fractionated and quantified (Ashworth *et al.,* 2001; Moberg, 2001). Sand, silt and clay were calculated from the density of aqueous soil suspension and soil textural classes were accomplished using USDA textural triangle (Davis and Bennett,1927; Moberg, 2001).

Soil pH was measured in water and 0.01 M $CaCl_2$ at a ratio of 1:2.5 soil-water and soil-$CaCl_2$ by dipping the reference and hydronium ion sensitive electrode in a soil solution mixture (Moberg, 2001). Electrical conductivity was determined in 1:2.5 soil water suspension potentiometrically, using an electrical conductivity meter (Frenkel and Rhoades, 1978; Moberg, 2001). Organic carbon (OC) was determined by Walkley and black wet oxidation method, through which organic matter (OM) was determined by multiplying organic carbon by factor of 1.724 (Nelson and Sommers, 1982; Moberg, 2001). Total Nitrogen (TN) was determined using micro-Kjeldahl digestion-distillation methods (Bremner and Mulvaney, 1982; Moberg, 2001). Available phosphorus was determined using Bray and Kurtz 1 method, whereby the contents are allowed to stand for 15 minutes for the blue color to develop and P content was determined in the solution on spectrophotometer 884 nm (Bray and Kurtz, 1945; Murphy and Riley, 1962). Cationic exchange capacity (CEC soil) was determined by 1M ammonium acetate saturation method (pH 7.0) (Coleman *et al.*, 1959). Cation exchange capacity of clay was calculated using the formula outlined by Baize (1993) as follows; [CEC clay = ({CEC soil-(%OM*2)}/% Clay) *100] (Eq. 3). The exchangeable bases; Mg^{2+} and Ca^{2+} in the ammonium acetate filtrate were quantified by Atomic Adsorption Spectrophotometer (AAS) whereas Na^{+} and K^{+} were quantified by flame photometer (FP) (Coleman *et al.*, 1959; Moberg, 2001). Extractable micronutrients (Zn, Cu, Fe and Mn) were extracted by DTPA method (Münz 1935; Moberg, 2001) and quantified by AAS. TEB for each sample was calculate as the sum of Mg^{2+}, Ca^{2+}, Na^{+} and K^{+} (Eq. 4) in exchangeable form expressed in milligram equivalent per 100g of soil (Day and Ludeke, 1993). Base saturation (BS), exchangeable sodium percentage (ESP), C/N, Ca/Mg, Ca/TEB, K/Mg, K/CEC and Silt/Clay ratio were computed using their respective formula as follows:

ESP= (Exchangeable Na / CEC) X 100 …………………………………..(Equation 5)

C/N = OC (%) / TN (%) …………………………………………..…....(Equation 6)

BS = (Mg^{2+}+ Ca^{2+}+ Na^{+} + K^{+})/CEC * 100…………………………...…..(Equation 7)

Ca/Mg = Ca^{2+} / Mg^{2+} ……………………………………………..…….(Equation 8)

Ca/TEB = Ca^{2}/ TEB …………………….…………….…………………..(Equation 9)

K/Mg = K^{+}/Mg^{2+} ……………………………………..……………….....(Equation 10)

K/CEC = (K^{+}/CEC) *100 …………..…………………….…….…...……...(Equation 11)

Silt/Clay ratio = % Silt / % Clay ……………………….……..…..…….(Equation 12)

3.3.2.2.3 Soil classification

Morphological, physical and chemical properties data determined in the field and laboratory were used to establish diagnostic horizons and other features that were used to classify the soils up to tier-2 category using World Reference Base (WRB) for Soil Resources (IUSS Working Group WRB, 2015) and up to family level by using Soil Taxonomy (USDA, 2014) classification systems.

3.4 Results and Discussions

3.4.1 Soil morphology

Descriptions of the selected morphological properties of studied soil profiles are presented in Table 3.3. All the six soil profiles were deep (>140 cm depth) and well drained.

Table 3.1: Locations and characteristics of pedons at MATI Mubondo farm, Kasulu, Kigoma region

Pedon	**Geographic location**		**Altitude (m asl)**	**Land form**	**Soil depth**		**Location**
	Latitude	**Longitude**			Depth (cm)	Class	
MBD-P1	04.52276^{O}S	030.18216^{O}E	1257	Plain	160+	deep	Middle
MBD-P2	04.63029^{O}S	030.17797^{O}E	1226	Plain	150+	deep	Middle
MBD-P3	04.52196^{O}S	030.18805^{O}E	1253	Plain	96+	deep	Middle
MBD-P4	04.52196^{O}S	030.18805^{O}E	1236	Plain	140+	deep	Upper
MBD-P5	04.53635^{O}S	030.18298^{O}E	1238	Plain	160+	deep	Middle
MBD-P6	04.53678^{O}S	030.19053^{O}E	1229	Plain	160+	deep	Middle

Table 3.2: Vegetation and surface characteristics of the representative pedons

Profile	Site characteristics	Drainage characteristics	Native vegetation	Land use
MBD-P1	Slope: 0.5% (level); Slope type: straight; Slope length:500 m; Position on slope: middle	Well drained	Brachystegia spp.	NF
MBD-P2	Slope: 0.5% (level); Slope type: straight Slope length: 500 m; Position on slope: middle	Well drained.	Brachystegia spp.	AL
MBD-P3	Slope: 0.5% (level); Slope type: straight; Slope length: 2000 m; Position on slope: middle.	well drained	Brachystegia spp.	CL
MBD-P4	Slope: 1.0% (nearly level); Slope type: straight; Slope length:1500 m; Position on slope: upper slope.	Well drained.	Brachystegia spp	AL
MBD-P5	Slope: 5%; Slope type: straight; Slope length:1500 m Position on slope; middle	Well drained.	Brachystegia spp	NF
MBD-P6	Slope:2%; Slope type: straight; Slope length: 1000 m Position on slope: middle	Well drained	Brachystegia spp	CL

AL=Abandoned land; CL= Cultivated land; NF=Natural forest; m.a.s.l=mean above sea level.

Table 3.3: Selected morphological properties of the studied soil profiles

Depth (cm)	Horizon	Pores	Munsell soil Color	Structure	Roots	Consistency		HB
			Moist			moist	wet	
MBD-P1								
0-15	Ah	MA and FI	vdur (7.5R2.5/3)	MO FI GR	CO and ME	VFR	SST PL	CS
15-26/34	A/B	CO and FI	dur (10R 3/3)	MO ME SB	F and ME	FR	SST SPL	GW
26/34-160+	Bo	CO and VF	dur (10R 3/4)	WE FI SB	F and VF	VFR	SST SPL	-
MBD-P2								
0-15	Ap	MA and FI	vdur (2.5YR 2.5/2)	MO VFI GR	MA and FI	FR	ST PL	GW
15-36	AB	MA and FI	darb (7.5YR 4/6)	MO FI P	MA and FI	FR	ST PL	CS
36-85/96	Bt	F and FI	darb (2.5YR 3/4)	MO ME P	VF and FI	FM	ST SPL	CW
85/96-150+	Bo	CO and FI	darb (2.5YR 2.5/4)	WE FI GR	VF and FI	FR	SST SPL	-
MBD-P3								
0-15	Ap	MA and FI	dab (7.5YR 3/4)	WE FI GR	MA and FI	FR	ST PL	GW
15-34	A/B	MA and VF	2.5YR 2.5/4	MO FI GR	CO and VF	FR	ST SPL	CS
34-140+	Bo	CO and VF	10R 3/4	MO ME P	VF and ME	VFR	ST SPL	-
MBD-P4								
0-10	Ap	CO and FI	dur (10R 3/3)	MO ME GR	MA and ME	FR	ST PL	GS
10-140+	Bs	CO and FI	dur (10R 3/4)	MO FI GR	CO and FI	FR	ST SPL	-
MBD-P5								
0-4	A	CO and FI	darb (5YR 2.5/2)	MO ME P	MA and FI	FR	ST PL	CS
4-18	O	MA and CE	b (GREY1 2.5/N)	MO ME GR	MA and FI	VFR	SST NPL	AS
18-27	BO	F and FI	darb (2.5YR 3/3)	S ME GR	CO and VF	FR	ST PL	CS
27-160+	Bs	VF and VFI	dur (10R 3/3)	MO ME BL	CO and VF	FR	SST SPL	-
MBD-P6								
0-10	Ap	MA and FI	vdur (10R 2.5/2)	MO FI GR	MA and VFI	VFR	PVP	AS
10-50	BA	MA and FI	darb (2.5YR 3/4)	-	CO and VFI	FR	-PL	GS
50-123	Bo	CO andVF	darb (2.5YR 2.5/4)	-	VF and VFI	FR	-SPL	AS
123-150+	C	MA and ME	darb (2.5YR 2.5/4)	-	VF and VFI			

WE=Weak; MO=Moderate; GR=Granular; VF =Very fine; FI=Fine; ME=Medium; SB=Sub-angular blocky; FR= Friable; FM=Firm; ST=Sticky; SST= Slightly sticky; PL=Plastic; SPL= Slightly plastic. C=Clay; SCL=Silty Clay loam; HB=Horizon boundary: CS=Clear and smooth; GS=Gradual and smooth; CW= Clear and wavy; FVR=Few and very fine; FME=Few and medium; COME=Common and medium; MAFI=Many and fine; VFFI=very few and fine; COVF=Common and very fine; VFME= Very few and medium; COFI=Common and fine; MAVFI=Many and very fine; MACE=Many and coarse; FM= Firm. vdur=very dusky red; dur=dusky red; darb=dark reddish brown; dab=dark brown; darb=dark reddish brown; dur=dusky red; dark reddish brown; b= black; vdur=very dusky red

3.4.1.1 Soil color

Soil color indicate the composition of the soil and give clues to the condition of the soil. It is used to distinguish and identify soil horizons and to group soil according to soil classification systems. The soil color has little effect on plant growth but indicates soil characteristics that affect plant growth such as OM content, drainage and aeration (Manjula and Nathan, 2009). Generally, the studied soils of all pedons were yellowish and/or reddish in color which indicates that the soil is low in OM, well drained and presence of ferric oxides. Soil color is presented in Table 3.3 and Plate 3.1.

MBD-P1

MBD-P2

MBD-P3

MBD-P4

MBD-P5

MBD-P6

Plate 3.1: MBD-P1 – MBD-P6 showing Representative soil profiles in MATI-Mubondo Farm, Kasulu district Kigoma

3.4.1.2 Consistence

Soil consistence is the strength with which soil materials are held together or the resistance of soils to deformation and rupture. It is characterized with dry, moist and wet, stickiness and plasticity (Ditzler *et al.,* 2017). Soil consistence was determined for wet and moist samples because it was raining. The soils of all pedons were friable to very friable moist, slight sticky to sticky and slight plastic to plastic wet, the condition which is favorable for root penetration.

3.4.1.3 Structure

Soil structure refers to the unit composed of primary particles such as clay, silt and sand, and characterized with grade, size and shape (Ditzler *et al.,* 2017). The structure of the soils in most part of the pedons were moderate fine granular which is good for maize and beans production. It allows water to move easily through such soils Table 3.3. Generally, consistence and structure determine water retention capacity of the soil which is essential for plant growth (Rawls and Pachepsky, 2002).

3.4.1.4 Roots abundance and size

Roots abundance and size are described in terms of numbers and size per unit area and the observed value used to assign a class (Ditzler *et al.,* 2017). The interactions between roots and soil are physical, chemical and biological (Tinker and Barraclough, 1988). Table 3.3. shows the roots abundance and sizes of the studied profiles. The distribution of roots throughout the profiles were due to good soil structure exhibited by those soils.

3.4.1.5 Soil pores

Soil pore describe the portion of the soil volume isolated by solid material Table 3.3. Pore spaces affect the movement of water, air, transportation and chemical reactions that occur in the soil (Nimmo, 2004). The pores are associated with the arrangement of the primary soil separates (clay, silt and sand) rooting patterns, soil fauna and other soil forming processes such as cracking, translocation (eluviation and illuviation) and leaching (FAO, 2006).

3.4.1.6 Horizon boundary, distinctness and topography

Horizon boundaries refer to the delineation between two horizons of soil profile and are described in terms of depth, distinctness and topography. Depth is the thickness of the horizon from surface to lower boundary column in the soil profile. Distinctness refers to the thickness of the zone in which horizon boundary can be located. Topography indicates the smoothness of depth variation of the boundary (FAO, 2006; Ditzler *et al.,* 2017). In MBD-P1 Pedon, horizon boundary between horizon Ah and A/B was clear smooth and gradual wavy between horizon A/B and Bo. Profile MBD-P2, horizon boundary between topsoil (Ap) and underlying horizon (AB) is gradual wavy, clear smooth between horizons AB and Bt, and clear wavy between horizons Bt and Bo. Soil profile MBD-P3, topsoil (Ap) and underlying subsoil (A/B) were characterized by gradual wavy boundary, and subsoil A/B and Bo were characterized by clear smooth boundary.

The MBD-P4 was characterized by gradual smooth boundary between topsoil Ap and subsoil Bs. The MBD-P5 had clear smooth boundary between horizon A and Op, abrupt smooth between horizon O and BO, and clear smooth between horizon BO and Bs. The MBD-P6 had abrupt smooth boundary between horizon Ap and BA, gradual smooth between horizon BA and Bo, and abrupt smooth between horizon Bo and C. Pedons MBD-P1, MBD-P2, MBD-P3 and MBD-P4 are characterized by gradual boundaries between horizons which indicated that the soils are deep, highly weathered and old. Pedon MBD-P6 is characterized by both abrupt and gradual boundaries, implying that, the soil deep, highly weathered and old but there is sudden change between horizon Bo to C. Pedon MBD-P5 is characterized by abrupt boundary between horizon O and BO.

3.4.1.7 Particle size distribution and textural classes

Soil texture was determined in the laboratory by hydrometer method and the results are presented in Table 3.4. Generally, the results of the particle size distribution of the six profiles showed that percentage clay content is higher than silt and sand in all horizons. Moreover, the results signified that clay content increased from topsoil to underlying horizons. Despite the increase in clay content down the profile, clay skins (Cutans) were not found on the sides of ped faces which implying that clay illuviation did not occur except in profile MBD-P2 horizon Bt. Therefore, high clay content of subsoil horizons is due to in situ weathering of the parent material (Alemayehu *et al.*, 2014). Textural classes were determined using textural triangle, and were clayey for all pedons except for the pedon MBD-P2 surface horizon Ap was silt clay and pedon MBD-P5 underlying horizon O was silt clay loam (FAO, 2006). Clayey texture is associated with high water and nutrients retention capacity because of large surface area of clay particles.

3.4.1.8 Silt/clay ratio

Silt/Clay ratios are presented in Table 3.4. It is reported that old parent materials have silt/clay ratio below 0.15 while silt/clay ratio above 0.15 are indicative of young parent materials. Topsoil of all pedons have silt/clay ratio greater than 0.15 indicating low degree of weathering when compared to the subsoil except for underlying horizon O of MBD-P5 that had silt/clay ratio greater than topsoil. This is due to the fact that horizon O is a buried horizon, therefore it exhibits properties of the topsoil (Sharu *et al.*, 2013).

3.4.1.9 Bulk density

Measure of soil bulk density is important for understanding the compaction, physical, chemical and biological properties of soil. Table 3.4 presents bulk density values of the study area. Bulk density was determined only in topsoil of each pedon, ranged from 1.26 to 1.47, the values that are good for agriculture since BD higher than 1.6 gcm^{-3} tends to restrict root growth and permeability (Al-Shammary *et al.,* 2018). It is desirable to have soil with a low BD (<1.5 g cm^{-3}) for optimum movement of air and water in the soil (Hunt and Gilkes, 1992).

Table 3.4: Selected physical soil properties of MATI-Mubondo farm

Profile No.	Horizon	Depth (cm)	Particle Size Distribution (%)			Textural class	Silt/Clay Ratio	BD
			Clay	Silt	Sand			
MBD-P1	Ah	0-15	66.76	13.00	20.24	C	0.19	1.36
	A/B	15-26/34	78.76	11.00	10.24	C	0.14	nd
	Bo	26/34-160+	73.76	12.00	14.24	C	0.16	nd
MBD-P2	Ap	0-15	47.76	38.00	14.24	SC	0.80	1.43
	AB	15-36	63.76	16.00	20.24	C	0.25	nd
	Bt	36-85/96	82.76	9.00	8.24	C	0.11	nd
	Bo	85/96-150+	81.76	8.00	10.24	C	0.10	nd
MBD-P3	Ap	0-15	73.76	12.40	13.84	C	0.17	1.26
	A/B	15-34	81.76	10.80	7.44	C	0.13	nd
	Bo	34-140+	85.76	12.00	2.24	C	0.14	nd
MBD-P4	Ap	0-10	79.76	12.40	7.84	C	0.16	1.40
	Bo	10-140+	83.76	6.00	10.24	C	0.07	nd
MBD-P5	A	0-4	59.76	14.00	26.24	C	0.23	1.47
	O	4-18	37.76	56.00	6.24	SCL	1.48	nd
	Bo	18-27	79.76	10.00	10.24	C	0.13	nd
	Bs	27-160+	89.76	6.20	4.04	C	0.07	nd
MBD-P6	Ap	0-10	67.76	14.00	18.24	C	0.21	1.43
	BA	10-50	83.76	10.00	6.24	C	0.12	nd
	Bo	50-123	85.76	9.00	5.24	C	0.10	nd
	C	123-150+	82.76	7.00	10.24	C	0.08	nd

Keys: C = Clay; SC = Silt Clay; SCL = Silt Clay Loam; BD = Bulk Density; nd = not determined

3.4.2 Soil chemical properties

The selected chemical properties of the studied soil profiles in MATI -Mubondo farm were determined.

3.4.2.1 Soil pH

The data of soil reaction (pH) generally showed that all soils were acidic according to the ratings by Msanya *et al.* (2001). The pH change (ΔpH) obtained from subtraction of pH in calcium chloride from pH in water (pH_{H2O} – pH_{CaCl2}) and the values were positive ranged between 0.53 to 0.95 in all pedons. The positive values of ΔpH indicates the presence of negatively charged clay colloid. The higher the ΔpH values indicates the presence of appreciable amount of negatively charged clay colloids (Alemayehu *et al.*, 2014). Kebeney *et al.* (2014), pointed out that, the optimal level of pH is about 6.5 to7.5 for most crops and the pH<5.5 (observed in all pedons) have potential to cause toxicity and deficiency of some essential plant nutrients and hinder microbial activities in the soil. According to the results, liming materials need to be considered to raise the pH to the optimal range. Also, soil pH<5.5 enhance solubility of aluminum (Al^{3+}), manganese (Mn^{2+}) and iron ($Fe^{3+,2+}$) which precipitate or form complexes with phosphorus ions causing its fixation and become unavailable for the plant uptake (Thiagalingam and Mangi, 2005).

3.4.2.2 Electrical Conductivity (EC)

Soil electrical conductivity is a measurement of how much electrical current soil can conduct. The electrical conductivity values in soil and water suspensions (EC1:2.5) for the studied pedons are presented in Table 3.5. The topsoil EC ranged from 0.04 to 0.32 dS/m while EC of the subsoil ranged from 0.01 to 0.08 dS/m. The trend decreases down the profiles regularly with soil depth. According to Msanya et al. (2001), the electrical conductivity of these soils is very low (<1.7 dS/m) indicating that no yield reduction will be caused by soluble salts in this farm.

3.4.2.3 Organic carbon and organic matter

Soil organic matter is a surrogate for soil carbon and is measured as a reflection of overall soil health (Horneck *et al.,* 2011). Topsoil organic carbon (OC) ranged from 1.56% (medium) to 4.10% (very high) while organic matter (OM) ranged from 2.69% (medium) to 7.06% (very high). The subsoil OC ranged from 0.35% (rated very low) to 2.81% (high) and OM ranged from 0.61% (very low) to 4.84% (high) as listed in Table 3.5. Organic matter percentage was estimated by multiplying the percentage organic carbon by 1.724 (Msanya *et al.,* 2001). From the results (Table 3.5), OC and OM showed a decreasing trend with increase in soil depth to all pedons. This may be due to low or no inputs of fairly stable OM to deeper soil horizon (Lorenz and Lal, 2005).

3.4.2.4 Total Nitrogen (TN)

The data on Total nitrogen (TN) of the studied pedons of MATI-Mubondo farm showed that, the topsoil TN were ranged from 0.19% (rated low) to 0.31% (rated medium) and that of subsoil horizons ranged from 0.04 % (very low) to 0.15% (low) (Msanya *et al.,* 2001). Pedon MBD-P1, MBD-P3 and MBD-4 all had low total nitrogen while MBD-P2, MBD-P5 and MBD-P6 had medium total nitrogen. Percentage TN showed the decreasing tendency down the profiles (Table 3.5).

3.4.2.5 Carbon to Nitrogen (C: N) ratio

The soil C:N ratio is the weight of organic carbon to the weight of total nitrogen in a soil or organic matter. It gives an indication of the quality of organic matter (Msanya *et al.,* 2001). The data of the C:N ratio of the representative soil profiles are shown on the Table 3.5. Msanya (2001) reported the category of C: N as of good quality (8-13), moderate quality (14-20) and poor quality (>20). Topsoil of profiles MBD-P2 and MBD-P4 had the C:N ratios 13.30 and 13.46 respectively, which were good quality, topsoil of profiles MBD-P1, MBD-P3, MBD-P6 had C:N ratios 18.57, 15.38 and 15.82 respectively, which were moderate quality and topsoil of profile MBD-P5 had C:N ratio 5.71 was poor quality. The C:N ratios in all pedons showed irregular trend with increase depth. The C:N ratio influence decomposition rate in the soil. The wide C:N ratio leads to slow decomposition rate and nutrient immobilization while narrow C:N ratio, Carbon and energy starvation occur since plant residues decompose quickly and release nitrates readily.

3.4.2.6 Available Phosphorus (P)

Data on available P are presented in Table 3.5. The topsoil available P was 0.67, 4.6, 5.61, 6.18, 7.19 and 3.93 mg kg^{-1} for MBD-P1, MBD-P2, MBD-P3, MBD-P4, MBD-P5 and MBD-P6 respectively. The topsoil value for phosphorus were high compared to the values for subsoil of the studied profiles except for the profile MBD-P1 and MBD-P5, where the underlying horizons A/B and Op respectively had high P value than the surficial horizon. The P values were rated low for all profiles except profile MBD-P5 which was rated medium (Msanya *et al.,* 2001).

3.4.2.7 Sulfur

Soil test data for extractable sulfur are presented in Table 3.5. The topsoil extractable sulfur (S) data ranged from 25.31 to 67.32 mg kg^{-1} while those of the subsoil ranged from 21.21 to 67.32 mg kg^{-1}. The values of sulfur in all the representative pedons showed irregular trend with depth.

Table 3.5: Selected chemical soil properties of MATI-Mubondo Farm in Kasulu district

Depth	Horizon	pH_w	pH_{CaCl2}	Δ pH	EC	OC	OM	TN	C/N	Av.P	Ext.S
Cm		1:2.5	1:2.5		dS/m	%	%			mg kg^{-1}	mg kg^{-1}
MBD-P1											
0-15	Ah	4.61	3.72	0.89	0.09	3.51	6.05	0.19	18.57	0.67	48.87
15-26/34	A/B	4.68	4.05	0.63	0.03	1.46	2.52	0.09	16.07	1.01	28.38
26/34-160+	Bo	4.69	3.98	0.71	0.01	0.35	0.61	0.04	8.36	0.45	46.82
MBD-P2											
0-15	Ap	5.60	4.95	0.65	0.32	4.10	7.06	0.31	13.30	4.60	67.32
15-36	AB	4.90	4.09	0.81	0.08	1.77	3.06	0.11	16.90	2.58	31.45
36-85/96	Bt	5.04	4.24	0.8	0.04	0.60	1.04	0.06	10.79	1.12	67.32
85/96-150+	Bo	5.40	4.84	0.56	0.02	0.39	0.67	0.06	6.96	0.34	25.31
MBD-P3											
0-15	Ap	4.83	3.95	0.88	0.07	2.48	4.27	0.16	15.38	5.61	27.36
15-34	A/B	4.00	3.33	0.67	0.05	1.35	2.32	0.09	14.79	0.90	35.55
34-140+	Bo	4.93	4.26	0.67	0.02	0.60	1.04	0.05	12.34	0.90	35.55
MBD-P4											
0-10	Ap	4.59	3.93	0.66	0.04	1.70	2.92	0.13	13.46	6.18	25.31
10-140+	Bo	4.96	4.13	0.83	0.01	0.53	0.91	0.05	10.74	3.82	33.50
MBD-P5											
0-4	Ah	5.33	4.55	0.78	0.20	1.56	2.69	0.27	5.71	7.19	47.85
4-18	O	5.44	4.53	0.91	0.06	2.81	4.84	0.15	19.10	8.20	47.85
18-27	Bo	5.45	4.6	0.85	0.05	1.13	1.95	0.10	11.54	1.12	50.92
27-160+	Bs	4.96	4.31	0.65	0.01	0.39	0.67	0.04	11.14	1.01	21.21
MBD-P6											
0-10	Ap	5.08	4.37	0.71	0.13	3.43	5.92	0.22	15.82	3.93	33.50
10-50	BA	4.51	3.98	0.53	0.06	0.88	1.51	0.08	11.40	0.90	50.92
50-123	Bo	5.17	4.33	0.84	0.06	0.64	1.11	0.06	10.21	0.64	40.68
123-150+	C	4.98	4.38	0.6	0.02	0.51	0.87	0.04	14.49	0.49	41.70

EC = Electrical conductivity; OC = Organic carbon; OM = Organic matter; TN = Total nitrogen

3.4.2.8 Exchangeable bases

Exchangeable Ca

Exchangeable Ca in the surface horizons of the soil profiles MBD-P1 and MBD-P4 were rated very low, MBD-P3, MBD-P4 and MBD-P6 were rated low, and MBD-2 was rated medium, according to Roy et al. (2006). The values of the topsoil ranged from 0.7 to 8.53 while for the subsoil ranged from 0.26 to 4.2 cmol (+) kg^{-1}. The values of calcium decrease regularly in the soil profiles MBD-P1, MBD-P2, MBD-P4, and MBD-P5 while decrease irregularly in soil profiles 3 and 6 as shown in Table 3.6. and ratings presented in Table 3.8.

Exchangeable Mg

The exchangeable magnesium contents varied from 0.93 to 3.14 for the surface horizon and from 0.32 to 0.19 (cmol (+) kg^{-1}) for the subsoils. According to Hazelton and Murphy (2016), subsoil values of Mg were rate low for MBD-P1 and MBD-P4, medium for MBD-P2, MBD-P3 and MBD-P6, and high for MBD-P5. The values for Mg decrease regularly with increase in depth for the soil profile MBD-P1, MBD-P4, MBD-P5 and MBD-P6 while decrease irregularly for profiles 2 and 3 as shown in Tables 3.6 and Table 3.8 ratings.

Exchangeable K

Exchangeable K status of the soil is very low to low in most of the soil horizons. For the topsoil ranged from 0.05 to 1.42 and that of the subsoil ranged from 0.03 to 0.14 (cmol (+) kg^{-1}). Values of the topsoil were rated very low for MBD-P1, MBD-P3, MBD-P4 and MBD-P6, high for MBD-P2 and low for MBD-P5 (Hazelton and Murphy, 2016). The values decrease down the profiles.

Exchangeable Na

Na^+ is present in soils and taken up and utilized by plants, but are not considered as plant nutrients because they do not meet the definition of essentiality (Subbarao *et al.,* 2003). The Na^+ exchangeable level ranged from 0.03 to 0.07 cmol (+) kg^{-1} in the topsoil and 0.03 to 0.06 (cmol (+) kg-1) in the subsoil. The values in all horizons were rated very low according to Hazelton and Murphy (2016).

3.4.2.9 Cation Exchange Capacity (CEC)

Cations are positively charged ions such as calcium (Ca^{2+}), magnesium (Mg^{2+}), potassium (K^+) and sodium (Na^+). The capacity of the soil to hold on to these cations called the cation exchange capacity (Mukhopadhyay *et al.,* 2019). It is a measure of the total number of sites available in a soil for the exchange of cations. The CEC decreases down the profiles except for profile MBD-P5 where the underlying horizon Op had CEC value greater than the surface horizon. The topsoil values ranged from 13.20 to 36.40 cmol (+) kg^{-1} and from 5 to 64 cmol (+) kg^{-1} of the subsoil rated very low to very high respectively. The topsoil values were rated medium for profile MBD-P1, MBD-P3 and MBD-P4, and high for profile MBD-P2, MBD-P5 and MBD-P6 (Hazelton and Murphy, 2016).

The CEC of clay (CEC_{clay}) for the topsoils ranged from 8.23 to 46.65 cmol (+) kg^{-1} and that of subsoil range from 0.2 to 143.85 cmol (+) kg^{-1}. The CEC of clay in subsoils were low (<24) for all soil profiles except horizon AB in profile MBD-P2 and horizon O in profile MBD-P5, which signifies that the soils are highly weathered. These results agree with findings reported by Kebeney *et al*. (2014) on highly weathered soils.

3.4.2.10 Base Saturation (BS)

Base saturation (BS) represents the percentage of CEC occupied by bases (Ca^{2+}, Mg^{2+}, K^+, and Na^+). The availability of Ca^{2+}, Mg^{2+}, and K^+ increases with increasing % BS which increases with increasing pH (Havlin, 2014). The percentage base saturation of the studied pedons is presented in Table 3.6 and their ratings are presented in Table 3.7. Topsoil value range from 10.39 to 34.33% while of the subsoil ranged from 7.67 to 41.89%. There is no consistent trend of the percentage base saturation with increase in depth of the studied pedons. Topsoil values were rated very low and low while subsoil values were rated very low, low and moderate (MBD-P2 horizon Bo), Table 3.7, which might be attributed to low pH (Hazelton and Murphy, 2016).

3.4.2.11Exchangeable Sodium Percentage (ESP)

The ESP results of the studied profiles are shown in Table 3.6. The values in topsoil ranged from 0.14 to 0.32 % while in subsoil ranged from o.14 to 2.02 % and all are rated non-sodic (Hazelton and Murphy, 2016). Msanya *et al*. (2001) opined that ESP of 15 % up to 50 % can cause yield reduction of sensitive crops such as maize and beans.

Table 3.6: Exchangeable bases and related chemical properties of the studied soil profiles

Depth	Horizon	Exchangeable Bases cmol (+) kg^{-1}				TEB	CEC_{soil}	CEC_{clay}	BS %	ESP
Cm		Ca	Mg	Na	K	cmol (+) kg^{-1}				
MBD-P1										
0-15	Ah	0.70	0.93	0.06	0.14	1.83	17.60	8.23	10.39	0.32
15-26/34	A/B	0.47	0.32	0.05	0.05	0.90	5.20	0.20	17.26	1.01
26/34-160+	Bo	0.42	0.15	0.13	0.06	0.76	6.40	7.04	11.95	2.02
MBD-P2										
0-15	Ap	8.53	2.49	0.07	1.42	12.50	36.40	46.65	34.33	0.18
15-36	AB	4.23	1.01	0.06	0.14	5.44	22.40	25.54	24.30	0.27
36-85/96	Bt	2.90	0.88	0.07	0.07	3.91	10.40	10.05	37.63	0.63
85/96-150+	Bo	2.54	1.05	0.04	0.05	3.69	8.80	9.12	41.89	0.50
MBD-P3										
0-15	Ap	2.13	1.07	0.03	0.15	3.37	21.60	17.71	15.62	0.14
15-34	A/B	0.65	0.40	0.04	0.08	1.17	15.20	12.92	7.67	0.26
34-140+	Bo	0.92	0.72	0.06	0.04	1.73	6.40	5.03	27.05	0.89
MBD-P4										
0-10	Ap	1.20	0.52	0.03	0.05	1.80	13.20	9.22	13.65	0.24
10-140+	Bo	0.26	0.19	0.03	0.03	0.51	6.40	5.47	7.94	0.42
MBD-P5										
0-4	A	4.29	3.14	0.05	0.26	7.74	29.20	39.86	26.51	0.18
4-18	O	3.72	2.93	0.07	0.11	6.83	20.4	28.38	10.68	0.12
18-27	Bo	2.30	1.08	0.06	0.06	3.49	11.60	9.65	30.05	0.49
27-160+	Bs	0.51	0.50	0.04	0.04	1.08	6.40	5.63	16.88	0.62
MBD-P6										
0-10	Ap	3.17	1.35	0.05	0.16	4.74	25.60	20.32	18.52	0.20
1o-50	BA	0.93	0.58	0.04	0.04	1.59	10.00	8.33	15.86	0.44
50-123	Bo	0.95	0.55	0.05	0.03	1.58	7.20	5.81	22.01	0.73
123-150+	C	0.84	0.50	0.06	0.04	1.44	6.00	5.14	23.97	0.94

TEB = Total exchangeable bases; BS = Base saturation; ESP = Exchangeable Sodium Percentage

Table 3.7: Ratings of Base saturation

Range (% BS)	Rating
0 – 20	Very low
20 – 40	low
40 – 60	moderate
60 – 80	high
>80	Very high

Source: Hazelton and Murphy (2016)

Table 3.8: Ranges of exchangeable cation in soil for the interpretation of cation exchange data

Rating	Exch. Ca	Exch. Mg	Exch. K	Exch. Na	CEC
		(cmol/Kg)			
Very high	>20	>8	>1.2	>2	>40
High	10 - 20	3 – 8	0.6 – 1.2	0.7 - 2	25 - 40
Medium	5 - 10	1 – 3	0.3 – 0.6	0.3 – 0.7	12 - 25
Low	2 - 5	0.3 – 1	0.2 – 0.3	0.1 – 0.3	6 - 12
Very low	<2	<0.3	<0.2	<0.1	<6

Source: Roy *et al.*, (2006)

3.4.3 Nutrient Balance

The nutrient ratios of exchangeable bases for studies profile are presented in Table 3.9. The topsoils ratio of Ca/Mg in studied profiles ranged from 0.75 to 3.43 while in subsoil ranged from 1.45 to 4.21. The values (except for the underlying horizon AB of profile MBD-P2) were not within the range 4 – 6 which is balanced/favorable for plant uptake, growth and development, and the values below the stated range, calcium is reported to become unavailable and above which calcium become toxic (Hazelton and Murphy, 2016).

The K/Mg ratio of topsoil ranged from 0.08 to 0.57 and that for subsoils ranged from 0.04 to 0.41. Mtama *et al.* (2014), opined that ratio K/Mg should be less than 1.5 for the optimal uptake of Mg^{2+} plants. Therefore, all the values are in desirable range for the crop uptake. According to Kopittke and Menzies (2007), maximum plant growth would be achieved only when the soils exchangeable Ca, Mg and K concentrations are approximately 65% Ca, 10% Mg and 5% K, termed as ideal soil. Therefore, if the K/Mg is > 0.5 it may cause magnesium deficiency, so it is appropriate to maintain the ratio between 3-7%.

The K/CEC ratios in the studied profiles ranged from 0.4 to 3.89 for topsoils and 0.17 to 1.02 subsoils. There was irregular trend of variation of values with depth of profiles. The

K/CEC values were smaller than 2% in studied soils signifying unfavorable conditions for production of crops (Mtama *et al.,* 2014).

Table 3.9: Nutrients Ratios for the representative soils of MATI-Mubondo Farm

Depth	Horizon	Nutrient Ratio			
cm		Ca/Mg	Ca/TEB	K/Mg	K/CEC (%)
MBD-P1					
0-15	Ah	0.75	0.38	0.15	0.78
15-26/34	A/B	1.45	0.52	0.16	1.02
26/34-160+	Bo	2.74	0.55	0.41	0.99
MBD-P2					
0-15	Ap	3.43	0.68	0.57	3.89
15-36	AB	4.21	0.78	0.14	0.64
36-85/96	Bt	3.31	0.74	0.08	0.66
85/96-150+	Bo	2.42	0.69	0.05	0.60
MBD-P3					
0-15	Ap	1.99	0.63	0.14	0.69
15-34	A/B	1.63	0.56	0.20	0.52
34-140+	Bo	1.29	0.53	0.05	0.59
MBD-P4					
0-10	Ap	2.32	0.67	0.10	0.40
10-140+	Bo	1.36	0.51	0.16	0.47
MBD-P5					
0-4	A	1.36	0.55	0.08	0.88
4-18	Op	1.27	0.54	0.04	0.17
18-27	Bo	2.13	0.66	0.05	0.48
27-160+	Bs	1.03	0.47	0.07	0.55
MBD-P6					
0-10	Ap	2.34	0.67	0.12	0.64
1o-50	BA	1.61	0.59	0.07	0.38
50-123	Bo	1.73	0.60	0.06	0.42
123-150+	C	1.67	0.58	0.09	0.72

3.4.4 Selected soil micronutrients

Micronutrients are essential elements that are used by plants in small quantities. The micronutrients Cu, Zn, Fe and Mn were selected and analyzed in mg kg^{-1} as presented in Table 3.10 and ratings in Table 3.11. In topsoil, Cu ranged from 7.06 to 21.02 and 0.01 to 26.11mg kg^{-1} in subsoil, and showed consistent decrease in amount with soil depth except in profile MBD-P2. In topsoils, Cu was rated high while very low to high in subsoil. Zn in topsoils ranged from 0.58 to 3.36 and 0.2 to 1.19 mg kg^{-1} in subsurface soil, and rated low to medium in topsoil and very low to medium in subsoil. Zn values decrease regularly with depth except in profile MBD-P6. The Fe content in subsoils ranged from 23.52 to 43.52

and subsurface ranged 2.14 to 45.59 mg kg^{-1} and the content decrease down the profile. The Fe content was rated high and very low to high in topsoil and subsoil respectively. Mn contents ranged from 0.84 to 248 in topsoil and 3.51 to 99.56 in subsoil and the trend did not show consistent of decrease down the profile. The Mn values were rated very low to high and medium to high in topsoil and subsoil respectively.

Table 3.10: Distribution of micro-nutrients in soils of MATI Mubondo

Depth	Horizon	Cu (mg/kg)	Zn (mg/kg)	Fe (mg/kg)	Mn(mg/kg)
MBD-P1					
0-15	Ah	7.25	0.67	43.52	37.33
15-26/34	A/B	4.98	0.48	24.21	18.84
26/34-160+	Bo	0.45	0.34	4.21	1.07
MBD-P2					
0-15	Ap	21.02	3.36	36.62	248.00
15-36	AB	26.11	0.76	45.59	216.89
36-85/96	Bt	6.68	0.39	10.41	28.44
85/96-150+	Bo	1.58	0.39	4.21	6.22
MBD-P3					
0-15	Ap	10.83	0.58	29.72	75.11
15-34	A/B	8.00	0.43	21.45	28.44
34-140+	Bo	1.21	0.29	4.21	5.07
MBD-P4					
0-10	Ap	7.06	0.39	42.14	0.84
10-140+	Bo	1.02	0.29	4.90	3.51
MBD-P5					
0-4	A	8.38	1.52	31.10	52.89
4-18	Op	7.81	1.19	30.69	24.00
18-27	Bo	4.98	0.39	14.55	34.67
27-160+	Bs	0.45	0.29	2.83	24.00
MBD-P6					
0-10	Ap	8.00	0.58	23.52	114.67
10-50	BA	2.15	0.48	9.72	74.67
50-123	Bo	0.08	0.20	2.83	92.89
123-150+	C	0.01	0.53	2.14	99.56

Table 3.11: A general guide to micronutrient critical level

Rating	Zn	Fe	Cu	Mn
High	5 – 15		5 – 15	50 – 500
Medium	0.8 – 5	>4.5	0.3 – 5	2 – 50
Low	0.3 – 0.8	2.5 – 4.5	0.1 – 0.3	1 – 2
Very low	<0.3	<2.5	<0.1	<1.0

Source: Thiagalingam and Mangi (2005)

3.4.5 Correlation between soil properties

Pearson correlation matrix (Table 3.12) revealed weak positive correlation between pH and soil fertility parameters such as Ca, Mg, and BS. Clay showed negative correlation with other selected properties. Silt showed weak to strong positive correlation with OC, TN, Av. P, CEC, Ca, Mg, and K. Sand showed weak positive correlation with TN. OC reveal strong to weak positive correlation with TN, Av.P, CEC, Ca, Mg, K and negative correlation with ESP. TN showed positive correlation with Av. P, CEC, Ca, Mg, K and negative correlation with ESP. CEC showed weak and strong positive correlation with Ca and Mg respectively and negative correlation with ESP. Ca showed positive correlation with Mg, K and BS. Mg showed positive correlation with K and negative correlation with ESP. Na showed positive correlation with ESP. The results which are more or less similar to results reported by Tolera *et al*. (2016).

Table 3.12: Pearson correlation coefficient between selected soil properties for the studied soil profiles at MATI-Mubondo farm

	pH	**%Clay**	**%Silt**	**%Sand**	**OC**	**TN**	**Av.P**	**CEC**	**Ca**	**Mg**	**Na**	**K**	**BS**	**ESP**
	(H_2O)				**(%)**	**(%)**	(mg/Kg)			($cmol_{(+)}kg^{-1}$)			(%)	(%)
pH	1													
Clay	NS	1												
Silt	NS	-0.890*	1											
Sand	NS	NS	NS	1										
OC	NS	-0.757*	0.614*	NS	1									
TN	NS	-0.742*	0.505*	0.657	0.856*	1								
Av.P	NS	-0.686*	0.621*	NS	0.521*	0.636*	1							
CEC	NS	-0.931*	0.922*	NS	0.698*	0.655*	0.767*	1						
Ca	0.640*	-0.737*	0.625*	NS	0.607*	0.741*	NS	0.663*	1					
Mg	0.641*	NS	0.729*	NS	0.570*	0.770*	0.714*	0.852*	0.785*	1				
Na	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	1			
K	NS	-0.571*	0.509*	NS	0.619*	0.708*	NS	NS	0.828*	0.526*	NS	1		
BS	0.633*	NS	NS	NS	NS	NS	NS	NS	0.518*	NS	NS	NS	1	
ESP	NS	NS	NS	NS	-0.565*	-0.568	-0.579*	-0.547*	NS	-0.523*	0.675*	Ns	NS	1

Significant at p≤ 0.05; NS = Not significant

3.4.6 Soil Classification

Soil morphological and physico-chemical data were used to define diagnostic horizons and other features used for soil classification. The soils have been classified according to the USDA Soil Taxonomy (USDA, 2014) and correlated with the World Reference Base (WRB) for soil resources (FAO, 2015).

3.4.6.1 Classification of soils using USDA Soil Taxonomy System

3.4.6.1.1 Diagnostic horizon and features

An inventory results on diagnostic horizons and properties of the soil profiles in MATI-Mubondo Farm using USDA Soil Taxonomy are presented in Table 3.13.

Table 3.13: Diagnostic horizons and properties of the studied soil profiles in MATI-Mubondo Farm

Profile no.	Diagnostic epipedon	Diagnostic subsurface horizon	Other diagnostic features/materials
MBD-P1	Umbric epipedon	Cambic horizon	Clayey, Very strongly acid, Ustic SMR, Isohyperthermic STR, Level, Very deep
MBD-P2	Umbric epipedon	Oxic horizon	Clayey, Very strongly, strong to moderate acid, Ustic SMR, Isohyperthermic STR, Level, Very deep
MBD-P3	Umbric epipedon	Kambic horizon	Clayey, Extremely to Very strongly acid, Ustic SMR, Isohyperthermic STR, Slope-0.5% (Level), Very deep
MBD-P4	Umbric epipedon	Kandic horizon	Clayey, Very strongly acid, Ustic SMR, Isohyperthermic STR, nearly Level, Very deep
MBD-P5	Ochric epipedon	Oxic horizon	Clayey, Strongly to Very strongly acid, Ustic SMR, Isohyperthermic STR, sloping, Very deep
MBD-P6	Umbric epipedon	Kandic horizon	Clayey, Strongly to Very strongly acid, Ustic SMR, Isohyperthermic STR, gently sloping, Very deep

3.4.6.1.2 Soil Classification according to the USDA Soil Taxonomy System

Using the information in Table 3.13, the soils of MATI Mubondo Farm were classified up to the family level as shown in Table 3.14 (Soil Survey staff, 2014).

Table 3.14: Classification of Soils of MATI Mubondo Farm in the USDA Soil Taxonomy (USDA, 2014)

Pedon no.	Order	Suborder	Great group	Subgroup	Family
MBD-P1	Oxisols	Ustox	Haplustox	Typic Haplustox	*Level, very deep, clayey, very strongly acid, Isohyperthermic, Typic Haplustox.*
MBD-P2	Oxisols	Ustox	Haplustox	Rhodic Haplustox	*Level, very deep, clayey, very strongly, strongly to moderate acid, Isohyperthermic, Rhodic Haplustox*
MBD-P3	Oxisols	Ustox	Kandiustalfs	Typic Kandiustox	*Level, very deep, clayey, extremely to very strongly, Isohyperthermic, Typic Kandiustox.*
MBD-P4	Oxisols	Ustox	Kandiustalfs	Typic Kandiustox	*Nearly level, very deep, clayey, very strongly acid, Isohyperthermic, Typic Kandiustox.*
MBD-P5	Oxisols	Ustox	Haplustox	Inceptic Haplustox	*Sloping, very deep, clayey, strongly to very strongly acid, Isohyperthermic*, Inceptic Haplustox.
MBD-P6	Oxisols	Ustox	Kandiustox	Rhodic Kandiustox	*Gently sloping, very deep, clayey, strongly to very strongly acid, Isohyperthermic, Rhodic Kandiustox*.

3.2.6.2 Classification of soils by World Reference Base for Soil Resources (WRB)

Information of the studied soil pedons, the diagnostic horizons, diagnostic features/materials, principals and supplementary qualifiers, Reference Soil group (RSGs) and eventually the classification of soils to the second level (Tiers 2) are presented in Table 3.15. According to the IUSS Working Group WRB (2015), soils were classified as *Rhodic Umbric Ferralsols (Clayic, Dystric)* for MBD-P1, MBD-P3 and MBD-P4, *Umbric Ferralsols (Clayic, Dystric)* for MBD-P2 and MBD-P6 and *Rhodic Cambic Ferralsols (Clayic, Dystric)* for MBD-P5.

Table 3.15: Summary of morphological, diagnostic features, principal and supplementary qualifiers of MATI Mubondo Farm soils and classification according to World Reference Base for Soil resources (WRB)

Pedons	Diagnostic horizons	Other diagnostic features/materials	Prefix Qualifiers	Suffix Qualifiers	Reference Soil group (RSG)-TIER1	WRB soil name-Tier2
MBDP1	Ferralic	Presence of illuvial clay/sesquioxide	Umbric, Rhodic	Dystric, Clayic	Ferralsols	*Rhodic Umbric Ferralsols (Clayic, Dystric)*
MBDP2	Argic	Presence of clay skins/cutans	Umbric	Dystric, Clayic	Ferralsols	*Umbric Ferralsols (Clayic, Dystric)*
MBDP3	Umbric	Presence of sesquioxide, dusky and dark red	Umbric, Rhodic	Dystric, Clayic	Ferralsols	*Rhodic Umbric Ferralsols (Clayic, Dystric)*
MBDP4	Umbric	Presence of sesquioxides, dark red colour	Umbric, Rhodic	Dystric, Clayic	Ferralsols	*Rhodic Umbric Ferralsols (Clayic, Dystric)*
MBDP5	Umbric	Presence of sesquioxide	Umbric Rhodic	Dystric, Clayic,	Ferralsols	*Rhodic Cambic Ferralsols (Clayic, Dystric)*
MBDP6	Ferralic	Presence of sesquioxide	Umbric, Rhodic	Dystric, Clayic	Ferralsols	*Rhodic Umbric Ferralsols (Clayic, Dystric)*

MBDP1=Soil profile 1; MBDP2=Soil profile 2; MBDP3=Soil profile 3; MBDP4=Soil profile 4; MBDP5=Soil profile; 5 MBDP6=Soil profile 6

3.3 Conclusions and Recommendations

3.3.1 Conclusions

There was slightly variation in terms of morphological, physical and chemical properties of the soils in all pedons. The soils were very deep, fine textured, well drained and highly weathered dominated by kaolinite clay and sesquioxides. All the studied soils were classified as Oxisols and Ferralsols according to Soil Taxonomy and World Reference Base for Soil Resources respectively. The soils were extremely clayey but well drained because of the tendency of kaolinitic clay to aggregates into strong grade of fine and very fine granular structure which exhibit the properties of coarser soils. The results showed no correlation between soil reaction, TN, OC, Av. P, CEC and soil separates, but weak correlation between Ca, Mg and %BS (Table 3.12). Those correlations between soil parameters are similar to the results reported by Tolera et al. (2016) in soils of Bako Tibe and Toke Kutaye Districts of western Showa, Ethiopia.

3.3.2 Recommendations

Characterization of the soils revealed that soils were low in inherent fertility such as low base saturation, nitrogen, available phosphorus and strong acidic condition (pH<5.5). The reserve of plant nutrients in Oxisols soils is low due to reaching. To sustain yields, application of fertilizers and limes are needed. The study has brought about relevant soils information that can guide decision making on the use and management in sustainable manner.

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CHAPTER FOUR

4.0 SUITABILITY ASSESSMENT OF SOILS OF MATI MUBONDO FARM FOR MAIZE AND BEANS PRODUCTION

4.1 Abstract

Soil suitability is a function of crop requirements matched with soil and land characteristics of a place. After reconnaissance survey, MATI Mubondo farm was partitioned into six sampling units represented by six profiles namely; MBD-P1, MBD-P2, MBD-P3, MBD-P4, MBD-P5 and MBD-P6. Soils were characterized in terms of their morphological and physio-chemical properties to find out the current suitability of soils for maize and beans. The suitability assessment was done by considering maximum limitation method, which consists of matching soil characteristics against crop requirements and assigning a suitability rate for each soil characteristics. The quality of soils was rated moderately suitable (s2) and highly suitable (s1) for both crops due to the identified limitations for crop production. Generally, the most limiting factors for the crops were found to be soil acidity (pH<5.4), low pH, available phosphorus, total nitrogen and base saturation. Top soil macronutrients and other chemical properties such as CEC, pH and % BS were also used to predict and generate soil suitability map of the study area in geographic information system (GIS) environment.

Keywords: MATI Mubondo farm, sampling units, soil suitability, soil characterization

4.2 Introduction

Soil is one of the most important natural resource which need to be maintained in good health for meeting out the increasing demand for food, fibres, fodder and fuel due to the increase in world population (Khan and Khan 2014; Taghizadeh-Mehrjardi *et al.,* 2020).

Soil evaluation is the assessment of the soil in both the intrinsic and extrinsic properties (Dorronsoro, 2002). The fitness of soil for crop cultivation is referred to as soil suitability (Mandal, 2013).

Agriculture is among the dominant economic sector in Tanzania, and it accounts for 26.4% of the total Gross Domestic Product (GDP), 30% of export earnings and 65% of raw material for domestic industries (Senkoro *et al.,* 2017; Katungi *et at.*, 2019). The sustainable and efficient use of soil resources is an important issue for agricultural development (Zhao *et al.,* 2005). Decline of soil fertility is alarming, which is a major factor affecting agricultural production in many parts of Tanzania (Hartemink *et al.,* 1996).

Previously, large area of MATI Mubondo farm was used by villagers/smallholders who used different farming systems such as shifting cultivation which led to the variability of soil fertility trends in such a way that other areas has been abandoned after depletion of plant nutrients. Those areas were overgrown with trees and shrubs (Miombo woodlands). Reconnaissance survey was carried out to determine the trend of variation and spatial distribution of soils in the farm by considering vegetation, soil and current land utilization type.

Maize and beans are the major crops in a study area as well as in Tanzania as whole (Lyimo *et al.,* 2014; Katungi *et al.,* 2019). Other major food crops in the country are paddy, wheat, sorghum, millet, cassava, sweet potatoes and bananas (Mkonda and He, 2016).

Soil suitability is a function of crop requirements and soil characteristics. This is the maximum limitation approach of soil suitability assessment which involves matching of soil characteristics with the crop requirements and provide suitability classes (Ritung *et al.*, 2007; Rabia and Terribile, 2013; Khan and Khan 2014; Maniyunda and Gwari, 2014).

Soil suitability has not been done in the study area. Therefore, this work will provide useful information that can help to resume and sustain productivity in the area and other areas nearby with the same presentation.

4.3 Materials and Methods

4.3.1 Description of study area

The study was conducted at MATI Mubondo farm, which is located 14 kilometers, South East of Kasulu township authority. The farm has an area of about 800 hectares and it is used for production of maize and beans (Urassa and Magweiga, 2017). More descriptions of the study area, field and laboratory work are given in chapter three of this document.

4.3.2 Assessment of soil suitability for Maize and Beans

Soil evaluation for crop suitability involves identifying parameters which will be considered in the analysis (Massawe, 2015). The parameters used for the soil quality included physical and chemical soil characteristics Tables 3.4, 3.5 and 3.6 (Abagyeh *et al.*, 2016).

The soil suitability assessment was performed using the maximum limitation method where by soils were put in suitability classes by matching their qualities with the established requirements for maize and beans (Table 4.2 and 4.3) (Abagyeh *et al.,* 2016). For each mapping unit, each soil quality was rated 1– 4, (Table 4.1.) A lower value is attributed when the parameter is less favorable. The soil quality rating was calculated from the sum of the sub-ratings correlated with 100. Each parameter was given equal importance, this is with accordance to the Liebig's Law of Minimum. The final suitability class was determined by the most limiting characteristics of the soils for the crop production. The suitability classes were determined by the value of the soil index:

S1: Very suitable soil 75 – 100

S2: Moderately suitable 50 – 75

S3: Marginally suitable soil 25 – 50

N: Currently unsuitable 0 - 25

Topsoil macronutrients and other chemical properties of soil such as CEC, pH and OM also were used to predict and generate soil suitability map of the study area after being digitized, classified, weighted and combined in GIS environment (Parry *et al.*, 2018). The evaluation was concerned with the assessment of soil performance for maize and beans (Massawe, 2015). The following process was followed:

4.3.2.1 Geospatial analysis

The boundary of the study area (Fig. 3.1) was created by digitizing and joining coordinates collected during field work. Soil profiles location coordinates were also digitized. Both files were put in the same coordinate reference system in order that they can overlay each other in ArcGIS interface. Profile points attribute table was joined with another comma separated value (CSV) format table which contained selected soil chemical parameters. Inverse distance weighting (IDW) method in ArcGIS was used for interpolation to generate topsoil partial suitability maps for selected soil chemical properties (Fig 4.1). This enabled interpolation to get soil raster map of each soil property considered for generation of suitability map (Fig. 4.2).

Table 4.1: Sub-rating of the physical and chemical characteristics of the soils

Factor	Unit	Values	Sub-rating	Mapping unit
Textural class		CL, C	4	MBD-P1 to MBD-P6
		SCL	3	
		SC, S	2	
		S	1	
Oxygen availability to roots	Soil drainage	Well drained	4	MBD-P1 to MBD-P6
		Moderately drained	3	
		Imperfectly drained	2	
		Poorly drained	1	
Rooting condition (Soil depth)	cm	>120	4	MBD-P1 to MBD-P6
		50 - 120	3	
		30 - 50	2	
		<30	1	
Soil reaction	pH	6.0 – 6.5	4	
		5.5 – 6.0 6.5 – 7.0	3	MBD-P2
		5.0 – 5.5 7.0 – 8.2	2	MBD-P5 and MBD-P6
		<5.0 >8.2	1	MBD-P1, MBD-P3 and MBD-P4
Organic C	%	>2.0	4	MBD-P1, MBD-P2, MBD-P3 and MBD-P6
		1.0 – 2.0	3	MBD-P4 and MBD-P5
		0.5 – 1.0	2	
		<0.5	1	
Total N	%	>0.2	4	MBD-P2, MBD-5 and MBD-P6
		0.1 – 0.2	3	MBD-P1, MBD-P3 and MBD-P4
		0.02 – 0.1	2	
		<0.02	1	
Avail. P	mg kg^{-1}	>40	4	
		10 – 40	3	
		3 – 10	2	MBD-P2, MBD-P3, MBD-P4, MBD-P5 and MBD-P6
		<3	1	MBD-P1
Ext. K	Cmo (+) kg^{-1}	>0.5	4	MBD-P2
		0.2 – 0.5	3	MBD-P5
		0.1 – 0.2	2	MBD-P1, MBD-P3 and MBD-P6
		<0.10	1	MBD-P4
CEC	Cmo (+) kg^{-1}	>25	4	MBD-P2, MBD-P5 and MBD-P6
		13 – 25	3	MBD-P1, MBD-P3, MBD-P4
		6 – 12	2	
		<6	1	

CL = Clay loam, C = Clay, SCL = Sand clay loam, S = sand

Table 4.2: Soil Requirements for Suitability Rating of Maize (Zea mays)

Land quality	Diagnostic factor	Unit	Factor rating: Highly suitable (S1)	Moderately suitable(S2)	Marginally suitable (S3)	Not suitable (N)
Textural class			CL, C	SCL	SC, S	S
Oxygen availability to roots	Soil drainage	Class	Well drained	Moderately well drained	Imperfectly drained	Poorly drained
Rooting condition	Soil depth	cm	>120	50 - 120	30 - 50	<30
Nutrient availability:	Soil reaction	pH	6.0-6.5	5.5-6.0, 6.5-7.0	5.0-5.5, 7.0-8.2	<5.0, >8.2
	Topsoil OC	%	>2.0	1.0-2.0	0.5-1.0	<0.5
	Topsoil N	%	>0.2	0.1-0.2	0.02-0.1	<0.02
	Topsoil Av.P	$mgkg^{-1}$	>40	10-40	3-10	<3
	Extractable K	Cmol $(+)kg^{-1}$	>0.5	0.2-0.5	0.1-0.2	<0.10
Nutrient retention capacity	Topsoil CEC	Me/100g	>25	13-25	6-12	<6

Key: C - Clay, CL – Clay Loam, SCL-Sand Clay Loamy, S-Sand, SC –Sand Clay, S1 – Highly suitable, S2 – Moderately suitable, S3 – Marginally suitable, N1 – Currently not suitable
Source: Kaaya et al. (1994). (Modified)

Table 4.3: Soil Requirements for Suitability Rating of beans

Land quality	Diagnostic factor	Unit	Factor rating: Highly suitable (S1)	Moderately suitable(S2)	Marginally suitable (S3)	Not suitable (N)
Textural class			CL, C	SCL	SC, S	S
Oxygen availability to roots	Soil drainage	Class	Well drained	Moderately well drained	Imperfectly drained	Poorly drained
Rooting condition	Soil depth	cm	>120	50 - 120	30 - 50	<30
Nutrient availability:	Soil reaction	pH	6.0-6.8	5.6-6.0, 6.8-7.0	5.2-5.5, 7.0-7.2	<5.2, >7.2
	Topsoil OC	%	>2.0	1.0-2.0	0.5-1.0	<0.5
	Topsoil N	%	>0.2	0.1-0.2	0.02-0.1	<0.02
	Topsoil Av.P	$mgkg^{-1}$	>40	10-40	5-10	<5
	Extractable K	Cmol $(+)kg^{-1}$	>0.5	0.2-0.5	0.1-0.2	<0.10
Nutrient retention capacity	Topsoil CEC	$Cmolkg^{-1}$	>25	13-25	6-12	<6

Key: C - Clay, CL – Clay Loam, SCL-Sand Clay Loamy, S-Sand, SC –Sand Clay, S1 – Highly suitable, S2 – Moderately suitable, S3 – Marginally suitable, N1 – Currently not suitable
Source: Kaaya *et al*. (1994). (Modified)

4.3.2.2 Reclassification

The produced soil properties raster maps were reclassified to provide partial suitabilities using ratings for maize and beans available in literature including Roy et al. (2006) and Hazelton and Murphy (2016). The classes were as follows: very low = 1, low = 2, medium = 3 and High = 4 (where by 1, 2, 3 and 4 were class values). Equal numbers of class units were applied on each parameter.

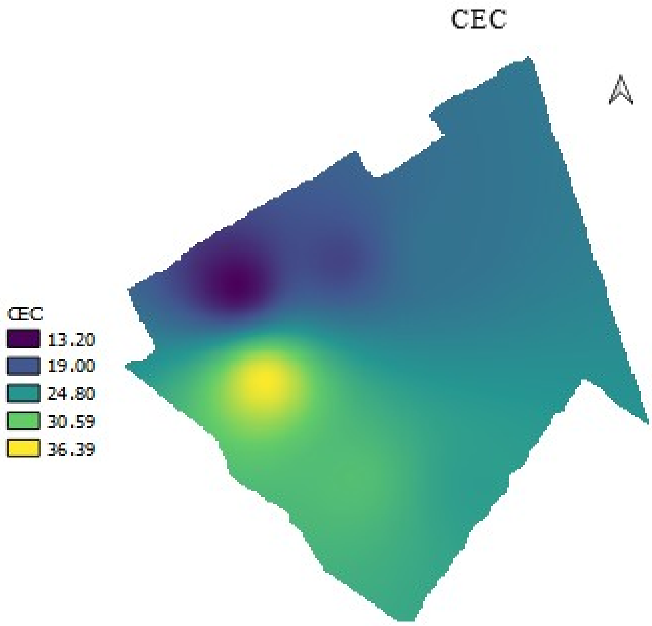
4.3.2.3 Production of overall suitability map

Weighting and ranking of soil classes in those raster maps were done before combining reclass raster maps. The layers were given equal weights when combining them to get overall suitability. Overall suitability maps were produced through Map Algebra Raster Calculator tool in spatial analysisTool extension of ArcGIS Toolbox. The classes in overall suitability map were; very low suitability = 1, low suitability = 2, medium suitability = 3 and high suitability = 4. 1, 2, 3 and 4 were class values.

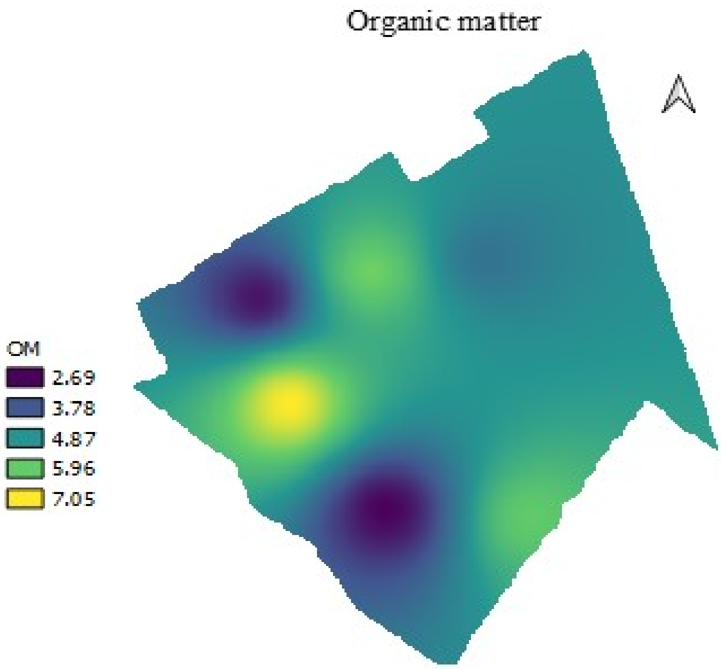
4.5 Results and Discussion

4.5.1 Results

The generated partial suitability maps for the selected chemical characterisics of the soil are showed in Figure 4.1 below (a to h) and the soil suitability maps are showed in figure 4.2 (a and b). The results for soil suitability by kriging are summarized in Table 4.4 and 4.5, and by traditional method in Table 4.6. The suitability maps for beans and maize respectively are shown in Figure 4.2.

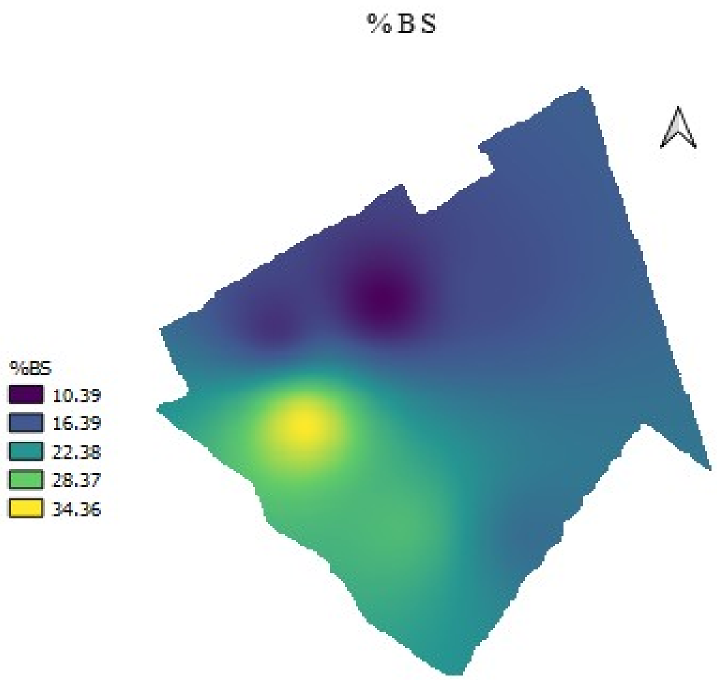


(a)

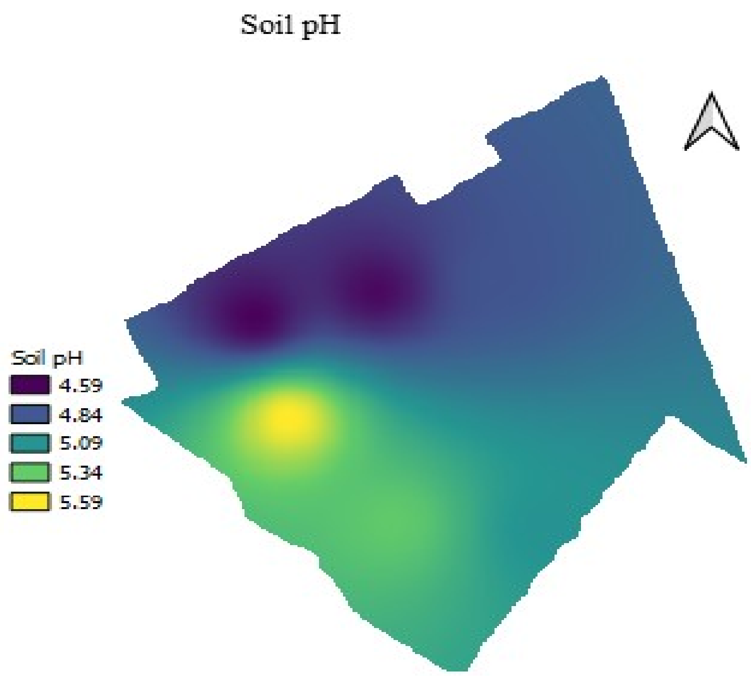


(b)

Figure 4.1(a) and (b): Raster maps for CEC and organic matter

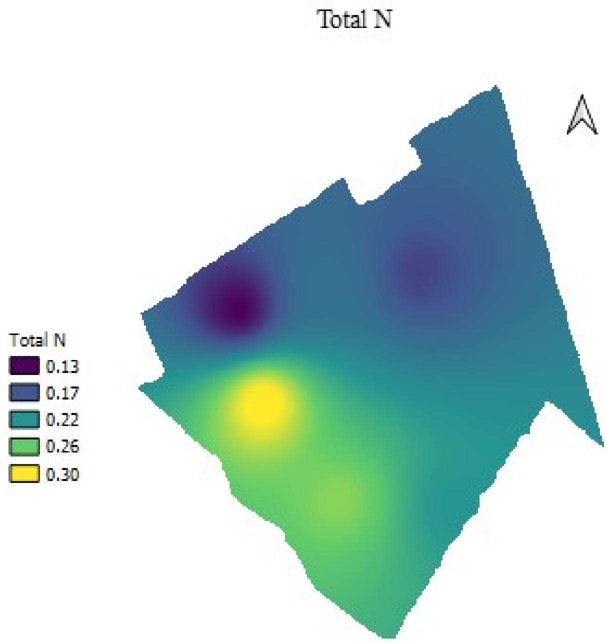


(c)

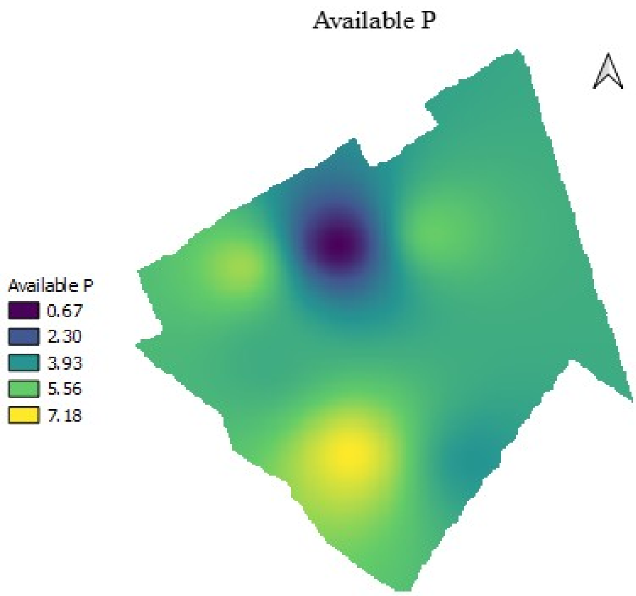


(d)

Figure 4.1(c) and (d): Raster maps for % BS and soil pH

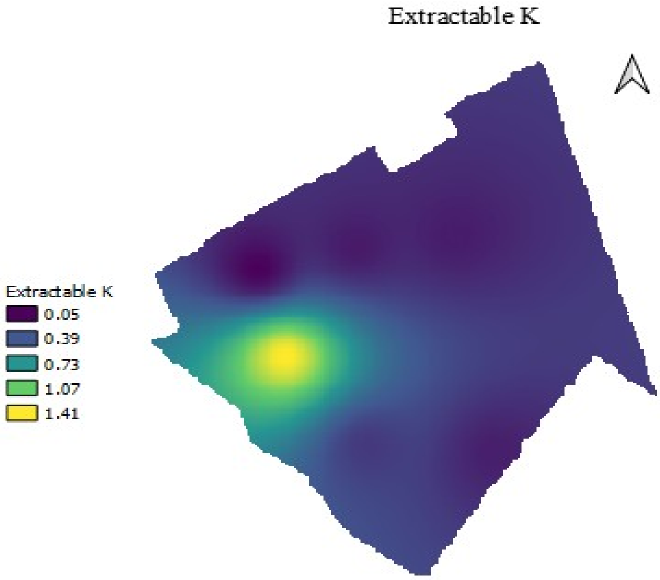


(e)

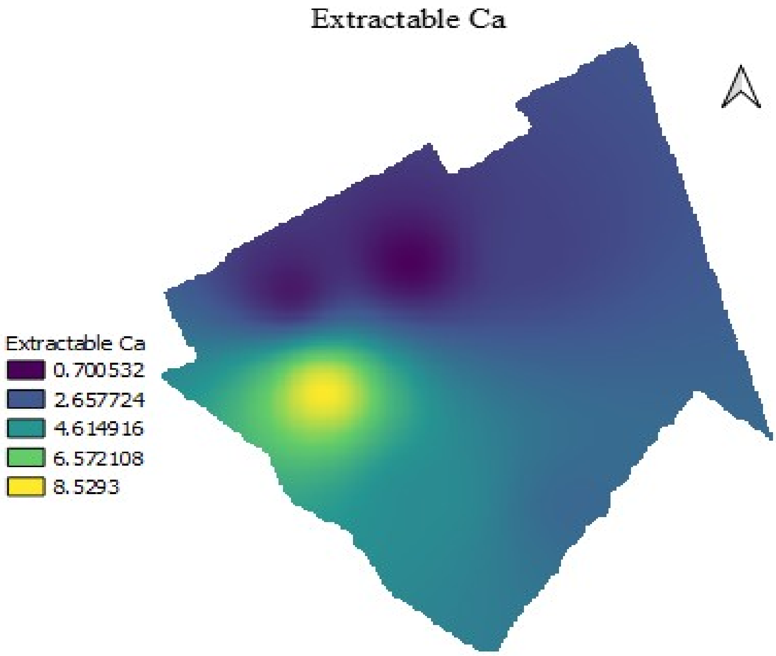


(f)

Figure 4.1(e) and (f): Raster maps for total N and available P



(g)



(h)

Figure 4.1(g) and (h): Raster maps for extractable K and extractable Ca

Table 4.4: Percentage of area of MATI Mubondo suitable for beans

S/N	Suitability status	Area (hectare)	% of total area
1	Very low suitability	150.59	22.00
2	Low suitability	286.03	41.78
3	Medium suitability	177.29	25.90
4	High suitability	70.73	10.32
Total		684.64	100

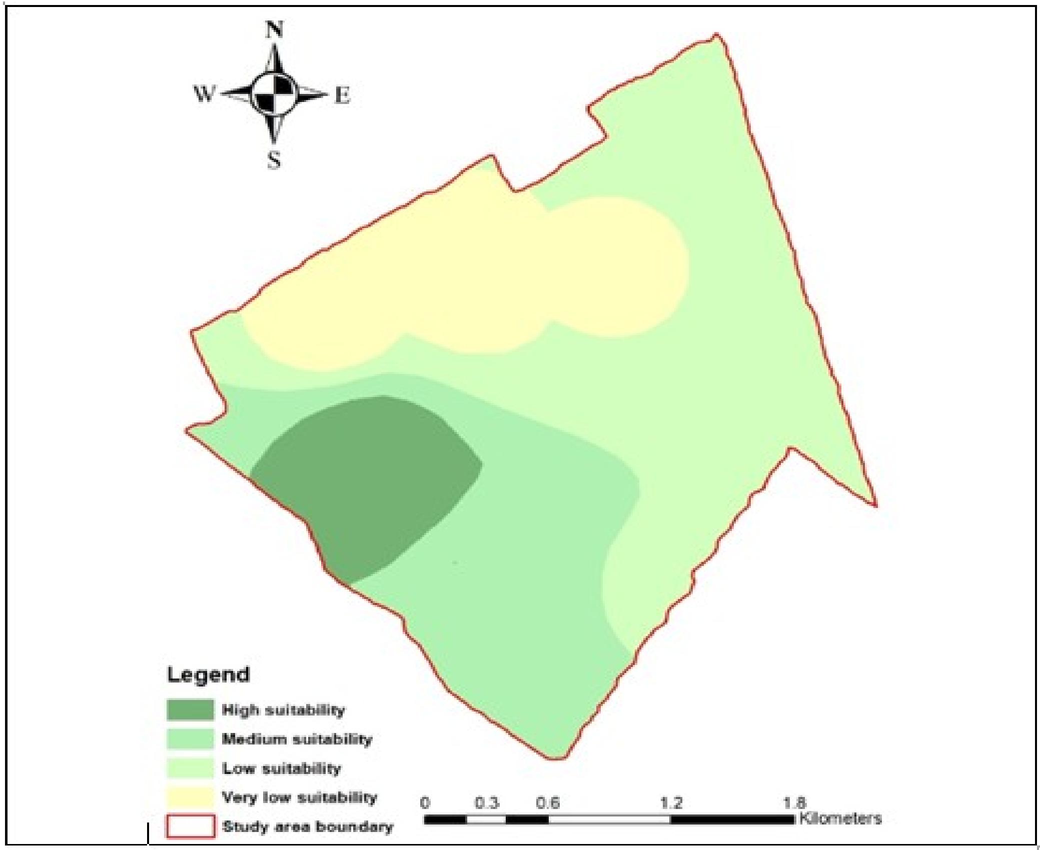


Figure 4.2(a): Soil suitability for beans base on chemical properties

Table 4.5: Percentage of area of MATI Mubondo suitable for maize

S/N	Suitability status	Area (hectare)	% of total area
1	Very low suitability	150.59	22.00
2	Low suitability	258.67	37.78
3	Medium suitability	189.28	27.65
4	High suitability	86.09	12.57
Total		**684.64**	**100**

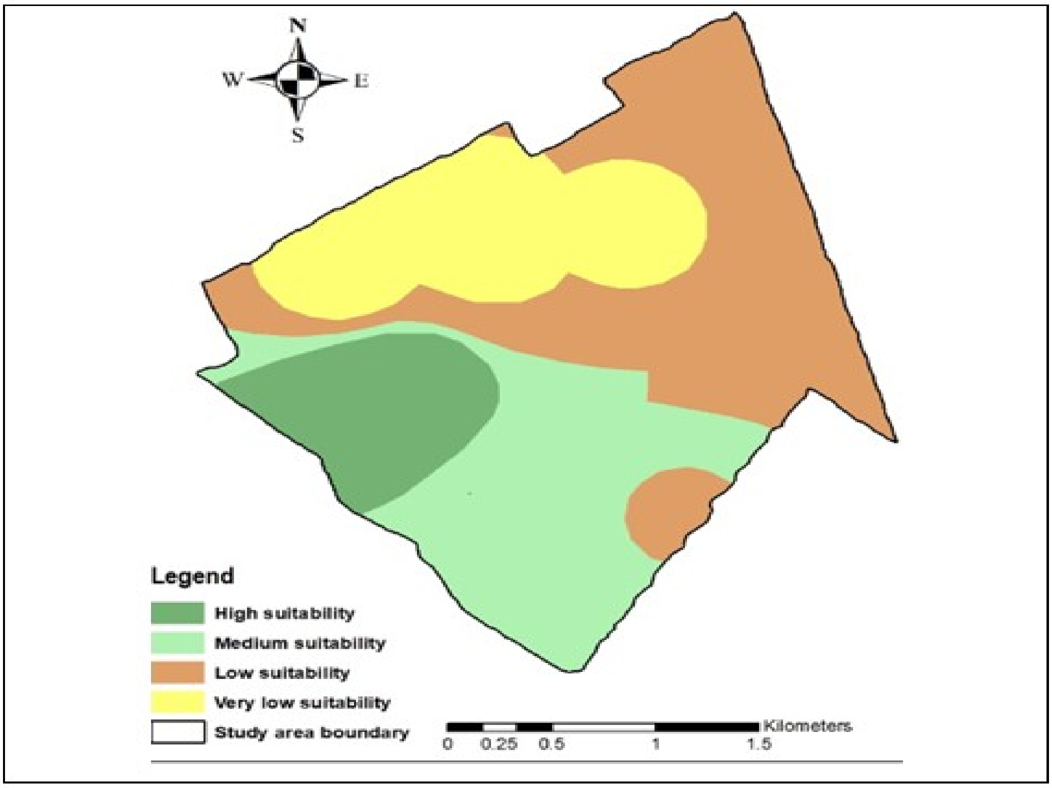


Figure 4.3(a): Soil suitability for maize base on chemical properties

4.5.2 Discussion

The results of soil suitability evaluation showed that the soils of MATI Mubondo farm slightly varied in suitability for maize and beans crops. The soils represented by MBD-P2, MBD-P5 and MBD-P6 are moderately suitable (subclass S_2f) Table 4.6. The soils represented by MBD-P1, MBD-P3 and MBD-P4 are marginally suitable (subclass S_3f) Table 4.6. Other works which are more or less the same to this were done by Kaaya *et al.* (1994), Sharififar (2013) and Selassie *et al.* (2014).

The geospatial analysis of the selected soil chemical properties was done, the results are presented in Table 4.2 (a) and (b), and Figure 4.2 (a and b), which shows that 22 % of the area was very low suitable (N1) for maize and beans, 37.78% and 41.78% were low suitable (S3) for maize and beans, 27.63% and 25.90% moderate suitable (S2) for maize and beans, and 12.57% and 10.32% were highly suitable (S1) for maize and beans respectively. The major limitations for the crops are low fertility status attributed by low amount of available phosphorus, low base saturation and low pH (Tables 4.3 and 4.4). The results demonstrated that kriging prediction were less similar to the actual data set obtained from sampling areas (Table 4.6). This is because kriging is a regression model that generates an estimated surface model from the spatial description of the scattered set of data points.

Table 4.6: Soil suitability ratings for rainfed maize and beans

Soil quality	Diagnostic factor	Mapping units and their suitability ratings					
		Pedon 1	Pedon 2	Pedon 3	Pedon 4	Pedon 5	Pedon 6
Soil texture	Class	s1	s1	s1	s1	s1	s1
Oxygen availability to roots	Soil drainage	s1	s1	s1	s1	s1	s1
Rooting condition	Effective soil depth	s1	s1	s1	s1	s1	s1
Nutrient availability:	Soil reaction	N	s2	N	N	s3	s3
	Topsoil OC	S1	s1	s1	s2	s2	s2
	Topsoil N	s2	s1	s2	s2	s1	s1
	Topsoil Avail. P	N	N	s3	s3	s3	N
	Ext. K	s3	s1	s3	N	s2	s3
Nutrient retention capacity:	Topsoil CEC	s2	s1	s2	s2	s1	s1
Overall soil suitability		s3f	s2f	s3f	s3f	s2f	s2f

Key: S1: Highly suitable; S2: Moderately suitable; S3: Marginally suitable; N1: Currently not suitable; f: soil fertility limitation.

4.6 Conclusions and Recommendations

4.6.1Conclusions

The assessment of soil suitability can help decision makers recognize the most limiting soil parameters and assessing the potential for improvement of such factors under the current situation. The suitability was done by two methods; the traditional and kriging methods.

Soil suitability in mapping units MBD-P1, MBD-P3 and MBD-P4 fall under marginally suitable for maize and beans production because of low fertility status attributed to strong acidic (<pH 5.4), low available phosphorus, base saturation and zinc. Soil mapping units MBD-P2, MBD-P5 and MBD-P6 were put under moderately suitable class for maize and beans due to identified limitations such as low available phosphorus, base saturation, pH and Zinc for optimum maize and beans production. Also, there were antagonistic effects between calcium and magnesium because their ratios are not within the desirable range. This is according to Kopittke and Menzies (2007).

The study has produced map on the suitability of soils of MATI Mubondo Farm for maize and beans production. The maps were produced by kriging method. The suitability assessment of soil will allow growing the crops at right sites by using right amount of fertilizer for optimum yields. The results demonstrated by kriging prediction were less similar to the traditional method. This is because kriging predicts values in an area using known value.

4.6.2 Recommendations

Good agricultural practices (GAP) such as addition of organic matter and liming to raise the soil pH, and improve cation exchange capacity of the soil and availability of other plant nutrients is strongly recommended. Routine soil analysis is very important to know the nutrient status of the soil. Further studies are required to other crops for diversification purpose or as alternative crops to maize and beans.

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CHAPTER FIVE

5.0 GENERATION OF SITE AND CROP SPECIFIC NUTRINETS RECOMMENDATIONS FOR MAIZE AND BEANS PRODUCTION

5.1 Abstract

A nutrient recommendation is the way conclusions are put forward based on soil test. Soil test tells the nutrients status of the soil, hence fertility which is the ability of the soil to supply nutrients for the plants at optimum level. It is important for maintenance of soil quality by applying right amount of nutrients and reduces the misuse of soil resources and increase farming productivity. Therefore, being acquainted with the amount of plant nutrient available in the soil, it is easy to decide the amount and type of nutrients to recommend regarding the target yield. Strong acidic (pH <5.4), low available phosphorus (Available P <7 ppm), CEC (< 12 cmol (+)/kg) and base saturation ($< 40\%$) were the major limiting factors for crop production in MATI Mubondo farm. The low pH of the soil might have attributed to the deterioration of other soil chemical properties in the farm. The buildup and maintenance approaches for nutrient recommendations were proposed.

Key words: Nutrient recommendation, soil test, soil fertility, plant nutrients

5.2 Introduction

Nutrient recommendations refer to the way conclusions are drawn based on soil tests (Hochmuth *et al.,* 2014). Soil test tells the status of nutrients currently available for plants growth and development since nutrients get depleted if the land is used without appropriate management (Xu *et al.,* 2014; Sultana *et al.,* 2015). For maintenance of soil quality and attainable crop yield, it is required to apply appropriate amount of fertilizers and minimize the misuse of soil resources which is possible by testing the soil and knowing the actual situation of its characteristics (Sultana *et al.,* 2015). The success of any nation is dependent upon several factors, the most important one being the maintenance of soil fertility as basis for an indigenous food supply (FAO, 1979).

Soil fertility is the ability of soil to supply plant nutrient at optimum level, which interact with other components of fertility such as water and air. In agricultural land, nutrients get lost from soil plant system in a number of ways such as removal of harvested grains, leaching and erosion (FAO, 1979). Thus, to maintain soil nutrient status at its existing level it is necessary to apply nutrients to the soils to compensate losses. This enable crops to reach their full growth and yield potential. Therefore, the use of fertilizers and organic manures is necessary for the maintenance of cropped soils (FAO, 1979). For sound recommendations of nutrients use to be possible, it is necessary to know the nutrient status of the soil and the nutrients requirements of the crops to be grown. The cropping system to be followed and the amount of nutrients already present in the soil, must all be taken into account during nutrient recommendations. Balanced fertilizer recommendations based on soil test value has become necessary to increase fertilizer use efficiency, maintain soil health, protect environment and reduce production cost (Sultana *et al.*, 2015). The objective of this study was to use available soil information to make calculations and recommendations on nutrients types and amounts to be applied to attain optimum yield levels for maize and beans in Mubondo Farm.

5.3 Materials and Methods

This study was based on the soil test values obtained (Chapter 3) and nutrient requirements, uptakes and removal (Table 5.1) for beans and maize respectively.

Table 5.1: Some nutrients plant uptake and removal by maize and beans

Parameter	Maize		Beans	
	Total uptake	Removal with grains	Total uptake	Removal with grains
		$kgha^{-1}$ (macronutrients)		
N	119.17	69.17	158.05	115.52
P_2O_5	47.50	37.50	27.59	22.41
K_2O	84.17	27.50	98.85	44.83
CaO	77.78	11.03	90.92	8.05
MgO	41.05	11.81	47.99	8.62
SO_4-	32.50	18.75	32.76	18.97
		gha^{-1} (micronutrients)		
ZnO	249.00	154.00	231.03	96.55
MnO	361.33	48.00	341.15	84.60
Fe_2O_3	819.87	147.77	697.74	202.17
CuO	73.44	21.36	45.64	27.99

Source: Bende *et al.* (2013) and Bender *et al.* (2015)

The plant nutrients analyzed were converted into mg kg^{-1} from percentage (total nitrogen) and Cmol (+) kg^{-1} (cations) (Table 5.2). Percentage values of total nitrogen were multiplied by 10000 to convert to mg kg^{-1}. The cations Cmol (+) kg^{-1} were convert to mg kg^{-1} by multiplying Cmol (+) kg^{-1} of elements by their respective equivalent weights multiplied by ten (Deenik,2005): mg kg^{-1} = Cmol kg^{-1} *Ew*10 (13).

The studied nutrient values (mg kg^{-1}) were multiplied by their respective factors to convert them into their oxide forms except nitrogen which exist in elemental form. The mapping units' bulk density determined, the plough depth (15 cm) and the area (hectare = 10000 m^2) were used to calculate the total weight of soil per area (kg ha^{-1}) (Table 5.3). The bulk density in g cm^{-3} was converted to kg m^{-3} by multiplying by a factor of 1000, and plough depth (15 cm) was converted to meter by dividing by 100.

The nutrient elements in mg kg^{-1} (Table 5.2) were converted to kg ha^{-1} (Table 5.4). This was done by converting milligram of nutrient elements into kilogram and correlating with the weight of soil per hectare (Table 5.3).

5.4 Results and Discussion

5.4.1 Results

Tables 5.2 present topsoil elements analyzed in milligram per kilogram, Table 5.3 present bulky density of the areas and corresponding weight of soil per hectare, and Table 5.4 present plant nutrients available per hectare at MATI Mubondo Farm. Soil test results showed that, some parameters were not in optimum level for plant growth and are limiting optimum yields. The pH was low generally very strongly acid (Msanya *et al.*, 2001), available P is low (Kebeney *et al.*, 2014), exchangeable Ca and K are low (Roy *et al.*, 2006; Hazelton and Murphy, 2016), exchangeable Mg was low for MBD-P1 and 4, medium for MBD-P2, 3 and 6 and high for MBD-P5 and low base saturation as presented in Table 3.5 (Havlin, 2014; Hazelton and Murphy, 2016).

Table 5.2: Topsoil elements analyzed in milligram per kilogram (mg kg^{-1})

DEPTH	HORIZON	N	P_2O_5	K_2O	CaO	MgO	SO_4	Fe_2O_3	ZnO	MnO	CuO
						mg kg^{-1}					
MBDP1 0-15	Ah	1900	1.541	65.52	196	186.372	146.61	62.23	0.83	48.16	9.06
MBDP2 0-15	Ap	3100	10.58	664.56	2388.4	498.996	201.96	52.37	4.19	319.92	26.28
MBDP3 0-15	Ap	1600	12.90	70.2	596.4	214.428	82.08	42.5	0.72	96.89	13.54
MBDP4 0-10	Ap	1300	14.214	23.4	336	104.208	75.93	60.26	0.49	1.08	8.83
MBDP5 0-15	A	2100	17.71	121.68	1120	629.256	143.55	44.47	1.89	49.60	10.48
MBDP6 0-10	Ap	2200	9.039	74.88	887.6	270.54	100.5	33.63	0.72	147.92	10

Table 5.3: Bulk Density of the areas (sampling units) and corresponding weight of soil per hectare

Depth	Horizon	BD (gcm^{-3})	BD (kgm^{-3})	Volume of soil (m^3/ha)	Weight of soil (kg/ha)
MBDP1					
0-15	Ah	1.36	1360	1500	2040000
MBDP2					
0-15	Ap	1.43	1430	1500	2145000
MBDP3					
0-15	Ap	1.26	1260	1500	1890000
MBDP4					
0-10	Ap	1.40	1400	1500	2100000
MBDP5					
0-15	A	1.47	1470	1500	2205000
MBDP6					
0-15	Ap	1.43	1430	1500	2145000

Table 5.4: Plant nutrients available per hectare at MATI Mubondo farm

DEPTH	HORIZON	N	P_2O_5	K_2O	CaO	MgO	SO_4^-	Fe_2O_3	ZnO	MnO	CuO
MBDP1						kg ha^{-1}					
0-15	Ah	3876	3.14	133.66	399.84	380.2	299.08	126.95	1.7	98.24	18.49
MBDP2											
0-15	Ap	6649.5	22.69	1425.48	5123.12	1070.35	433.20	112.33	8.98	686.23	56.36
MBDP3											
0-15	Ap	3024	24.39	132.68	1127.2	405.27	155.13	80.33	1.37	183.13	25.59
MBDP4											
0-10	Ap	2730	29.84	49.14	705.6	218.84	159.45	126.55	1.02	2.28	18.53
MBDP5											
0-15	A	4630.5	39.05	268.30	2469.6	1387.51	316.53	98.06	4.18	150.44	23.09
MBDP6											
0-15	Ap	4719	19.39	160.62	1903.9	580.31	215.57	74.15	1.55	317.3	21.45

5.4.2 Discussions

5.4.2.1 Total nutrient uptake and removal

Total nutrient uptake and removal at physiological maturity and removal with grains are presented in table 5.1. These nutrient parameters are associated with producing potentially 5 and 2 tones for maize and beans respectively (Bender *et al.*, 2013; Bender *et al.*, 2015). Macronutrients are expressed in kg ha^{-1} whilst micronutrients are expressed in g ha^{-1}. The information is similar to the study by Heckman *et al*. (2003) for measuring the nutrient uptake in Mid-Atlantic region of the USA and Aulakh *et al*. (1985).

5.4.2.2 Nutrient management recommendations

Levels of essential elements (nutrients) available in the soil influence the growth and development of the plant (Warncke *et al.,* 2009). To achieve this, maintenance of soil health is crucial by placing right amount of nutrients according to the crop requirements and taking into consideration nutrients already available in the soil (Cottenie, 1980). According to Tisdale *et al.* (1999), when soil test level of nutrients is very low or low, the nutrient recommendations amount should be equal to the crop uptake. If the soil test is optimum the recommendation should be equal to crop removal, if the soil test is high or very high, the recommendation should be 0.5 or 0.25 of crop removal and if the soil test is excessively high none recommendation is given.

5.4.2.3 Nutrient recommendations for maize and beans

Nutrient recommendation for maize and beans in each sampling unit for macronutrients are presented in Table 5.5 to 5.10 respectively. The recommendations for calcium are equal to 13 times of potassium and that of magnesium are equal to 2 time that of potassium which adhere the Basic Cation Saturation ratio concept according to Firman Bear and coworkers (1940), cited by Kopittke and Menzies (2007). Improved maize varieties (IMVs) grown in the study area are Pannar, Pioneer and Delkab seeds and spacing adopted is 60 cm between plant and 75 cm between rows. Improved beans varieties grown in the farm are Uyole Njano and Lyamungo, and also indigenous varieties. Spacing adopted is 20 cm between plants and 40 cm between rows.

Table 5.5: Macronutrients soil test values, status and recommendations for MBD-P1

Element	Soil test value (kg ha^{-1})	Status	Recommendation (kg ha^{-1})	
			Maize	Beans
N	3876	Low	119.17	158.05
P_2O_5	3.14	Low	47.50	27.59
K_2O	133.66	Very low	84.17	98.85
MgO	380.2	low	41.05	47.99
CaO	399.84	Very low	77.78	90.92
SO_4^-	299.08	High	9.38	9.9

Table 5.6: Macronutrients soil test values, status and recommendations for MBD-P2

Element	Soil test value (kg ha^{-1})	Status	Recommendation (kg ha^{-1})	
			Maize	Beans
N	6649.5	Medium	69.17	115.52
P_2O_5	22.69	Very low	47.50	27.59
K_2O	1425.48	Very high	84.17	98.85
MgO	1070.35	Medium	11.81	8.62
CaO	5123.12	Medium	11.03	8.05
SO_4^-	433.20	High	9.38	9.9

Table 5.7: Macronutrients soil test values, status and recommendations for MBD-P3

Element	Soil test value (kg ha^{-1})	Status	Recommendation (kg ha^{-1})	
			Maize	Beans
N	3024	Low	119.17	158.05
P_2O_5	24.3	Low	47.50	27.59
K_2O	132.68	Very low	84.17	98.85
MgO	405.27	Medium	11.81	8.62
CaO	1127.2	Low	77.78	90.92
SO_4^-	155.13	High	9.38	9.9

Table 5.8: Macronutrients soil test values, status and recommendations for MBD-P4

Element	Soil test value (kg ha^{-1})	Status	Recommendation (kg ha^{-1})	
			Maize	Beans
N	2730	Low	119.17	158.05
P_2O_5	29.84	Low	47.50	27.59
K_2O	49.14	Very low	84.17	98.85
MgO	218.84	Low	41.05	47.99
CaO	705.6	Very low	77.78	90.92
SO_4^-	159.45	High	9.38	9.9

Table 5.9: Macronutrients soil test values, status and recommendations for MBD-P5

Element	Soil test value (kg ha^{-1})	Status	Recommendation (kg ha^{-1})	
			Maize	**Beans**
N	4630.5	Medium	69.17	115.52
P_2O_5	39.05	Medium	37.50	22.41
K_2O	268.30	Low	84.17	98.85
MgO	1387.51	High	5.91	4.31
CaO	2469.6	Low	77.78	90.92
SO_4^-	316.53	High	9.38	9.9

Table 5.10: Macronutrients soil test values, status and recommendations for MBD-P6

Element	Soil test value (kg ha^{-1})	Status	Recommendation (kg ha^{-1})	
			Maize	**Beans**
N	4719	Medium	69.17	115.52
P_2O_5	19.39	Low	47.50	27.59
K_2O	160.62	Very low	84.17	98.85
MgO	580.31	Medium	11.81	8.62
CaO	1903.9	Low	77.78	90.92
SO_4^-	215.57	High	9.38	9.9

5.5 Nutrient Recommendation Philosophy Based on Cations

The recommendation is based on an ideal ratio of soil cations. It was put forward in order to achieve the Basic Cation Saturation Ratio (BCSR) of nutrient recommendations. The philosophy focuses on cations Ca, Mg and K and try to maintain ratios of these cations on the soil cation-exchange complex, which are approximately 65% Ca, 10% Mg and 5% K and 20% H. The resulting desired ratios are 6.5Ca:1Mg, 13Ca:1K, and 2Mg:1K (Hochmuth *et al.*, 2014). In subsequent season, "The Build-Up and Maintenance" should be used by applying amount of nutrients removed by the crop (Murdock, 1997; Hochmuth *et al.*, 2014). These nutrient recommendations are based on monocropping system for both maize and beans.

5.6 Conclusions

The climate of Kigoma region and Kasulu in particular, exhibit tropical with a distinct long wet rainy season beginning from late October to May with a short dry spell of 2–3 weeks in January or February. Annual rainfall is variable ranging from 600–1500 mm which is favorable for maize and beans production. Therefore, the yield decline is due to low soil fertility status which was revealed after soil test.

The nutrient recommendations for MATI Mubondo farm were based on soil testing of fertility status, the plant uptake and removal of maize and beans respectively, which adhere to the buildup philosophy of fertilizer recommendations. In succeeding year/cropping seasons the recommendations will be based on amount of nutrients removed by harvested crops in order to maintain the soil health. The recommendations were done only on macronutrient since micronutrients were not limiting factors for the crop production except zinc which can be corrected using foliar fertilizer.

5.7 Recommendations

Routine soil analysis is important in determining the nutrient status of the soil, so that right amount of nutrients or amendment can be applied to the crops to increase production. Application of lime materials is crucial so as to raise soil pH values which will bring about more availability of plant nutrients. Addition of organic matter into the soil can mask the impact of acidic condition, increase nutrient and water retention of the soil and hence survival of the crops.

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CHAPTER SIX

6.0 CONCLUSIONS AND REOMMEDNATIONS

6.1 Conclusions

i. The soils of MATI Mubondo farm were characterized and classified as Oxisols in USDA soil taxonomy system (ST) and Ferralsols in World Reference Base for Soil Resources (WRB).

ii. The soils showed slightly variation in terms of morphological and physical properties. The soils were very deep, fine textured and highly weathered dominated by kaolinitic clay and sesquioxides developed predominantly by in situ weathering of parent materials.

iii. Soils had low inherent fertility (low plant nutrients reserve) such as low available phosphorus, low exchangeable bases (Ca, Mg and K) and acidic condition. This is because of the tendency of Oxisols soil to have low nutrient holding capacity.

iv. The assessment of soils suitability under the current situation helps to distinguish the most limiting factors and assessing the potential for improvement of factors.

v. The soils for mapping units 1, 3, and 4 were marginally suitable whilst mapping units 2, 5 and 6 were moderately suitable for the maize and beans production due to the identified limitations.

vi. The fertilizers are recommended on basis of soil fertility status, buildup and maintenance approach, whereby nutrients whose indexes were interpreted medium or low per soil test are added to high category levels.

6.2 Recommendations

The study recommends the following:

i. Due to low nutrient status, the soils need to be amended through an integrated nutrient management such as application of a combination of inorganic and organic nutrient sources.

ii. Since this study was done qualitatively, therefore further studies are required in quantitative terms of soil suitability evaluation for maize and beans as well as other crops in the area and should be confirmed by field experiments.

iii. Routine soil analysis is crucial to determine the amount of available plant nutrients, physical and biological soil properties are important for plant nutrition and general soil health.

iv. For maintenance of plant nutrients in the farm especially when beans are cropped, amount of nutrient uptake, is equal to the amount removed since during harvesting the whole plant is uprooted and taken away. For the case of maize, grains and cobs are removed from the field during harvesting, therefore determining nutrient available in cob also is important in order to know the actual nutrients removal. This is because of the financial constraint, that crops are manually harvested. But in those areas where combine harvesters are used only grains are removed and fertilizer recommendations are low.

APPENDICES

Appendix 1: Soil profile description and analytical data

Profile number: MBD-P1 Mapping unit: M1
Region: Kigoma
District: Kasulu
Coordinates: 030.18216ºE/04.52276ºS
Location: 50 m north of Mkwawa domitory.
Author: N.P. Mwakinyala and B.M. Massawe
Date: 191223. Weather condition: rainy season. Landform: Plain. Elevation: 1257 masl. Parent material: in situ weathering. Site characteristics: Slope: 0.5% (level); straight; 500m long; middle slope. SMR: Ustic. STR: Isohyperthermic.
Natural drainage class: Well drained; Soils are deep well drained. Natural vegetation type: trees (50%), grasses (30%), shrubs (15%) and herbs (5%). Dominant species: trees. Land use: Natural forest. Soil fauna: Termites. Regenerated natural forest.

Ah 0-15 cm: very dusky red (7.5R2.5/3) moist; clay, very friable moist, slightly sticky and plastic wet, moderate, fine and granular, many fine pores; common and medium roots, clear smooth boundary to

A/B 15-26/34 cm: dusky red (10R3/3) moist; clay; friable moist, slightly sticky and slightly plastic wet; moderate, medium and subangular blocky; common and fine pores; few and medium roots.

Bo 26/34-160+ cm: dusky red (10R3/4) moist; very friable moist, slightly sticky and slightly plastic wet; weak and fine subangular blocky;
common and very fine pores: few and very fine roots.

SOILCLASSIFICATION: WRB (FAO, 2015) Rhodic umbric Ferralsols (Clayic, Dystric). USDA Soil Taxonomy (Soil Survey Staff, 2014): Typic Haplustox.

ANALYTICAL DATA FOR PROFILE MBD-P1

Horizon	Ah	A/B	Bo
Depth (cm)	0-15	15-26/34	26/34-160+
Clay (%)	66.76	78.76	73.76
Silt (%)	13.00	11.00	12.00
Sand (%)	20.24	10.24	14.24
Texture class	Clay	Clay	Clay

Bulky density	1.36	nd	nd
pH H_2O 1:2.5	4.61	4.68	4.69
pH $CaCl_2$	3.72	4.05	3.98
EC1:2.5(dS/m)	0.0933	0.028	0.0125
ESP	0.32	1.01	2.02
Organic C (%)	3.51	1.4625	0.351
Total N (%)	0.189	0.091	0.042
C/N ratio	18.57	16.07	8.36
Avail.P Bray1(mgkg^{-1})	6.71875	3.59375	6.40625
Ext. S (mg Kg-1)	48.87	28.38	46.82
CEC NH4OAc cmol (+) kg^{-1}	17.6	5.2	6.4
Exch.Ca cmol (+) kg^{-1}	0.7033	0.4683	0.4196
Exch.Mg cmol (+) kg^{-1}	0.9330	0.3237	0.1529
Exch.K cmol (+) kg^{-1}	0.1365	0.0531	0.0632
Exch.Na cmol (+)kg^{-1}	0.0566	0.0524	0.1291
Base saturation (%)	10.39	17.26	11.95
CEC_{Clay} cmol(+)kg^{-1}	8.23	0.20	7.04

Profile number: MBD-P2 Mapping unit: M2
Region: Kigoma.
District: Kasulu.
Location: 70 m South of cattle dip tank.
Coordinates: 030.17797ºE/04.63029ºS
Author: N.P. Mwakinyala and B.M. Massawe
Date: 191223. Weather condition: rainy season. SMR: Ustic. STR: Isohyperthermic. Landform: Plain. Elevation: 1226 masl. Parent material: Alluvium. Site characteristics; Slope: 0.5% (level). straight; 500m long; middle slope. Natural drainage class: Well drained. Natural vegetation type: trees (15%), shrubs (25%), herbs (10%) and grasses (50). Dominant species: grasses. Land use: fallow/previously under annual crops. Soil fauna: Termites. Human influences: Cultivation.

Ap 0-15 cm: very dusky red (2.5YR2.5/2) moist; silt clay, friable moist, sticky and plastic wet, moderate, very fine and granular, many fine pores; many and fine roots, gradual wavy boundary to

AB 15-36 cm: dark reddish brown (5YR3/3) moist; clay; friable moist, sticky and plastic wet; moderate, fine plate; many and fine pores; many and fine roots, clear smooth boundary to

Bt 36-85/96 cm: dark reddish brown (2.5YR3/4) moist; firm moist, sticky and slightly plastic wet; moderate and medium plate; many distinct clays, few and fine pores: very few and fine roots; clear wavy boundary to

Bo 85/96-150+ cm: dark reddish brown (2.5YR2.5/4) moist; friable moist; slightly sticky and slightly plastic wet; weak and fine granular; common and fine pores; very few and fine roots.

SOILCLASSIFICATION: WRB (FAO, 2015) Haplic Umbric Ferralsols (Clayic, Dystric). USDA Soil Taxonomy (Soil Survey Staff, 2014): Kanhaplic Rhondustalfs.

ANALYTICAL DATA FOR PROFILE MBD-P2

Profile number: MBD-P3 Mapping unit: M3
Region: Kigoma.
District: Kasulu.
Location: 1000 m South of main road (Kibondo road).
Coordinates: 030.18805ºE/04.52196ºS
Author: N.P. Mwakinyala and B.M. Massawe
Date:191225. Season/weather conditions: rainy season. SMR: Ustic. STR: Isohyperthermic. Landform: Plain. Elevation: 1253 masl. Parent material: alluvium. Site characteristics; Slope: 0.5% (level); straight; 2000 m long; middle slope. Natural drainage class: well drained. Natural vegetation type: trees (15%), shrubs (15%), herbs (50%) and grasses (20%), dominant species; herb. Land use: farming; annual crops. Soil fauna: Termites. Human influences: farming

Ap 0-15 cm: dark brown (7.5YR3/4) moist; Moisture condition: moist; clay, friable moist, sticky and plastic wet, weak and fine granular structure, many fine pores; many and fine roots, gradual wavy boundary to
A/B 15-34 cm: dark reddish brown (2.5YR2.5/4) moist; moisture condition: moist; clay; friable moist, sticky and slightly plastic wet; moderate and fine granular structure; many and very fine pores; common and very fine roots, clear smooth boundary to

Bo 34-140+ cm: dusky red (10R3/4) moist; moisture condition: moist; clay, very friable moist, sticky and slightly plastic wet; moderate and medium platy structure; common and very few pores; very few and medium roots.

Horizon	Ap	AB	Bt	Bo
Depth (cm)	0-15	15-36	36-85/96	85/96-150+
Clay (%)	47.76	63.76	82.76	81.76
Silt (%)	38.00	16.00	9.00	8.00
Sand (%)	14.24	20.24	8.24	10.24
Texture class	Silt Clay	Clay	Clay	Clay
Bulky density	1.43	nd	nd	
pHH_2O 1:2.5	5.6	4.90	5.04	5.40
pH $CaCl_2$	4.95	4.09	4.24	4.84
EC1:2.5(dS/m)	0.323	0.0801	0.0407	0.0228
ESP	0.18	0.27	0.63	0.50
OrganicC (%)	4.095	1.7745	0.6045	0.39
Total N (%)	0.308	0.105	0.056	0.056
C/N	13.30	16.9	10.79	6.96
Avail.P Bray1(mgkg^{-1})	4.6041	2.5828	1.1229	0.3369
Ext. S(mgkg^{-1})	67.32	31.45	67.32	25.31
CEC NH4OAc (cmol (+) kg^{-1})	36.40	22.40	10.40	8.80
Exch.Ca cmol (+) kg^{-1}	8.5294	4.2337	2.9031	2.5385
Exch.Mg cmol (+) kg^{-1}	2.4863	1.0054	0.8766	1.0508
Exch.K cmol (+) kg^{-1}	1.4157	0.1441	0.0683	0.0531
Exch.Na cmol (+) kg^{-1}	0.0652	0.0609	0.0652	0.0439
Base saturation (%)	34.33	24.3	37.63	41.89
CEC_{Clay} cmol (+)kg^{-1}	46.65	25.54	10.05	9.12

SOILCLASSIFICATION: WRB (FAO, 2015) Rhodic Umbric Ferralsols (Clayic, Dystric). USDA Soil Taxonomy (Soil Survey Staff, 2014): Typic Kandiustox.

ANALYTICAL DATA FOR PROFILE MBD-P3

Horizon	Ap	A/B	Bo
Depth (cm)	0-15	15-36	36-85/96
Clay (%)	73.76	81.76	85.76
Silt (%)	12.40	10.80	12.00
Sand (%)	13.84	7.44	2.24
Texture class	Clay	Clay	Clay
Bulky density	1.26	nd	nd
pHH_2O 1:2.5	4.83	4.00	4.93
pH $CaCl_2$	3.95	3.33	4.26
EC1:2.5(dS/m)	0.0683	0.0486	0.0176
ESP	0.14	0.26	0.89
OrganicC (%)	2.4765	1.3455	0.6045
Total N (%)	0.161	0.091	0.049
C/N	15.38	14.79	12.34
Avail.P Bray1(mg/kg)	5.6147	0.8984	0.8984
Ext. S(mg/kg-1)	27.36	35.55	35.55
CEC NH4OAc (cmol (+) kg^{-1}	21.60	15.20	6.40
Exch.Ca cmol (+) kg^{-1}	2.1262	0.6499	0.9210
Exch.Mg cmol (+)/kg^{-1}	1.0667	0.3981	0.7157
Exch.K cmol (+) kg^{-1}	0.1491	0.0784	0.0379
Exch.Na cmol (+) kg^{-1}	0.0311	0.0396	0.0566
Base saturation (%)	15.62	7.67	27.05
CEC_{Clay} cmol (+) kg^{-1}	17.71	12.92	5.03

Profile number: MBD-P4 Mapping unit: M4
Region: Kigoma.
District: Kasulu.
Location: 800 m South of main road (Kibondo road).
Coordinates: 030.18805ºE/04.52196ºS
Author: N.P. Mwakinyala and B.M. Massawe
Date:191226. Season/weather conditions: rainy season
SMR: Ustic. STR: Isohyperthermic. Landform: Plain. Elevation: 1236 masl. Parent material: alluvium. Site characteristics; Slope: 1.0% (nearly level); straight; 1500m long; upper slope.
Natural drainage class: Well drained. Natural vegetation type: trees (30%), herbs (20%) and grasses (50%), dominant species: grasses. Land use: Abandoned land. Soil fauna: Termites. Human influences: Burning

Ap 0-15 cm: dusky red (10R3/4) moist; Moisture condition: moist; friable moist, sticky and plastic wet, moderate and medium granular structure, common and fine pores; many and medium roots, gradual smooth boundary to

Bs 10-140+ cm: dusky red (10R3/4) moist; moisture condition: moist; clay; friable moist, sticky and slightly plastic wet; moderate and fine granular structure; common and very fine pores; common and fine roots.

SOILCLASSIFICATION: WRB (FAO, 2015) Rhodic Umbric Ferralsols (Clayic, Dystric). USDA Soil Taxonomy (Soil Survey Staff, 2014): Typic Kandiustox.

ANALYTICAL DATA FOR PROFILE MBD-P4

Horizon	Ap	Bs
Depth (cm)	0-10	10-140+
Clay (%)	79.76	83.76
Silt (%)	12.40	6.00
Sand (%)	7.84	10.24

Texture class	Clay	Clay
Bulky density	1.40	nd
pHH_2O 1:2.5	4.59	4.96
pH $CaCl_2$	3.93	4.13
EC1:2.5(dS/m)	0.0364	0.0087
ESP	0.24	0.42
OrganicC (%)	1.6965	0.5265
Total N (%)	0.126	0.049
C/N	13.46	10.74
Avail.P Bray1(mgkg^{-1})	6.1762	3.8180
Ext. S(mgkg^{-1})	25.31	33.50
CECNH4OAc cmol (+) kg^{-1}	13.20	6.40
Exch.Ca cmol (+) kg^{-1}	1.1996	0.2602
Exch.Mg cmol (+) kg^{-1}	0.5174	0.1908
Exch.K cmol (+) kg^{-1}	0.0531	0.0303
Exch.Na cmol (+) kg^{-1}	0.0311	0.0268
Base saturation (%)	13.65	7.94
CEC_{Clay} cmol (+)kg^{-1}	9.22	5.47

Profile number: MBD-P5 Mapping unit: M5
Region: Kigoma.
District: Kasulu.
Location: 100 m west of Ruhita road.
Coordinates: 030.18298ºE/04.53635ºS
Author: N.P. Mwakinyala and B.M. Massawe
Date:191229. Season/weather conditions: rainy season. SMR: Ustic. STR: Isohyperthermic. Landform: Plain. Elevation: 1238 masl. Parent material: In situ weathering. Site characteristics: Slope: 5% (Gently sloping); straight;1500m long; middle slope. Natural drainage class: Well drained. Natural vegetation type: trees (30%), herbs (30%) and grasses (40%), dominant species; grasses. Land use: Natural forest. Soil fauna: Termites. Human influences: Burning

A 0-4 cm: dark reddish brown (5YR2.5/2) moist; Moisture condition: moist; clay, friable moist, sticky and plastic wet, moderate and medium platy structure, common and fine pores; many and fine roots, clear smooth boundary to

Op 4-18 cm: black (Gley1 2.5/N) moist; clay, friable moist, slightly sticky and non-plastic wet; moderate and medium granular structure; many and coarse pores; many and fine roots, abrupt smooth boundary to

Bo 18-27 cm: dark reddish brown (2.5YR3/3) moist, friable moist, sticky and plastic, strong and medium granular structure, few and fine pores, common and very fine roots, clear smooth boundary to

Bs 27-160+ cm: dusky red (10R3/3) moist, friable moist, slightly sticky and slightly plastic, moderate and medium blocky structure, very few and very fine pores, common and very fine roots.

SOILCLASSIFICATION: WRB (FAO, 2015): Rhodic Cambic Ferralsols (Clayic Dystric). USDA Soil Taxonomy (Soil Survey Staff, 2014): Typic Ustorthents.

ANALYTICAL DATA FOR PROFILE MBD-P5

Horizon	A	Op	Bo	Bs
Depth (cm)	0-4	4-18	18-27	27-160+
Clay (%)	59.76	37.76	79.76	89.76
Silt (%)	14.00	56.00	10.00	6.20
Sand (%)	26.24	6.24	10.24	4.04
Texture class	Clay	Silty clay loam	Clay	Clay
Bulky density	1.47	nd	nd	nd
pHH_2O 1:2.5	5.33	5.44	5.45	4.96
pH $CaCl_2$	4.55	4.53	4.6	4.31
EC1:2.5(dS/m)	0.201	0.0609	0.0536	0.0113
ESP	0.18	0.12	0.49	0.62
OrganicC (%)	1.56	2.808	1.131	0.39

Total N (%)	0.273	0.147	0.098	0.035
C/N	5.71	19.10	11.54	11.14
Avail.P Bray1(mg/kg)	7.1868	8.1975	1.1229	1.0106
Ext. S(mg/kg^{-1})	47.85	47.85	50.92	21.21
CEC NH4OAc cmol (+) kg^{-1}	29.20	64.00	11.60	6.40
Exch.Ca cmol (+)/kg^{-1}	4.2882	3.7211	2.2956	0.5104
Exch.Mg cmol (+) kg^{-1}	3.1438	2.9265	1.0784	0.4951
Exch.K cmol (+) kg^{-1}	0.2579	0.1112	0.0556	0.0354
Exch.Na cmol (+) kg^{-1}	0.0524	0.0737	0.0566	0.0396
Base saturation (%)	26.51	10.68	30.05	16.88
CEC_{Clay} cmol (+)kg^{-1}	39.86	143.85	9.65	5.63

Profile number: MBD-P6 Mapping unit: M6
Region: Kigoma.
District: Kasulu.
Location: 500 m east of Ruhita road.
Coordinates: 030.19053ºE/04.53678ºS
Author: N.P. Mwakinyala and B.M. Massawe
Date:200107. Season/weather conditions: rainy season. SMR: Ustic. STR: Isohyperthermic. Landform: Plain. Elevation: 1229 masl. Parent material: alluvium. Site characteristics: Slope:2% (very gently sloping); straight; 1000 m long; middle slope. Natural drainage class: Well drained. Natural vegetation type: trees (20%), shrubs (5%) herbs (15%) and grasses (60%), dominant species; grasses. Land use: annual crops (maize and groundnut). Soil fauna: Termites and small black ants. Human influences: cultivation

Ap 0-10 cm: very dusky red (10R2.5/2) moist; very friable moist, sticky and very plastic wet, moderate and fine granular structure, many and fine pores; many and very fine roots, abrupt smooth boundary to

BA 10-50 cm: dark reddish brown(2.5YR3/4) moist, clay, friable moist, plastic wet; many and fine pores, common and very fine roots, gradual smooth boundary to

Bo 50-123 cm: dark reddish brown (2.5YR2.5/4) moist, moisture condition: moist, friable moist, slightly plastic, common and very fine pores, very few and very fine roots, abrupt smooth boundary to

C 123-150 cm: dark reddish brown (2.5YR2.5/4) moist, very friable moist, slightly sticky and non-plastic, many and medium pores, very few and very fine roots.

SOILCLASSIFICATION: WRB (FAO, 2015): Umbric Ferralsols (Clayic, Dystric). USDA Soil Taxonomy (Soil Survey Staff, 2014): Rhodic Kandiustox.

ANALYTICAL DATA FOR PROFILE MBD-P6

Horizon	A	BA	Bo	C
Depth (cm)	0-10	10-50	50-123	123-160+
Clay (%)	67.76	83.76	85.76	82.76
Silt (%)	14.00	10.00	9.00	7.00
Sand (%)	18.24	6.24	5.24	10.24
Texture class	Clay	Clay	Clay	Clay
Bulky density	1.43	nd	nd	nd
pHH$_2$O 1:2.5	5.08	4.51	5.17	4.98
pH CaCl$_2$	4.37	3.98	4.33	4.38
EC1:2.5(dS/m)	0.1291	0.0552	0.0615	0.0161
ESP	0.20	0.44	0.73	0.94
OrganicC (%)	3.432	0.8775	0.6435	0.507
Total N (%)	0.217	0.077	0.063	0.035
C/N	15.82	11.40	10.21	14.49
Avail.P Bray1(mgkg^{-1})	3.9303	0.8984	0.6363	0.4866
Ext. S(mgkg^{-1})	33.50	50.92	40.68	41.70
CEC NH4OAc cmol (+) kg^{-1}	25.60	10.00	7.20	6.00
Exch.Ca cmol (+) kg^{-1}	3.1709	0.9287	0.9510	0.8373
Exch.Mg cmol (+) kg^{-1}	1.3544	0.5760	0.5509	0.5012
Exch.K cmol (+)	0.1643	0.0379	0.0303	0.0430

kg^{-1}				
Exch.Na cmol $(+)kg^{-1}$	0.0524	0.0439	0.0524	0.0566
Base saturation (%)	18.52	15.86	22.01	23.97
CEC_{Clay} cmol $(+)kg^{-1}$	20.32	8.33	5.81	5.14

Appendix 2: An inventory of the diagnostic horizons and features of the profiles.

(1) Name: MBD-P1, REGION KIGOMA

Diagnostic epipedons/surface horizon(s)	Diagnostic subsurface horizon(s)	Any other diagnostic features/materials
USDA Soil Taxonomy	USDA Soil Taxonomy	USDA Soil Taxonomy
Check for Mollic epipedon	Check for Argillic Horizon	
I. Structure √ II. Colour √ III. Base saturation **X** IV. Organic carbon √ V. Thickness X VI. N.Value √ VII. P2O5 √ VIII. Moisture content √	I. Clay increase √ II. Texture √ III. Thickness √ IV. Clay skins X V. Lack properties of oxic horizon √	I. Mineralogy- not known II. Clayey III. Very strongly acid IV. Ustic SMR V. Isohyperthermic STR VI. Slope-0.5% (Level) VII. Soil depth-Very deep
Umbric epipedon	Cambic horizon	

Classification of the profile up to Family level using USDA Soil Taxonomy

Order	Suborder	Great group	Subgroup	Family
Oxisol	Ustox	Haplustox	Typic Haplustox	*Level, very deep, Clayey, Very strongly acid, Ustic SMR, Isohyperthermic STR, Typic Haplustox.*

(2) Name: MBD-P2, REGION KIGOMA

Diagnostic epipedons/surface horizon(s)	Diagnostic subsurface horizon(s)	Any other diagnostic features/materials
USDA Soil Taxonomy	USDA Soil Taxonomy	USDA Soil Taxonomy
Check for Mollic epipedon	Check for Argillic Horizon	
i. Structure √ ii. Colour √ iii. Base saturation **X** iv. Organic carbon √ v. Thickness X vi. N. Value √ vii. P2O5 √ viii. Moisture content √	i. Clay increase √ ii. Texture √ iii. Thickness √ iv. Clay skins √ v. Lack properties of oxic horizon √	i. Mineralogy- not known ii. Clayey iii. Very strongly, strong to moderate acid iv. Ustic SMR v. Isohyperthermic STR vi. Slope-0.5% (Level) vii. Soil depth-Very deep
Umbric epipedon	Oxic horizon	

Classification of the profile up to Family level using USDA Soil Taxonomy

Order	Suborder	Great group	Subgroup	Family
Oxisols	Ustox	Haplustox	Rhodic Haplustox	*Level, very deep, Clayey, Very strongly, strongly to moderate acid, Ustic SMR, Isohyperthermic STR, Rhodic Haplustox*

(3) Name: MBD-P3, REGION KIGOMA

Diagnostic epipedons/surface horizon(s)	Diagnostic subsurface horizon(s)	Any other diagnostic features/materials
USDA Soil Taxonomy	USDA Soil Taxonomy	USDA Soil Taxonomy
Check for Mollic epipedon	Check for Argillic Horizon	
i. Structure √ ii. Colour √ iii. Base saturation **X** iv. Organic carbon √ v. Thickness √ vi. N.Value √ vii. P2O5 √ viii. Moisture content √	i. Clay increase √ ii. Texture √ iii. Thickness √ iv. Clay skins (Cutans) **X** v. Lack properties of oxic horizon √	i. Mineralogy- not known ii. Clayey iii. Extremely to Very strongly acid iv. Ustic SMR v. Isohyperthermic STR vi. Slope-0.5% (Level) vii. Soil depth-Very deep
Umbric epipedon	Kambic horizon	

Classification of the profile up to Family level using USDA Soil Taxonomy

Order	Suborder	Great group	Subgroup	Family
Oxisol	Ustox	Kandiustalfs	Typic Kandiustox	*Level, very deep, Clayey, Extremely to very strongly, Ustic SMR, Isohyperthermic STR, Typic Kandiustox.*

(4) Name: MBD-P4, REGION KIGOMA

Diagnostic epipedons/surface horizon(s)	Diagnostic subsurface horizon(s)	Any other diagnostic features/materials
USDA Soil Taxonomy	USDA Soil Taxonomy	USDA Soil Taxonomy
Check for Mollic epipedon	Check for Argillic Horizon	
i. Structure √ ii. Colour √ iii. Base saturation **X** iv. Organic carbon √ v. Thickness **X** vi. N.Value √ vii. P2O5 √ viii. Moisture content √	i. Clay increase √ ii. Texture √ iii. Thickness √ iv. Clay skins (Cutans) **X** v. Lack properties of oxic horizon √	i. Mineralogy- not known ii. Clayey iii. Very strongly acid iv. Ustic SMR v. Isohyperthermic STR vi. Slope-1% (nearly Level) vii. Soil depth-Very deep
Umbric epipedon	Kandic horizon	

Classification of the profile up to Family level using USDA Soil Taxonomy				
Order	Suborder	Great group	Subgroup	Family
Oxisol	Ustox	Kandiustalfs	Typic Kandiustox	*Nearly level, very deep, Clayey, very strongly acid, Ustic SMR, Isohyperthermic STR, Typic Kandiustox.*

(5) Name: MBD-P5, REGION KIGOMA

Diagnostic epipedons/surface horizon(s)	Diagnostic subsurface horizon(s)	Any other diagnostic features/materials
USDA Soil Taxonomy	USDA Soil Taxonomy	USDA Soil Taxonomy
Check for Mollic epipedon	Check for Argillic Horizon	
i. Structure √ ii. Colour √ iii. Base saturation **X** iv. Organic carbon √ v. Thickness **X** vi. N.Value √ vii. P2O5 √ viii. Moisture content √	i. Clay increase **X** ii. Texture √ iii. Thickness **X** iv. Clay skins (Cutans) **X** v. Lack properties of oxic horizon √	i. Mineralogy- not known ii. Clayey iii. Strongly to Very strongly acid iv. Ustic SMR v. Isohyperthermic STR vi. Slope-5% (sloping) vii. Soil depth-Very deep
Ochric epipedon	Oxic horizon	

Classification of the profile up to Family level using USDA Soil Taxonomy				
Order	Suborder	Great group	Subgroup	Family
Oxisols	Ustox	Haplustox	Inceptic Haplustox	*Sloping, very deep, Clayey, strongly to very strongly acid, Ustic SMR, Isohyperthermic STR, Inceptic Haplustox*.

(6) Name: MBDP6, REGION KIGOMA

Diagnostic epipedons/surface horizon(s)	Diagnostic subsurface horizon(s)	Any other diagnostic features/materials
USDA Soil Taxonomy	USDA Soil Taxonomy	USDA Soil Taxonomy
Check for Mollic epipedon	Check for Argillic Horizon	
i. Structure √ ii. Colour √ iii. Base saturation **X** iv. Organic carbon √ v. Thickness √ vi. N.Value √ vii. P2O5 √ viii. Moisture content √	i. Clay increase √ ii. Texture √ iii. Thickness √ iv. Clay skins (Cutans) **X** v. Lack properties of oxic horizon √	i. Mineralogy- not known ii. Clayey iii. Strongly to Very strongly acid iv. Ustic SMR v. Isohyperthermic STR vi. Slope-2% (Gently sloping) vii. Soil depth-Very deep
Umbric epipedon	Kandic horizon	

Classification of the profile up to Family level using USDA Soil Taxonomy				
Order	Suborder	Great group	Subgroup	Family
Oxisols	Ustox	Kandiustox	Rhodic Kandiustox	*Gently sloping, very deep, Clayey, strongly to very strongly acid, Ustic SMR, Isohyperthermic STR, Rhodic Kandiustox*.

Appendix 3: Summary of morphological and diagnostic features of the MATI Mubondo Farm soils and classification according to World Reference Base for Soil resources (WRB)

Pedons	Diagnostic horizons	Other diagnostic features/materials	Prefix Qualifiers	Suffix Qualifiers	Reference Soil group (RSG)-TIER1	WRB soil name-Tier2
MBD-P1	Ferralic	Presence of illuvial clay/sesquioxide	umbric, Rhodic, Haplic	Dystric	Ferralsols	*Rhodic umbric Ferralsols (Clayic, Dystric)*
MBD-P2	Argic	Presence of clay skins/cutans	Umbric, haplic	Dystric, Clayic	Ferralsols	*Haplic Umbric Ferralsols (Clayic, Dystric)*
MBD-P3	Umbric	Presence of sesquioxide, dusky and dark red	Umbric, Rhodic, Haplic	Dystric	Ferralsols	*Rhodic Umbric Ferralsols (Clayic, Dystric)*
MBD-P4	Umbric	Presence of sesquioxides, dark red colour	Umbric, Rhodic,	Dystric	Ferralsols	*Rhodic Umbric Ferralsols (Clayic, Dystric)*
MBD-P5	Umbric	Presence of sesquioxide	Cambic, Haplic, Rhodic	Dystric, Clayic,	Ferralsol	*Rhodic Cambic Ferralsols (Clayic Dystric)*
MBD-P6	Ferralic	Presence of sesquioxide	Umbric, Haplic	Dystric	Ferralsol	*Umbric Ferralsols (Clayic, Dystric)*

MBD-P1=Soil profile 1 MBD-P2=Soil profile 2 MBD-P3=Soil profile 3 MBD-P4=Soil profile 4 MBD-P5=Soil profile 5 MBD-P6=Soil profile 6