OPTIMISING LOCALLY AVAILABLE RESOURCES FOR NUTRIENT MANAGEMENT TO IMPROVE BANANA PRODUCTIVITY IN THE FARMING SYSTEMS IN ROMBO DISTRICT, KILIMANJARO REGION

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EXTENDED ABSTRACT

Banana is an important staple food in East Africa and an essential cash crop in the national and local economies. In Kagera and Kilimanjaro regions of Tanzania, banana is cultivated by more than 70% of smallholder farmers as a staple food in home gardens ranging from 0.5 to 2 hectares. Decline in banana yield has been reported in banana farming systems as a result of abiotic constraints (nutrient deficiencies and drought stress) and biotic constraints (pests and diseases). Decline in soil fertility and the ensuing nutrient deficiencies are among the major causes of the decline in banana yield. In the banana farming systems, nutrient removal most times exceeds their input, along with years of continuous cultivation results into negative yield trends. Most smallholder farmers are resource-constrained and thus limited in use of inorganic fertiliser due to cost, availability and usage. In this study the aim was to evaluate soil nutrient factors that affect banana production in order to identify localized soil nutrient management practices tailored to the biophysical and socioeconomic conditions of the smallholder farmer improve crop productivity. In evaluating soil fertility status in the banana farming systems, adequate indicators were employed, namely, physico-chemical and nutrient analysis, spatial analysis, crop yield and critical nutrient levels, limiting nutrients and nutrient balances.

A survey approach was employed, involving sample collection in farmers' banana fields. Using the Probability Sampling Technique, six wards (namely: Aleni, Mamsera, Manda, Mengeni, Mengwe and Shimbi) were selected in a systematic random manner based on banana production areas. Then from the six wards, a total of 100 sites were selected in a stratified random manner and geo-referenced. Allometric measurements, namely: girth at base (G_{base}), girth at 1-m height (G_{1m}), number of *hands*, and number of banana *fingers* on the bottom row of the second last hand were taken from among three selected mats with a banana plant at fruiting stage per farm site. Analysis considered three banana cultivars, namely, *Malindi*, *Matoke* and *Mshare* that were dominant in the sites and had higher number of observations. Allometric data were used to determine banana bunch weights (*Bwt*) and above ground biomass (*AGB*). Results indicated that *Matoke* had significantly ($P \leq 0.05$) higher G_{base}, G_{1m} and *AGB* than *Malindi* and *Mshare,* whereas *Malindi* had significantly ($P \leq 0.05$) more number of *hands*. There was no significant difference (ns) ($P \leq 0.05$) for number of *fingers* and *Bwt* among the cultivars. Soil and plant samples were collected from every site and analysed for physicochemical properties and nutrients concentrations. Boundary line analysis was used to determine plant critical nutrient values. Results indicated critical levels were 2.39, 0.15, 1.5, 0.35 and 0.3% for N, P, K, Ca and Mg, respectively. Results from descriptive statistics, geo-statistics and nutrients maps, coefficient of variation diminished in the order P>Cu>K>Zn>Mn>S.

A survey was carried out to identify agronomic management practices and production constraints. Survey data were used to categorise farmers into wealth classes based on resources owned (Resource-rich *L3*, medium *L2* and poor *L1* households) as well as classes based on cattle ownership. Soil samples were collected from each farm at a depth of 30 cm and nutrient concentrations analysed. The aim was to determine most-limiting yield nutrients in the farms using nutritional index (*NI*). Bunch weight was compared to optimum attainable bunch weight of 28 kg and 69 low-yield farms were obtained. The major nutrient deficiencies were K>Mn>P=Zn>Cu in 40, 35, 34 and 32% of low-yield areas, respectively. *L3* owned more land area under banana than *L2* and *L1* households by 8% (ns). Yet L3 had significantly ($P \leq 0.05$) higher banana *Bwt*. Survey data along with data from nutrient analysis were used for estimating partial nutrient balances in home gardens across household classes. Large nutrient input observed was by farmyard manure application and removal by crops harvested and their residues. Higher negative N and K balances were obtained in home gardens of less resource households and those with few (≤ 2) cattle, while positive P balances were obtained for home gardens across all household classes indicating less P-removal,. Positive NPK balances were obtained for households with more (>2) dairy cattle, but these were just a few representation of households. Hence, indicating the need to employ an integrated nutrient management approach using other nutrient sources, other than farmyard manure, in order to increase nutrients input and thereby increase and sustain banana yield.

DECLARATION

I, Rutazaha JoanPaula Elliseus, 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 been submitted nor being concurrently submitted in any other institution.

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LIST OF ABBREVIATION AND SYMBOLS

a.m.s.l	Above mean sea level
Al	Aluminium
BLA	Boundary line analysis
Bwt	Bunch weight
Ca	Calcium
cm	Centimetre
Cmol (+) kg^{-1}	Centimole (+) per kilogram
Cu	Copper
CV	Coefficient of variation
DEM	Digital elevation model
et al	and others
FAO	Food and Agriculture Organization
Fe	Iron
G_{1m}	pseudostem girth at 1m height
G_{base}	pseudostem girth at base
IITA	International Institute of Tropical Agriculture
K	Potassium
MAFC	Ministry of Agriculture, Food Security and Cooperative
mg kg^{-1}	milligram per kilogram
Mg	Magnesium
Mn	Manganese
MSc	Master of Science
Mt.	Mountain
N	Nitrogen

Na	Sodium
NI	Nutritional Index
ns	non-significant
OC	Organic carbon
P	Phosphorous
pH	Power of hydrogen
PhD	Doctor of Philosophy
RDAICP	Rombo District Agriculture, Irrigation and Cooperation Profile
S	Sulfur
STRM	Shuttle Radar Topography Mission
SUA	Sokoine University of Agriculture
t ha^{-1}	ton per hectare
Zn	Zinc

CHAPTER ONE

1.0 GENERAL INTRODUCTION

1.1 Background Information

Banana is a key staple food in Tanzania for about 15 - 30 % of the population (Kalyebara *et al.*, 2007; Maerere *et al.*, 2008). It is also a main source of income for smallholder farmers and nutrition of 70 - 90 % of households in the areas that grow it (Lusty and Smale, 2002; Kalyebara *et al.*, 2007; Ndunguru, 2009). An estimated 942 965 households in Tanzania cultivated bananas on about 306 859 ha in 2008 (MAFC, 2012). The overall banana production is generally low, with average yields ranging from about 5 to 21 t ha^{-1} (MAFC, 2012), less than half the potential yield of about 60 - 70 t ha^{-1} year^{-1} (van Asten *et al.*, 2004; Kalyebara *et al.*, 2007; Wairegi *et al.*, 2010).

Several studies have reported declining banana yield in the banana farming systems as a result of abiotic constraints (nutrient deficiencies and drought stress) (Baijukya, 2004; Nyombi *et al.*, 2010; Mushi and Edward, 2017) and biotic constraints (pests and diseases) (van Asten *et al.*, 2004; Wairegi *et al.*, 2010; Shimwela *et al.*, 2017). Decline in soil fertility is a singular major cause of decline in banana productivity (Baijukya, 2004; Nyombi *et al.*, 2010; Marandu *et al.*, 2014). Nutrient deficiencies make bananas even more susceptible to biotic stresses (Taulya, 2013). There are indications for interactions between soil nutrient deficiencies and biotic stresses which compromise banana system resilience. For example, weevil damage in K-deficient banana plants is twice in K-sufficient plants (Taulya, 2015). There is a need to evaluate these soil nutrient factors that affect banana production and identify well-designed, localized soil nutrient management practices tailored to the biophysical and socio-economic conditions of the smallholder farmer so as to improve and sustain productivity.

1.2 Problem Statement and Justification

East Africa banana farming systems are traditionally low-input systems (Nyombi *et al*., 2010; Ndabamenye *et al.*, 2013) where low nutrients are added to the systems but more is mined, hence limiting yields. High nutrient losses from these banana systems have resulted into nutrient deficiencies in soil, occasioning negative yield trends (Baijukya, 2004; Nyombi *et al*., 2010). Moreover, most banana farmers are resource-constrained (Maerere *et al*., 2008), limited in use of inorganic fertiliser in terms of cost, availability and usage (Nyombi *et al*., 2010; Ndabamenye *et al.*, 2013). Blanket fertiliser recommendations prevail within agricultural extension services without considering characteristic soil fertility status and peculiarities of banana systems. This calls for site specific fertiliser recommendations to address these nutrient deficiencies (Nyombi *et al.*, 2010; Wairegi and van Asten, 2011). In Tanzania, banana studies have little or no suitable information on nutrient recommendations for banana systems (Mowo *et al*., 1993*;* Senkoro *et al.*, 2017).

Organic inputs have often been applied to replenish nutrients in smallholder banana farms (Kalyebara *et al*., 2007; Shekiffu 2011, Ndabamenye *et al*., 2013) but nutrients supply by organic sources is inadequate to sustain or improve banana system productivity (Nyombi *et al.*, 2010; Ndabamenye *et al.*, 2013). Enhancing banana system productivity calls for a judicious use of additional external inputs (van Asten *et al.*, 2004; Nyombi *et al*., 2010). These complexities requires quantitative insights to understand existing banana nutrient management so as to harness effective soil nutrient management practices for narrowing yield gaps (van Asten *et al.*, 2011).

1.3 Objectives

1.3.1 Overall objective

The overall objective is to develop balanced nutrient requirement for banana farming systems as a strategy to improve and sustain banana productivity in Rombo District, Kilimanjaro Region.

1.3.2 Specific objectives

The specific objectives of the study are to:

1. Establish the critical values and map the spatial distribution of the major nutrients needed for banana production.
2. Determine the most limiting soil nutrients in the banana farming areas
3. Develop a partial nutrient budget for the most limiting nutrients.

1.4 General Literature Review

1.4.1 Banana production in Tanzania

In Tanzania, banana is a perennial crop that is mainly grown in Kagera, Kilimanjaro, and Mbeya regions (Kalyebara *et al*., 2007; MAFC, 2012). Bananas are cultivated by smallholder farmers for cash and food on average fields of 1.5 ha or less (Maerere *et al*., 2008), as monocrop or intercropped with mainly coffee and beans (Baijukya, 2004). It has been reported by Maerere *et al*. (2008) that farmland allocated to banana production varied from 25 to 53 % among banana growing zones in Tanzania, with highest allocation in northern and lake zones as compared to southern and eastern zones. Banana production is mostly rain-fed (van Asten *et al.,* 2011), requiring about 2000 – 2500 mm of rainfall evenly distributed across the year (Luzi-Kihupi *et al*., 2015). Yield losses of between 40 - 65 % have been reported when rainfall is below 1100 mm (Wairegi *et al*., 2010).

1.4.2 Dynamics of nutrient supply in banana farming systems

Bananas require a large supply of Nitrogen (N), Potassium (K), Phosphorus (P), Magnesium (Mg) and Calcium (Ca) (Thangaselvabai *et al.*, 2009; Weinert and Simpson, 2016). Potassium deficiency is a foremost concern in banana systems, followed by N and Mg (van Asten *et al*., 2004). Nutrient losses of about 20 to 80 kg K ha^{-1} year^{-1} and 10 to 20 kg N ha^{-1} year^{-1} have been reported from banana farms (Taulya, 2015). Phosphorus-deficiency is a sporadic constraint for bananas in East African highlands (van Asten *et al.*, 2004; Senkoro *et al.,* 2017). Banana farming systems in East African highlands have low inorganic fertiliser inputs due to perceived high costs and lack of knowledge on how to use them in banana production (Nyombi *et al.,* 2010). Nutrient supply from organic or inorganic sources is a major promoter for banana crop growth when applied well in the banana farm, hence improving yield.

1.4.3 Boundary Line Analysis (BLA)

Boundary line analysis describes crop yield response to variations in biophysical factors. BLA offers possibilities to isolate single-factor yield responses where multiple factors control yield and to quantify identified yield gaps. A mathematical model (Equation 1) is fitted through upper points of a scatter plot relating biophysical factors to crop yield (or relative yield). The boundary line represents the maximum attainable yield over the range of measured biophysical factors while points below the line are considered limited by other factors (Schnug *et al*., 1996; Maia and Morais, 2015; 2016). Maia and Morais (2016) used BLA to estimate the sufficiency range based on yield estimated by the boundary line of nutrient; *i (P_i)*

$$Y_i = \frac{4.Y_{max}\cdot\beta}{(1+\beta)^2} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

Where: y_{max} is the maximum yield, and

$\beta = \exp\left[\frac{f*1.7145}{Max-Min}(\mu - x)\right]$, where f is the adjustment factor (here 2 was used);

x, μ, Max and Min stand for the sample nutrient concentration and the mean, maximum and minimum nutrient concentration in the database, respectively.

BLA has also been applied to determine nutrient sufficiency ranges for other crops other than banana (Blanco-Macias *et al*., 2010). Therefore, an important tool for estimating critical nutrient values in plant and/or soils.

1.4.4 Nutrient budget concept in soil fertility management

Nutrient budgets are useful indicators for optimising nutrient use, crop productivity, and resource management (Cobo *et al.*, 2010). The nutrient budget is the difference between nutrient inputs and outputs of a system with defined spatial-temporal boundaries (Bindraban *et al*., 2000). Generally, it is expressed in amount of nutrient(s) per unit of area and time (kg ha^{-1} $year^{-1}$). Negative balance (i.e. removal exceeds use) indicates declining soil fertility, hence, need for replenishment of the nutrient before soil nutrient concentration drops below critical value. Positive balance (i.e. use exceeds removal) defines increasing soil fertility but with risk of nutrient loss to the environment. Zero balance (i.e. use equals removal) describes soil fertility maintenance.

A partial nutrient budget ia simple input-output model of nutrient fluxes into/out of a system developed based on quantitative and qualitative analyses, with nutrient fluxes from difficult to measure processes such as denitrification, soil erosion and leaching, generally not considered in the model. These balances are calculated using the input and output model involving inorganic (IN1) and organic fertiliser (IN2) as inputs, and harvested crops (OUT1) and crop residues (OUT2) as output (Bekunda and Manzi, 2003; Zingore *et al.*, 2007; Wairegi and van Asten, 2011). Partial nutrient balances expressed in kg ha^{-1} $year^{-1}$, for most limiting selected nutrients are calculated as difference between inputs-outputs.

$$\text{Partial balance} = (\text{IN1} + \text{IN2}) - (\text{OUT1} + \text{OUT2}) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (2)$$

Several studies have reported the use of the nutrient budget approach for improving soil fertility and crop productivity (Baijukya and de Steenhuijsen Piters 1998; Bekunda and Manzi, 2003; Færge and Magid, 2004; Baijukya *et al.*, 2005; Cobo *et al*., 2010).

Partial balance is therefore a good determinant in depicting yield trends in order to monitor crop productivity.

1.4.5 Geospatial modelling

Geospatial modelling is a vital tool for understanding spatial distribution of production factors in farming systems (Cobo *et al.*, 2010; Papadopoulos *et al.*, 2015). This has been successfully used in spatially explicit studies for interpolation and scaling-up of data through ordinary kriging, semi-variogram (helps to describe the structure of spatial dependence) and associated procedures (Webster and Oliver, 2007). Spatial covariates such as land use, 30-m Shuttle Radar Topography Mission (STRM DEM) and its (digital elevation model) DEM derivatives are commonly used for a trend assessment (Hengl *et al*., 2007). Kriging is a geospatial modelling approach that has been used to map the spatial distribution of soil properties (Hengl *et al.*, 2007; Malone *et al.*, 2017). It involves the spatial prediction of properties at unsampled points using weighted data from measured points determined using a Semi-variogram (Hengl *et al.*, 2007). Therefore, geospatial information can be produced and enable in determining the variation in soil properties of farm area.

1.4.6 Allometric functions

Allometric data in relation to crops enables for crop growth assessment and yield estimation. Simple allometric functions have been developed for estimating dry matter content and the estimation of leaf area index (LAI) from the physical traits like plant girth and plant height (Nyombi *et al.*, 2009). Allometric functions are often used for a specific plant species, but with variation in a species like in banana, allometric differences may be observed. Therefore, comparisons between species are made to enable the use of a general allometric function, or in the case of wide variations the use of specific allometric function for a specific cultivar is employed. For the prediction of banana bunch weight a general regression function that incorporated various parameters to predict bunch weight (*Bwt*), assumed to have had the best prediction ability (Wairegi *et al.*, 2010) is used:

$$\ln(Bwt) = k + a\ln(G_{base}) + b\ln(G_{1m}) + c\ln(hands) + d\ln(fingers) \ldots\ldots\ldots\ldots \quad (3)$$

Where k is the intercept and a, b, c and d are parameter coefficients.

Therefore in evaluating soil fertility status in the banana farming systems, it is vital to employ adequate indicators, namely, physico-chemical and nutrient analysis, crop yield and critical nutrient levels, limiting nutrients and nutrient balances as employed in this study.

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CHAPTER TWO

2.0 SPATIAL VARIABILITY AND CRITICAL VALUES OF NUTRIENTS IN A HIGHLAND BANANA FARMING SYSTEM OF ROMBO DISTRICT, TANZANIA

ABSTRACT

The spatial distribution of nutrients and their respective critical values enable designing of site-specific nutrient management practices for optimal enhancement of crop productivity and sustainability. This study was conducted to map the spatial distribution of nutrients and to determine their respective critical values for banana production in Rombo District, Tanzania. Soil samples were collected at 0-30 cm depth along with plant samples and analysed for physicochemical properties and nutrients concentrations. Data on girth at base (G_{base}) and at 1-m height from the ground (G_{1m}), number of hands per bunch and number of fingers on the bottom row of the second-last hand were collected from three selected mats per farm for allometric estimation of fresh bunch weights. The aboveground biomass (*AGB*) for each of the enumerated mother plants was determined at harvest by taking samples of each biomass for dry matter content determination. Boundary line analysis was used to determine critical values. *Matoke* had a significantly ($P \leq 0.05$) higher G_{base}, G_{1m} and *AGB* than *Malindi* and *Mshare*, whereas *Malindi* had significantly ($P \leq 0.05$) more *hands*. There was no significant difference ($P \leq 0.05$) among the cultivars for *fingers* and bunch weight. The critical values in banana leaves were 2.39, 0.15, 1.5, 0.35 and 0.3% for N, P, K, Ca and Mg, respectively. Coefficient of variation was observed to decline reduced in the order P>Cu>K>Zn>Mn>S. The results give a base from which nutrient management practices can be carried out and fertiliser recommendations made in specific areas and for the specific nutrients considering the critical nutrient values.

Keywords: *Allometry, Geographic Information System, Musa Spp, critical value*

2.1 Introduction

Decline in soil fertility and ensuing nutrient deficiencies in banana farming systems, are one of the major causes of decline in banana productivity (Baijukya, 2004; Nyombi *et al*., 2010; Marandu *et al*., 2014). There has been continuous cultivation with limited fertiliser input. Senkoro *et al.* (2017) reported less than 5% of farmers in 50% of the districts in Tanzania use mineral fertilisers in the major food crops production. Most small holder farmers cannot afford, much less, correctly apply the recommended rate of fertiliser. Therefore, farmers mostly use organic inputs such as farmyard manure and other soil organic amendments like mulches (grass and crop residues), cover crops, intercrop and crop rotation (Shekiffu, 2011). Nevertheless, nutrients supply from these organic sources is too low at their current application rates to improve and sustain banana productivity. Nutrient management routines are needed to improve productivity and sustainability of the cropping system.

Management practices depend on the nutrients status in the soil, which in turn varies over time and space as a function of the soil mineralogical composition and past management. It is, therefore, imperative that site-specific nutrient management practices are developed based on the spatial variation in the nutrient. Currently, the spatial distribution of nutrients in Rombo district, for site-specific nutrient management in banana cropping systems is not well known. This can be determined from standardized semivariogram and ordinary kriging, widely used for mapping soil properties (Marques *et al*., 2015).

Rational management of most of the nutrients requires knowledge of their respective critical values, which is not well known for the banana farming systems of Rombo, Tanzania. Critical nutrient values help to further interpret nutrient analytical data from the relationship between nutrient concentration in soil and in plant tissue

(Memon *et al*., 2005; Seth *et al*., 2018). Critical nutrient levels helps in estimating nutrient bioavailability in soil, plant nutritional status, act as soil or leaf interpretation guide, and helps in fertiliser recommendations (Maia and Morais, 2015). However, the critical nutrient values for banana production in Rombo district, Tanzania are not identified. In determining the critical values, a boundary line approach (BLA) is used, where a line representing maximum potential yield for the nutrient concentration, is fitted above scattered data points (Shatar and McBratney, 2004; Maia and Morais, 2015). Correspondingly, it is more fulfilling to also employ nutrient maps to depict nutrient spatial variability in soil and show areas with specific nutrient sufficiency, deficiency or toxicity (White and Zasoski, 1999).

Therefore, this study was conducted to determine the spatial variation of nutrient status in soil and to determine the critical nutrient values for proper nutrient management in banana farms in Rombo district, Tanzania.

2.1 Materials and Methods

2.2.1 Description of the study area

The study was carried out in Rombo District (Fig. 2.1) in the Eastern Kilimanjaro Region. Rombo District is located between Latitudes 2° 52’ 48” S - 3° 23’ 60” S and Longitudes 37° 16’ 48” E - 37° 42’ 00” E. The District lies within an altitude of 800 - 2 000 m a.m.s.l, with an area of 1 442 km². The rainfall pattern in Rombo District is bimodal, with long rains falling between March to June while short rains fall between October to December. Mean annual rainfall ranges from 500 mm to 1 750 mm (RDAICP, 2019). Soils are predominantly sandy loam and clay loam with soil types described as Andosols, originating from volcanic rocks, ash and lava. The upper southern slopes of Mt. Kilimanjaro are characterised by the densely populated Chagga farming system, with banana home garden and food production systems to the lower slopes and adjacent plains (Soini, 2002; Misana *et al*., 2012). Banana is cultivated in at least 70 % of the households as food and/or cash crop, with planted area per household about 0.4 to 1.5 ha (Kalyebara *et al*., 2007; MAFC, 2012).

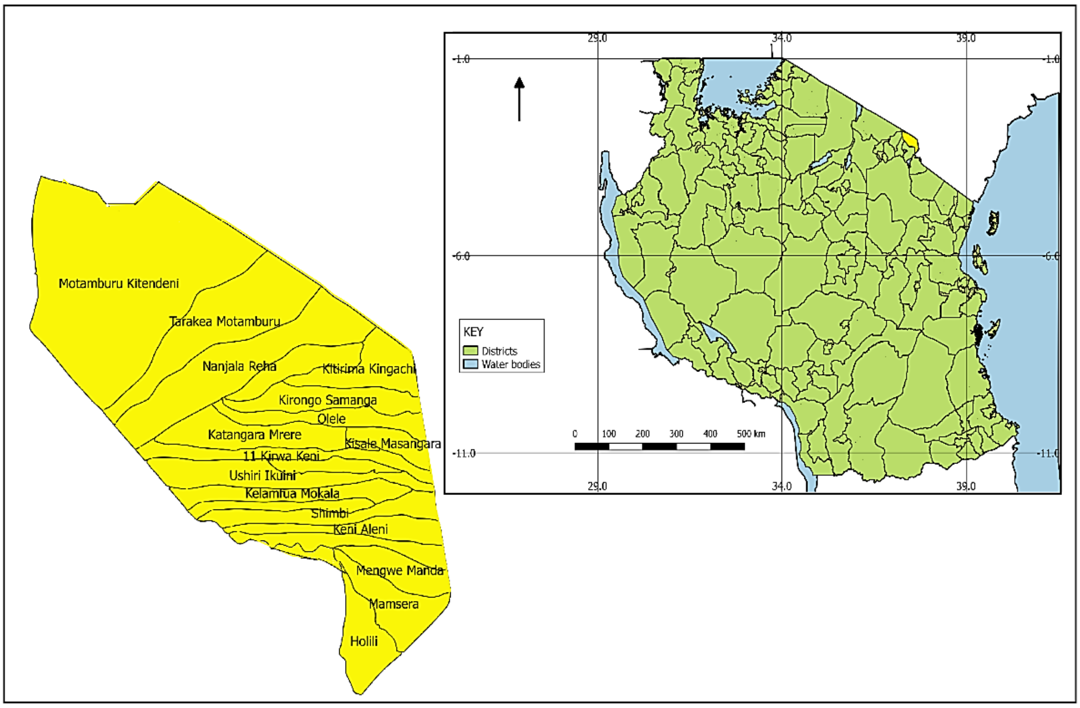

Figure 2.1: Map showing Rombo District (in yellow) in Tanzania

2.2.2 Study design

A survey approach was employed, involving sample collection in farmers’ banana fields. Using probability sampling technique, six wards, namely: Aleni, Mamsera, Manda, Mengeni, Mengwe and Shimbi, were selected in a systematic random way based on banana production areas. Then from the six wards, 100 sites were selected in a stratified random manner. The study area was divided into strata (0-99) and each stratum assigned 10 geo-points (a-j) from which a suitable site with a banana farming household was selected. These sites were geo-referenced.

2.2.2.1 Soil sampling and nutrient analysis

A total of eight subsamples were collected from each banana field at 0-30 cm depth in a zigzag pattern and mixed to obtain a composite samples from each field. Soil samples were prepared and analysed at the International Institute of Tropical Agriculture (IITA) soil laboratory in Dar es Salaam, Eastern Africa Hub. Soil samples were air dried for 12-24 h, ground and passed through a 2 mm sieve then analysed for soil physico-chemical properties (organic carbon, soil texture, and pH) and nutrients (N, P, K, Mg, Ca and S) based on procedures by Okalebo *et al*. (2002) and Webster (2008). Resulting datasets were shown in Appendix 1.

Soil pH was determined using a glass electrode pH meter in 1:2.5 (soil: water suspension). Organic carbon was determined by the Walkley and Black method using wet oxidation by potassium dichromate (Okalebo *et al*., 2002). Total nitrogen (N) was determined by the micro-Kjedahl digestion procedure followed by distillation (Okalebo *et al*., 2002). Available Phosphorous (P) was extracted using Mehlich-3 and determined by using a UV-Vis spectrophotometer (Okalebo *et al*., 2002; Webster, 2008). Exchangeable potassium (K), calcium (Ca), magnesium (Mg) and sodium (Na) were extracted using Mehlich-3 determined by Atomic Absorption Spectrophotometer (Okalebo *et al*., 2002). Micronutrients: copper (Cu), zinc (Zn), iron (Fe) and manganese (Mn) were determined using the Diethylentriaminepentaacetic acid (DTPA) extraction procedure (Okalebo *et al*., 2002; Webster, 2008).

2.2.2.2 Plant sampling and nutrient analysis

Composite foliar samples of 5 cm by 5 cm were taken from both sides of the mid-rib in the midpoint of the lamina of the third-youngest fully expanded leaf of three randomly selected banana plants at flowering stage (Memon *et al*., 2005), at the beginning of short rains. Also, plant samples were collected from the pseudo-stem, leaves, peduncle and fingers to determine the nutrient concentrations (N, P, K, Mg, and Ca) on the dry matter basis after harvest and further used to estimate the above ground biomass (ABG). Analysis for nutrients (N, P, K, Mg, and Ca) concentrations of the composite foliar samples was done at IITA soil laboratory in Dar es Salaam. Plant and foliar samples were oven dried at $60^{o}C$ for 24-64 hours, ground, and then digested in a mixture of sulphuric acid and selenium. Nitrogen was determined by the micro-Kjedahl digestion procedure followed by distillation, P was determined by a spectrophotometer (Okalebo *et al*., 2002), whereas K, Ca and Mg were determined using Atomic Absorption Spectrophotometer (AAS) (Okalebo *et al*., 2002).

2.2.2.3 Allometric measurements

Allometric measurements (girth at base; G_{base}, girth at 1-m height; G_{1m}, number of hands, and number of fingers in the bottom row of the second lowest hand) were taken from three banana plants at fruiting stage from each of the selected farms. Out of six cultivars in the dataset, variation was checked on three (Malindi, Matoke and Mshare) cultivars that were dominant, and in abundance.

2.2.3 Geostatistical analysis and mapping of soil parameters

Soil analysis results were further geostatistical analysed where results that deviated from the normal distribution, natural logarithm was applied to the variables before geostatistical analysis. Semi-variogram and ordinary-kriging were used to develop spatial distribution maps of measured soil nutrient and physico-chemical properties. Ordinary kriging method employed the spatial dependence among the neighbouring point samples and estimated variable values in the semi-variogram at any point within the study area (Webster and Oliver, 2007). Semi-variogram helps to describe the structure of spatial dependence. Appropriate semi-variogram model for each parameter was selected and adjusted, then parameters estimated and kriging was done. Spatial covariates such as land use, 30-m

STRM DEM and its DEM derivatives were used for a trend assessment (Hengl *et al*., 2007). Analyses were performed in raster-, ggplott2-, plyr-, random Forest- and gstat-packages of R version 3.6.0 software. Accuracy of the maps were estimated with a cross-validation approach employing performance indices, namely, coefficient of determination (R^2), mean error, mean square prediction error and root mean square error and linear regression as validation indices. Spatial dependency ratio (SDI) was determined to validate the actuality of spatial dependence. This ratio (nugget / (nugget +sill) articulates how much of the total variance is attributable to spatial dependence. If nugget = sill variance, the data have no spatial structure; it is not spatially dependent. On the other hand, If nugget = 0, there is high spatial structure and high spatial correlation between points (Gorres and Amador, 2005).

2.2.4 Data analysis

Descriptive analysis was done for the soil and plant data in Microsoft Excel 2013. Mean values of the parameters were generated for the three mats across each farm. Descriptive analyses for banana bunch weight, above ground biomass and relative yield were done in R software 3.6.0 version. Then Analysis of Variance (ANOVA) was employed to ascertain the significance difference. Tukey Honest Significant Difference test was used to further compute for separate (multiple comparisons of means) at 95% family wise confidence level. Analyses and plotting was conducted in the R 3.6.0 software.

Allometric data was used to estimate fresh banana bunch weight according to the method by Wairegi *et al*. (2009). Scatter plots of yield and each soil nutrient were constructed, with Boundary lines fitted for each scatter plot following Maia and Morais (2016) to predict the maximum yield at 95 % yield target. Nutrient values in soils corresponding to the 95 % yield target were then established as critical nutrient values.

In estimating the critical values, a boundary line was fitted to estimate the sufficiency range based on yield; mathematical equation 1 by Maia and Morais (2016):

$Y_i = \frac{4.Y_{max}.\beta}{(1+\beta)^2}$. Also, the concentrations corresponding to the lower limit (L_l) (which is the critical nutrient value) and upper limit (L_u) of the sufficiency range were calculated as Maia and Morais (2016):

$$L_l = \mu - \left[\frac{\text{Max}-\text{Min}}{\text{f}*1.7145}\ln(\beta_l)\right], \text{ where: } \beta_l = \left[\frac{2}{\text{P}_r}\left(1+\sqrt{1-\text{P}_r}\right)\right]-1$$

$$L_u = \mu - \left[\frac{\text{Max}-\text{Min}}{\text{f}*1.7145}\ln(\beta_u)\right], \text{ where: } \beta_u = \left[\frac{2}{\text{P}_r}\left(1-\sqrt{1-\text{P}_r}\right)\right]-1$$

Where: P_r is the desired relative yield in relation to P_{max} for which 0.95 was used, referring to 95% of the P_{max} of banana plant, f is the adjustment factor = 2.

2.3 Results and Discussion

2.3.1 Descriptive statistics of the soil properties in Rombo District

In general the soil analysis results for soil physico-chemical properties in Table 2.1 shows that pH was slightly acidic to neutral (6.0-7.0) which fits well as land use requirement for rain-fed banana production. Across the study area, the mean soil OC was relatively good, ranging from 1.94 – 8.88 %, could be attributed to the supply of farmyard manure and mulching. There was a variation in soil particle sizes, though percentage clay was fairly more, tallying with report by RDAIC (2016) indicating soils in Rombo to be more clayey, and this could be attributed to parent material and weathering processes.

Table 2.1: Soil physico-chemical properties of the selected banana farms, number of observations (n = 100)

	pH in water	OC	CLAY	SILT	SAND
		%			
	Mean ± se	Mean ± se	Mean ± se	Mean ± se	Mean ± se
Mean	6.45 ± 0.05	3.45 ± 0.11	41.49 ± 1.11	30.90 ± 0.59	27.61 ± 1.51
CV	7.13	32.5	26.7	19.1	43.7

OC=organic carbon; s.e = standard error; CV=Coefficient of variation (%)

The analysis result for soil nutrients are presented in Table 2.2. Total N ranged from 0.17 to 0.86%, with moderate mean N value required for banana plant growth may be as a result of use of farmyard manure and mulch in banana farms. Available P varied widely (CV = 111%) and range of 151 mg kg^{-1}, implying that soils low in P concentrations could be attributed to low P application, P being fixed in the soil colloids or eroded along with sediments during heavy rains. Potassium also varied markedly among the soils (CV = 78%), K ranged from 0.05 to 1.25 Cmol+ kg^{-1}. Potassium deficiency has been reported as a major concern in banana farming systems (van Asten *et al*., 2004; Taulya, 2015) as it is required in large amount for banana growth. Magnesium had high values range of 2.55 to 11.67 Cmol+ kg^{-1}, with low CV = 22%. Exchangeable Ca ranged from 7 to 70 Cmol+ kg^{-1}. Soil micronutrients varied widely among the site, with higher CV>50% except for Fe.

Table 2.2: Soil nutrient status of the selected banana farms in Rombo district, number of observations (n= 100)

	N	**Ca**	**Mg**	**K**	**Na**	**Av. P**	**S**	**Cu**	**Zn**	**Mn**	**Fe**
	%	**----------- Cmol+ kg^{-1} --------**				**-----------------mg kg^{-1} --------------**					
Mean	0.34	32.42	8.02	0.32	0.21	29.01	27.84	1.08	0.31	2.82	226.54
s.e	0.01	1.15	0.18	0.02	0.01	3.21	1.36	0.09	0.02	0.14	6.73
CV	32	35	22	78	29	111	50	85	58	51	30

Av. P=available Phosphorous; N= Total nitrogen; K= potassium; Ca= Calcium; Mg=Magnesium; Na= sodium; S=Sulphur; Cu=Copper; Zn=Zinc; Mn=Manganese; Fe=Iron; s.e=standard error; CV=Coefficient of variation (%)

2.3.2 Foliar nutrients concentration

A number of banana cultivars were found mixed in the selected farms, so foliar nutritional composition was characterised according to dominant cultivars, namely, *Malindi, Matoke* and *Mshare*. Although Malindi (*Cavendish spp.*) was most preferred by farmers especially for its shorter growth period, resistance to diseases and its market demand. There was no significant difference in foliar nutrients concentration among banana cultivars ($P \leq 0.05$) as shown in Table 2.3. In comparison with nutrient concentrations by Okalebo *et al*. (2002), mean values were considered marginal for N (2.60-2.80%) and P (0.13-0.19%), deficient for K (<2.50%) and Ca (<0.50%), and optimum for Mg (0.30-0.46).

Table 2.3: Means of foliar nutrient concentrations for *Malindi, Matoke* and *Mshare* variety

Variety	n	N	P	K	Ca	Mg
				----------- % ---------		
Malindi	196	2.58 (0.02)*	0.17 (0.01) *	1.68 (0.02) *	0.39 (0.01) *	0.34 (0.01) *
Matoke	53	2.65 (0.04) *	0.17 (0.01) *	1.66 (0.03) *	0.41 (0.01) *	0.33 (0.01) *
Mshare	25	2.65 (0.06) *	0.17 (0.01) *	1.73 (0.03) *	0.38 (0.01) *	0.32 (0.01) *

P= Phosphorous; N= nitrogen; K= potassium; Ca= Calcium; Mg=Magnesium; Figures in parentheses are standard errors for the means. * no significant difference at $P \leq 0.05$ by Tukey HSD

2.3.3 Allometric parameters

2.3.3.1 Observed and predicted sub-dataset

Allometric function (Equation 3) by Wairegi *et al* (2010) used to predict fresh bunch weights was considered relatively precise having a fairly high $R^2 = 0.7$ as shown in Fig. 2.2. The R^2 indicated that 70 % of the variance in the response variable (observed *Bwt*) can be explained by the explanatory variables (predicted *Bwt*). The remaining 30% can be attributed to unknown, lurking variables or inherent variability.

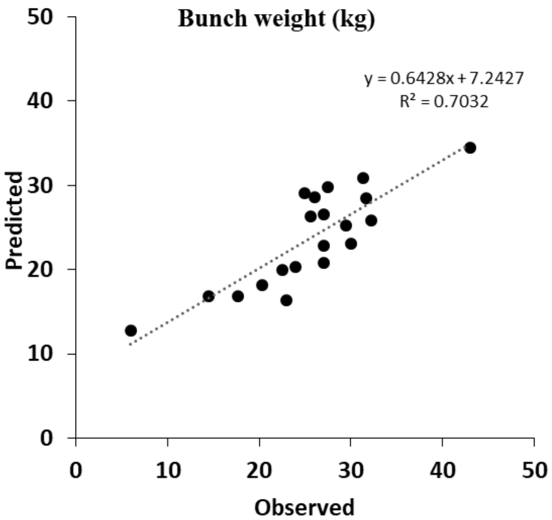

Figure 2.2: Relationship between the predicted and observed bunch weights

2.3.3.2 Allometric parameters

The mean values of allometric parameters characterised among the selected banana cultivars were shown in Table 2.5. Results showed that *Matoke* had a significantly ($P \leq 0.05$) higher G_{base}, G_{1m} and *AGB* than *Malindi* and *Mshare* cultivars, whereas *Malindi* had significantly ($P \leq 0.05$) more number of hands (*hands*). The number of hands ranged from 5 to 13. There was no significant difference ($P \leq 0.05$) among the cultivars for number of fingers (*fingers)* and bunch weight (*Bwt*).

Table 2.4: Descriptive statistics for allometric banana plant parameters for the selected banana cultivars

Variety	n	G_{base}	G_{1m}	Hands	Fingers	Bwt	AGB
		(cm)	(cm)			(kg)	
		Mean ± se	Mean ± se	Mean ± se	Mean ± se	Mean ± se	Mean ± se
Malindi	196	87.19±0.85ab	64.91±0.76a	9.2±0.13a	7.08±0.06 ns	24.56±0.59 ns	3.92±0.09a
Matoke	53	91.85±1.79a	69.87±1.7b	8.32±0.21b	7.19±0.14 ns	26.29±1.38 ns	4.44±0.2b
Mshare	25	81.06±3.93b	59.74±3.45a	8.56±0.35ab	7.12±0.19 ns	21.78±2.5 ns	3.49±0.37a

n= number of observations; $G_{base=}$ pseudostem girth at base (cm); $G_{1m=}$ pseudostem girth at 1m (cm); Hands= number of hands,, Fingers= number of fingers in the lower row of the second lowest hand; Bwt= bunch weight (kg) and AGB= Above Ground Biomass; s.e = standard error; ns=not significant at *P*≤0.05 means followed by a different letter are significantly different at P≤0.05 by Tukey HSD.

2.3.4 Relation between allometric parameters and the banana bunch weight

The relationship between allometric plant parameters (G_{base} and G_{1m},) is shown in Figure 2.3, which depicts the *Bwt* to G_{base} and G_{1m} relationship. Coefficient of determination (R^2) value for 'power' relations were higher than the 'linear' relations for G_{base}, G_{1m} and *Hands*. Where R^2 values for G_{base} was 0.9022 and 0.9199, and G_{1m} was 0.8136 and 0.8449 for 'linear' and 'power' relations, respectively. The R^2 value was 0.6186 and 0.6863 and *fingers* was 0.4040 and 0.3693 for 'linear' and 'power' relations, respectively (results not shown). This indicates variation in *Bwt* is dependent on the variation in pseudostem circumference (G_{base} and G_{1m}) in the uptake of water and nutrients for growth of the plant, proper fruiting to a desired bunch weight harvest.

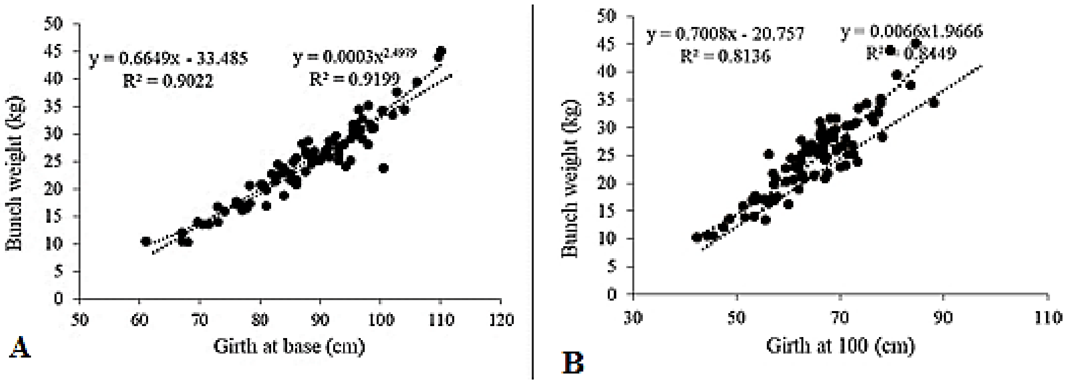

Figure 2.3: The relationship between bunch weight and pseudostem girth at base (A) and at 1m (B), linear and ''power'' relations lines shown.

2.3.5 Critical nutrient levels

Table 2.5 depicts critical values estimated for banana plant foliar concentration in Rombo district. The mean foliar nutrient concentrations were shown to be above the estimated foliar critical nutrient values. Although it is important to consider specific nutrient status (deficiency, sufficiency or toxicity) than the general mean foliar values.

Table 2.5: Estimated critical value or lower limit (L_l) and upper limit (L_u) of the sufficiency for plant foliar properties.

	N	P	K	Ca	Mg
			%		
Lower limit	2.39	0.15	1.53	0.35	0.30
Upper limit	2.77	0.20	1.85	0.43	0.37
Mean	2.58	0.17	1.69	0.39	0.33

N= Nitrogen; K= potassium; Ca=Calcium; Mg=Magnesium; P= Phosphorous

In comparison with results by Memon *et al.* (2005) critical values were lower for K (<3%), Ca (<0.5%), N (<2.6%) and P (<0.2%), but tallied for Mg (<0.3%). Mustaffa and Kumar (2012) reported critical levels in banana leaves (*Cavendish spp.*) to be 3.18 - 3.43, 0.46 - 0.54 and 3.36- 3.76% for N, P and K, respectively, also suggesting that these critical values vary with banana cultivars and nutrient management.

Critical values estimated for soil properties in selected farms were shown in Table 2.6. The mean nutrient concentrations for soil properties were depicted to be above the estimated soil critical nutrients. But mean values were not a good depiction, whereby with higher CV (>50%) as seen for P>Cu>K>Zn>Mn.

Table 2.6: Estimated critical values or lower limit (L_l) and upper limit (L_u) of the sufficiency range of soil properties

	pH	OC	N	K	Ca	Mg	Av.P	S	Fe	Cu	Zn	Mn
		%	%	------- Cmol+kg^{-1} ---			--------------------- mg kg^{-1}-----------------					
L_l	6.12	2.53	0.25	0.15	24.51	6.81	10.94	19.91	185.10	0.53	0.19	2.09
L_u	6.75	4.37	0.43	0.47	39.55	9.23	51.00	36.64	277.80	1.65	0.44	3.63

OC=Organic carbon; N= Total nitrogen; K= potassium; Ca=Calcium; Mg=Magnesium; Av. P=available Phosphorous; Na= Sodium; S=Sulphur; Cu=Copper; Zn=Zinc; Mn=Manganese; Fe=Iron;

The relative bunch weight, in relation to selected nutrients concentrations in banana leaves and in soil, was used to estimate critical values by fitting a boundary line shown in Fig. 2.4 and Fig. 2.5.

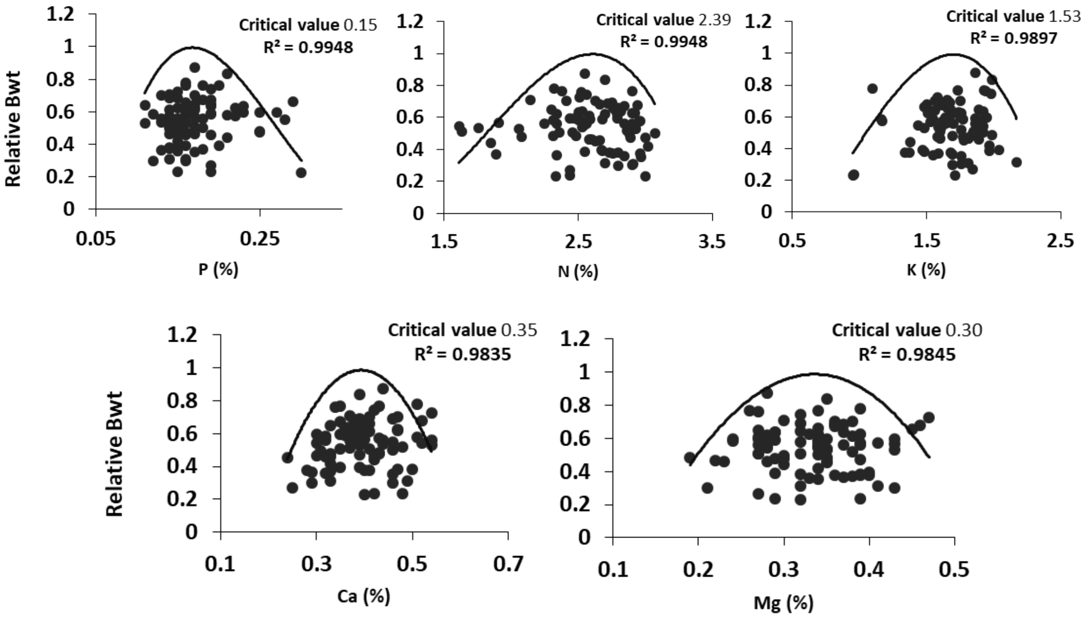

Figure 2.4: Relationship between bunch weight (*Bwt*) and nutrient concentration in banana leaves

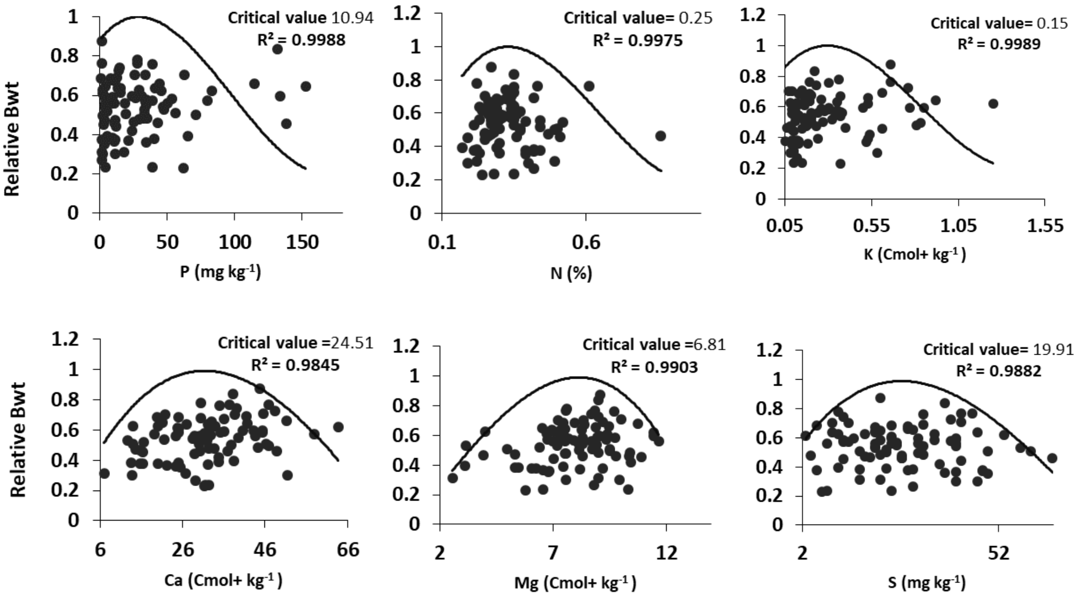

Figure 2.5: Bunch weight (*Bwt*) relation to selected nutrient concentrations in soil

The triangular distribution patterns that are seen in plots (Fig. 2.4) showing relation between the plant foliar nutrient contents and bunch weights indicate that the bunch weight are subjective to more than a single nutrient and involves other interacting factors. This inference was also observed in the work by Wairegi and van Asten (2011). Where maximum bunch weight indicated by the upper boundaries of the data, showed a positive yield-and-nutrient concentration relationship at low concentrations and a negative relationship at high concentrations. Excess nutrient concentration results in reduction in concentrations of other nutrients, and decline in yield (Havlin *et al.*, 2016).

2.4 Mapping Spatial Nutrient Distribution

High coefficient of variation for P>Cu>K and lower for OC=N>S>pH was observed. Different theoretic models of semi-variograms were obtained and adjusted to best fit each of the sample variograms for soil macronutrients (N, P, K, Ca, Mg, Na, S), micronutrients (Cu, Mn, Fe, Zn) and physical properties (pH, OC, Clay, Silt and Sand) as shown in Fig. 2.6. Spherical semi-variogram model was more prominent and considered suitable in depicting spatial variability with agricultural practices (Lu *et al.,* 2012).

Spatial dependency ratio (SDI) is rated (in %) as: >25 is strong, 25<SDI<75 is moderate and >75 is weak (Gorres and Amador, 2005). Spatial dependency ratio for the fitted variograms show there was a weak and decreasing spatial dependence in concentrations of Zn>N>P>Cu>Fe, indicating deficiencies in these nutrient elements in most of areas.

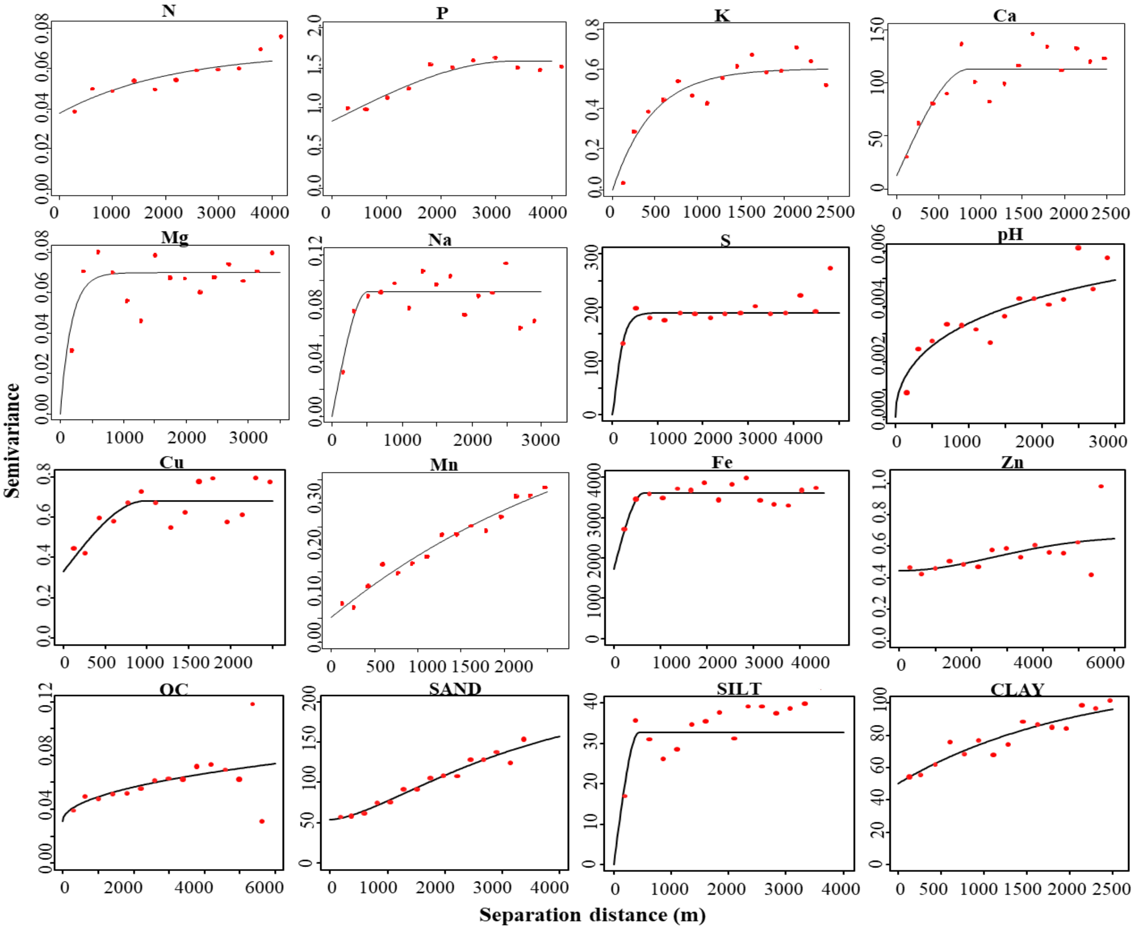

Figure 2.6: Fitted variograms of soil properties

Table 2.7 shows performance indices and SDI as validating indices. Results indicated that Fe had the highest mean value of 234.9 mg kg^{-1} which is equivalent to 52.3% of the total observed elements. On one hand, N, K, Na and Zn were found to have mean values <1 mg kg^{-1} each, which is equal to 0.2% of the total observation. Likewise P, with coefficient of variation (CV =105), seems to be more variable compared to the rest of elements. However, Mn, with the highest R^2 value, explains the fact that, 54.4% of the variations in dependent variable is due to the variation in independent variable, this implies that the regression model fits better for Mn as compared to the other elements.

Table 2.7: Descriptive statistics, performance indices, semi-variogram models and spatial dependence ratio for the soil properties n (number of observation) = 90

	pH	OC	N	Ca	Mg	K	Na	P	S	Cu	Zn	Mn	Fe	CL	SI	SA
Mean	6.50	3.30	0.30	31.9	8.0	0.30	0.20	31.4	27.6	1.1	0.3	3	234.9	42.7	30.9	26.5
CV	7.00	24.0	24.0	35.0	22.0	79.0	26.0	105	50	87	56	44	26	23	20	40
R^2	42.7	13.4	12.1	19.0	0.5	19.7	0.90	8.8	1.7	3.9	4	54.4	3.4	28.2	0.1	42.3
ME	0.01	0.08	0.01	0.00	0.24	0.06	0.01	10.9	0	0.27	0.05	0.13	0	0	0	0
MSPE	0.12	0.54	0.01	0.13	3.5	0.05	0.00	1098.05	0.45	0.89	0.03	0.83	0.06	0.04	0.07	0.12
RMSE	0.35	0.74	0.07	0.36	1.87	0.23	0.06	33.14	0.67	0.94	0.18	0.91	0.25	0.2	0.26	0.34
SDI	0.00	9.00	120	12.0	0.00	0.00	0.00	113	0	95	198	11	93	75	0	35
Model	Exc	Exc	Exp	Shp	Mat	Ste	Shp	Shp	Bes	Shp	Gau	Exp	Shp	Ste	Shp	Bes

OC=organic carbon; P= Phosphorous; N= Total nitrogen; K= potassium; Ca= Calcium; Mg=Magnesium; Na= sodium; S=Sulphur; Cu=Copper; Zn=Zinc; Mn=Manganese; Fe=Iron; CL=Clay; SI=Silt; SA=Sand; R^2=Coefficient of determination, ME=Mean Error; MSPE=Mean square prediction error; rmse/RMSE=Root mean square error; Exp=Exponential; Exc=Exponential class/stable; Shp=Spherical; Ste=Stein's parameterization; Bes=Bessel; Mat= Matern; Gau= Gaussian; CV=coefficient of variation (%); SDI=Spatial dependence ratio

The spatial distribution maps (Fig. 2.7 a, b and c) describe the pattern of soil nutrient and physico-chemical properties. Total N and OC concentrations had an almost similar pattern with higher concentration (>0.36%N, >3.8% OC) especially in the north west part, moderate at the central part in 47% of the study area, and lower concentrations in the far east of the map for 2% of the areas. This could be attributed to high organic matter from the residues of tree crops in higher altitudes that grow well due to enough moisture unlike the lowland areas (RDAIC, 2019). Available P concentration was higher in the sites north through the central to south western part (>35 mg kg^{-1}), while far west P was very low (<8 mg kg^{-1}) being high altitude areas (RDAIC, 2019), low P could be due to erosion by heavy rains. Exchangeable K is shown to be low in about 80% of the sites, could be due to large K-uptake by banana crop (harvest) as well as residue transfer, where K-input is low in soil or slow releasing-sources. For Mg, Ca and Na concentration were moderate to high for more than 75% of the study areas, range from 6 to 12, 28 to 50 and 0.15 to 0.30 cmol+ kg^{-1}, respectively. While Ca was low in about 12% of the areas and S was low in about 58 % of areas. For micronutrients, Zn and Mn were moderate to high for about 65% of the areas, unlike Cu and Fe which were low in most areas but had very high values in less than 2% of the areas, which could lead to toxicity.

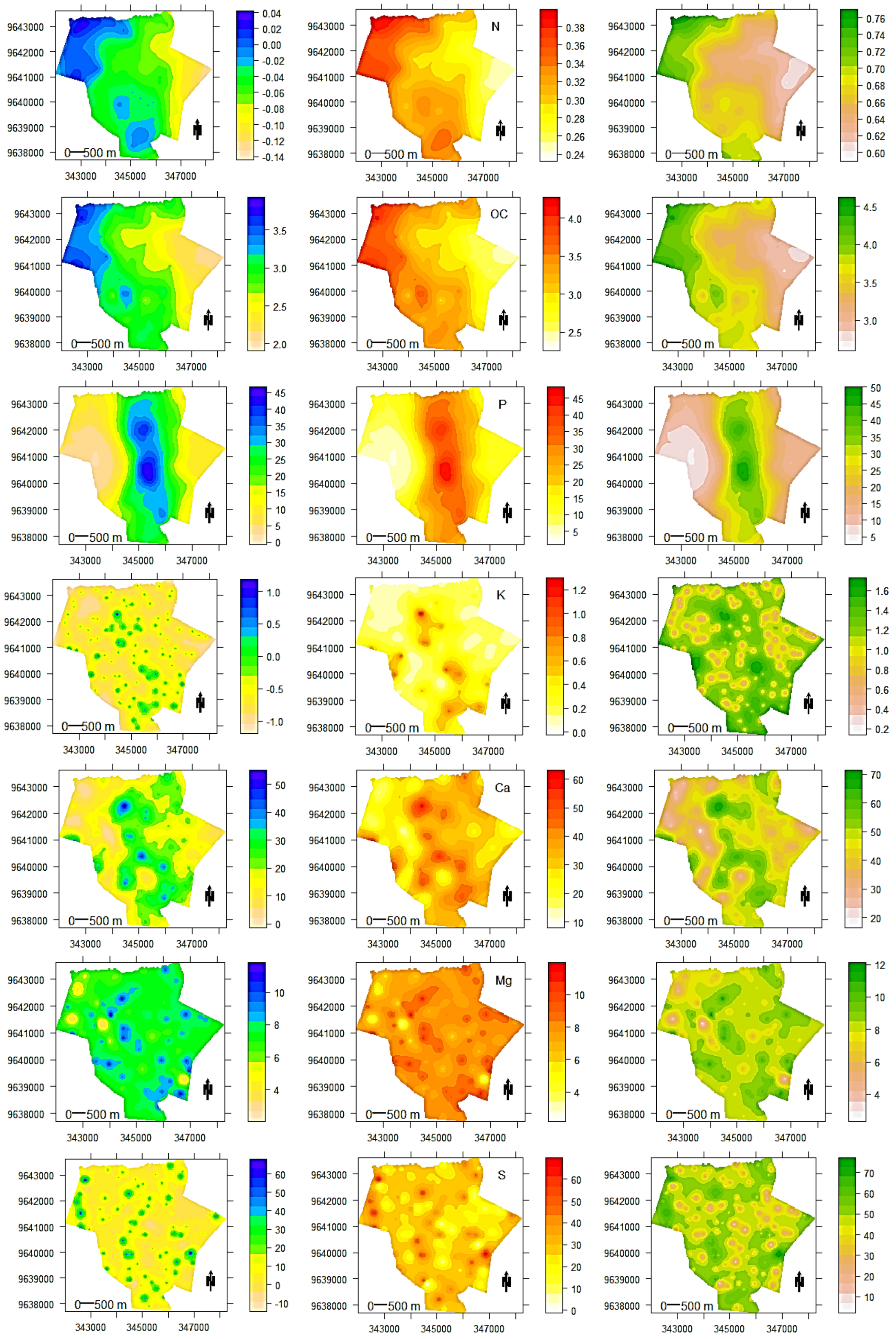

Figure 2.7a: Spatial distribution of OC and nutrients status in banana farms in Rombo District

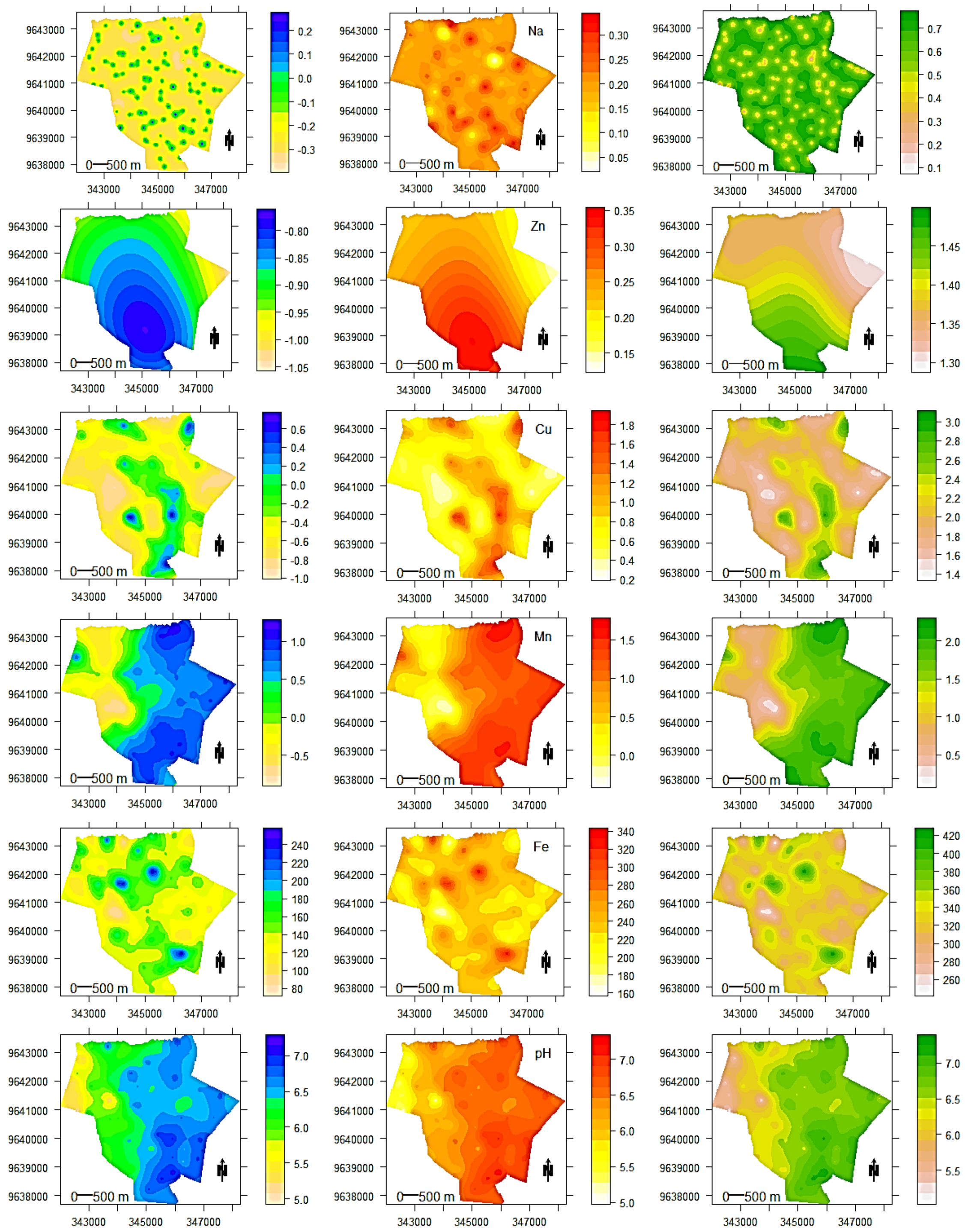

Figure 2.7b: Spatial distribution of micronutrients and pH in banana farms in Rombo District

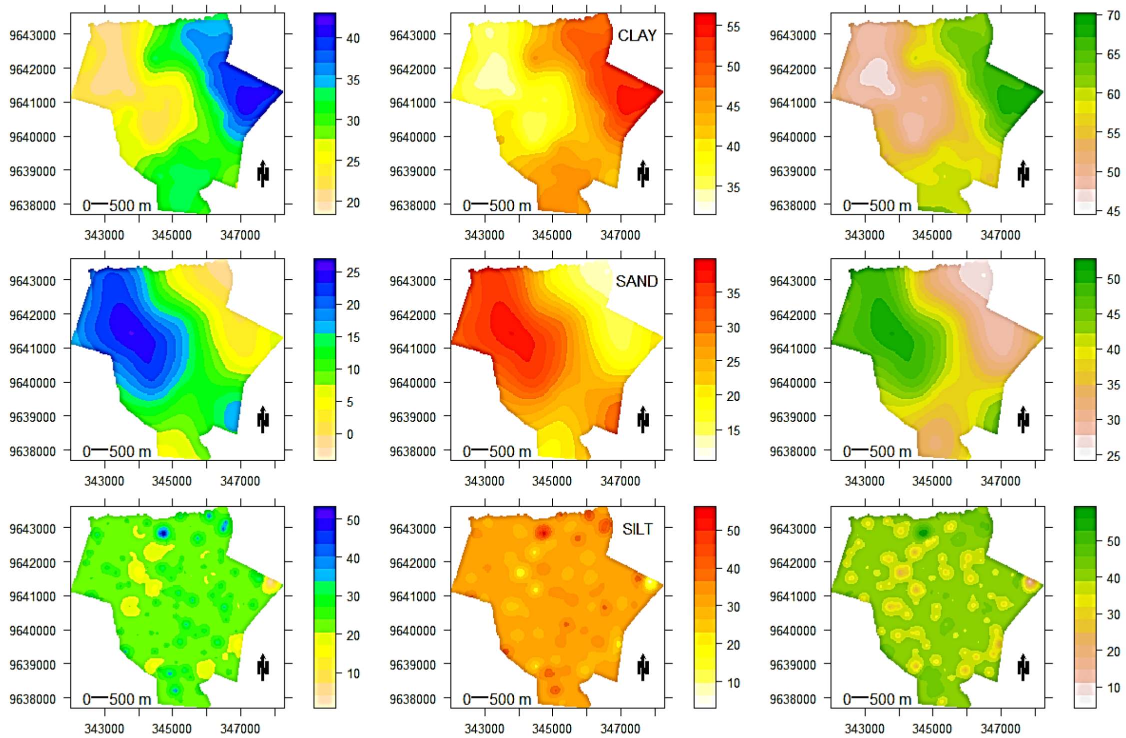

Figure 2.7c: Spatial distribution maps of soil texture in banana fields in Rombo District

2.5 Conclusion and Recommendation

Results showed that P>Cu>K>Zn>Mn>S concentrations in the soil varied more markedly with high coefficient of variation (>50%) in the selected areas in Rombo. The variation in mean nutrients concentrations was well displayed in the nutrient spatial distribution maps showing how nutrients were spatially distributed and their variation among the points sampled.

For proper nutrient management need to consider the variations and specific nutrient status in order to improve banana productivity. From the observation, localized nutrient management practices can be optimally carried out to replenish nutrient that are deficient and site specific recommendations given in future studies.

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CHAPTER THREE

3.0 DETERMINING THE MOST LIMITING NUTRIENTS IN THE BANANA FARMING AREAS

ABSTRACT

Nutrient depletion in agricultural soils is a major cause of low banana yields. A banana yield trend varies in response to yield-limiting factors. In this study, we aimed at determining yield-most-limiting factors in selected banana farms in Rombo District. An agronomic survey was carried out to identify production constraints and agronomic management practices, and socio-economic data was used to categorise households (HHs) into wealth classes, namely, Resource-rich *L3*, -medium *L2* and -poor *L1* HHs. Soil samples were collected from each farm and analysed for their nutrient concentrations. Nutritional status in soils was evaluated using nutritional index (*NI*). Banana bunch weights (*Bwt*) were compared to optimum attainable *Bwt* of 28 kg and obtained 69 low-yield farms. Major nutrient deficiencies were K>Mn>P=Zn>Cu in 40, 35, 34 and 32 % of low-yield areas, respectively. The results tallied with reports from previous studies indicating K as most limiting nutrient. Resource-rich HHs (*L3*) owned more land area under banana than *L2* and *L1* HHs by 8% no significant difference (ns). Also, *L3* had significantly ($P \leq 0.05$) higher banana *Bwt* and mulch depth, and higher mulch cover by about 15% (ns). Hence, there is a need to address limiting nutrient and their requirement mainly for K and in home gardens of less-resource HHs.

Keywords: *Most limiting nutrient, bunch yield, Socio-economic characterisation*

3.1 Introduction

There has been a continuous trend in the decline in banana crop production among the smallholder farmers. Studies have reported a decline in banana crop yield in banana farming systems as result of declining in soil fertility (nutrient deficiencies) among other abiotic and biotic constraints (Baijukya, 2004; Wairegi *et al*., 2010; Senkoro *et al.*, 2017). In low-input banana farming systems where nutrients applied is lower than nutrients required for plant uptake and growth, yield is impeded and major nutrients N, P or K acts as yield most limiting factors (Nyombi *et al*., 2010; Ndabamenye *et al.*, 2013; Taulya, 2015). Blanket recommendations is like a norm within agricultural extension service not considering much the peculiarities of banana farming system and their distinguishing soil fertility status (Baijukya, 2004; Wairegi and van Asten, 2011). Thus inability to properly address the problem in nutrient decline in the banana farms which limits banana yield.

Plant nutrient deficiency symptoms could indicate limiting nutrients, deducing measures to be taken although these symptoms can be misleading. Therefore, it is better to carry out plant and soil nutrient analysis to know the nutrient concentrations. Yield is increased by addition of a yield-limiting nutrient in required amount and time. Plant yield respond to growth/yield factors based on Liebig’s law of minimum. The law states that plant growth is limited by yield-influencing factor present in minimum amount (in relation to the plant’s needs), hence yield varies with changes in the limiting factor, until it is no longer a limiting factor, then the next limiting nutrient controls plant growth (von Liebig, 1863).

The concept of improving limiting nutrients does not imply an unending increase in the soil nutrient status, but simply an increase to an optimal supply level sufficient for high yields, but not up to luxury supply which would be unnecessary and detrimental in view of nutrient losses, imbalances or toxicity. When a particular nutrient is deficient (lower than the critical nutrient level), crop yield is impeded, but crop growth (or its relative yield) can increase in response to applying the limiting nutrient (Havlin *et al*., 2016). The boundary line approach is used to determine the sufficiency range including nutrient critical values to further indicate yield-limiting factors (Maia and Morais, 2015).

Therefore, the study is to determine banana yield-limiting nutrients in Rombo district; Tanzania. This will help define suitable nutrient management practices in addressing the existing nutrient deficiencies and improving banana production in the banana farming systems in Rombo district.

3.2 Materials and Methods

3.2.1 Description of the study area

The study was carried out in Rombo District (Fig. 2.1) in the Eastern Kilimanjaro Region. It is located between Latitudes 2° 52’ 48” S - 3° 23’ 60” S and Longitudes 37° 16’ 48” E - 37° 42’ 00” E. It lies within an altitude of 800 - 2000 m a.m.s.l, with an area of 1442 km². The rainfall pattern in Rombo District is bimodal, with long rains fall between March to June while short rains fall between October to December. Mean annual rainfall ranges from 500mm to 1750 mm (RDAICP, 2019). Soils are predominantly sandy loam and clay loam with soil types described as Andosols, originating from volcanic rocks, ash and lava. The upper southern slopes of Mt. Kilimanjaro are characterised by the densely populated Chagga farming system, with banana home garden and food production systems to the lower slopes and adjacent plains (Soini, 2002; Misana *et al.*, 2012). Banana is cultivated in at least 70 % of the households as food and/or cash crop, with planted area per household about 0.4 to 1.5 ha (Kalyebara *et al.*, 2007; MAFC, 2012).

3.2.2 Study design

A survey approach was employed, involving sample collection in farmers’ banana fields. Using probability sampling technique, six wards (namely: Aleni, Mamsera, Manda, Mengeni, Mengwe and Shimbi) were selected in a systematic random way based on banana production areas. Then from the six wards, 90 sites were selected in a stratified random manner. The study area was divided into strata (0-89) and each stratum assigned 10 geo-points (a-j) from which a suitable site with a banana farming household was selected and geo-referenced.

3.2.2.1 Survey and data collection

An agronomic survey was carried out in the selected banana producing households to identify banana production constraints and agronomic management practices over the past 12 months. A questionnaire and direct measurements was used to obtain the agronomic information. Information collected included farm size, number of years farm has existed, type of cropping system, cultivars, crop residue management, manure application (source, quantity and frequency), weeding frequency, inorganic fertiliser use, banana harvests, mat density, weed intensity, mulch thickness, pest and disease prevalence and pesticides used. Additionally, demographics and other socioeconomic factors about the respective household owning the selected banana farms were captured.

3.2.2.2 Socioeconomic characterisation

Data from the agronomic survey were used to describe socio-economic characteristics of the banana farmers in Rombo District. The banana farm household were categorised based on their possessions and three household (HH) groups were identified: HHs with low resources (L1), medium resource (L2), and high resources (L3). Wealth indicators included domestic assets owned such as means of transport (automobile and bicycle), television and radio; livestock ownership mainly cattle and their products (mainly manure) and landholding. Different socio-economic wealth classes have almost different nutrient management practices, hence yield variations. Farmers’ characterisation based on resources available to them and soil fertility variation in their home gardens is important in determining nutrient management practices and banana productivity at household level.

3.2.2.3 Soil sampling and nutrient analysis

A total of eight soil subsamples were collected at 0-30 cm depth in zigzag pattern and mixed to get a 0.5 kg composite soil sample from each banana field. Soil samples were prepared and analysed at the International Institute of Tropical Agriculture (IITA) soil laboratory in Dar es salaam; Eastern Africa Hub. Soil samples were air dried for 12-24 h, ground and passed through a 2 mm sieve then analysed for soil physico-chemical properties (organic carbon, soil texture, and pH) and nutrients (N, P, K, Mg, Ca and S) based on procedures by Okalebo *et al*. (2002) and Webster (2008). The resulting dataset were shown in Appendix 1.

Soil pH was determined using a glass electrode pH meter in 1:2.5 (soil: water suspension). Organic carbon was determined by Walkley and Black method using wet oxidation by potassium dichromate (Okalebo *et al*., 2002). Total nitrogen (N) was determined by the micro-Kjedahl digestion procedure followed by distillation (Okalebo *et al*., 2002). Available Phosphorous (P) was extracted using Mehlich-3 and determined using a spectrophotometer (Okalebo *et al*., 2002; Webster, 2008). Exchangeable potassium (K), calcium (Ca), magnesium (Mg) and sodium (Na) were extracted using Mehlich-3 determined by Atomic Absorption Spectrophotometer (Okalebo *et al*., 2002). Micronutrients; copper (Cu), zinc (Zn), iron (Fe) and manganese (Mn) were determined using the Diethylentriaminepentaacetic acid (DTPA) extraction procedure (Okalebo *et al*., 2002; Webster, 2008).

3.2.2.4 Plant sampling and nutrient analysis

Composite foliar samples of 5 cm by 5 cm were taken from both sides of the mid-rib in the midpoint of the lamina of the third-youngest fully expanded leaf of three randomly selected banana plants at flowering stage (Memon *et al.*, 2005), at the beginning of short rains. Also, plant samples were collected from the pseudo-stem, leaves, peduncle and fingers to determine the nutrient concentrations (N, P, K, Mg, and Ca) on the dry matter basis after harvest and further used to estimate the above ground biomass (ABG). Analysis for nutrients (N, P, K, Mg, and Ca) concentrations of the composite foliar samples was done at IITA soil laboratory in Dar es Salaam. Plant and foliar samples were oven dried at 60^{o}C for 24-64 hours, ground, and then digested in a mixture of sulphuric acid and selenium. Nitrogen was determined by the micro-Kjedahl digestion procedure followed by distillation. P was determined using a spectrophotometer (Okalebo *et al.*, 2002), whereas K, Ca and Mg were determined by Atomic Absorption Spectrophotometer (AAS) (Okalebo *et al.*, 2002).

3.2.3 Data analysis

Soil analysis data was sorted and calculations for critical nutrient values and yield-limiting nutrients done in Microsoft Office Excel 2013. Following Maia and Morais (2016) the maximum yield at 95 % yield target were predicted. Soil nutrient values corresponding to 95 % yield target on the scatter plot were then established as critical nutrient values.

The nutritional index of each sample was calculated as:

$$NI = \frac{\sum(P-P_i)}{n.P_{max}} \qquad (4)$$

Where: n is the number of analysed nutrients

Ninety banana farm areas with selected *Malindi* cultivar stands were considered and classified according to their bunch weight at harvest. Considering an optimum attainable bunch weight of 28 kg as a reference according Njuguna *et al*. (2008), out of the 90 farm areas, 62 low-yield areas and 28 high-yield areas were obtained. The nutritional status of the farm areas was evaluated through the nutritional index (*NI*) (Eqn 4). Where the more negative the index, the more intense the nutritional deficiency, that is, the most negative index value is considered the most limiting. The number of farms in which the soil nutrient was identified as most limiting was calculated (in percentage).

Agronomic survey data was sorted in Microsoft Office Excel 2013, and systematic characterisation of banana farmers into socio-economic wealth classes was done in R software based on the rare, moderate and common assets owned. Farmers' record from the agronomic survey interview on nutrient management practices carried out among farmers in the different wealth classes were subjected to Analysis of Variance (ANOVA) to ascertain the significance difference in R software 3.6.0 version. Tukey Honest Significant Difference test was used to further compute for the significant different between the means of the levels (multiple comparisons of means) at 95% family wise confidence level.

3.3 Results and Discussion

3.3.1 Most limiting nutrients

Following the nutritional index; *NI* (Eqn. 4), Table 3.1 shows Mn was generally shown to be most limiting nutrient with 31.1% and 33.3% of all selected farm areas Mn-deficient and Mn-excess, respectively. Manganese ranged from 0.47 to 2.01 mg kg^{-1}, mean of 1.12 mg kg^{-1} and 35.5% of low-yield areas were Mn-deficient, and from 0.28 to 1.87 mg kg^{-1}, mean of 1.21 mg kg^{-1} with 21.4% of high-yield areas were Mn-deficient. Mean for Mn concentration for both low- and high-yield areas were below the critical level (Table 3.1). Manganese-deficiency could be due to soil conditions such as soil pH and organic matter content (Uwitonze, 2016). Soils high in organic matter, near neutral pH soil or soils that have been limed are likely Mn-deficient, while Mn-toxicity is common in acid (below pH 5.5) soils (Zia *et al.*, 2006).

This result differ from Senkoro *et al.* (2017) that reported N to be the most limiting nutrient in most croplands in Tanzania. The nutrient limitations for N, P and K were 17.7, 33.9, and 40.3% of low-yield areas by deficiency, respectively, and were 14.4, 30.0 and 34.4% 40.3% of high-yield areas by deficiency, respectively. The nutrients in excess (beyond the sufficient range) were mainly Mn, Zn and S with 33.3, 28.9, and 28.9% of all selected farm areas, respectively. These nutrients in excess could lead to toxicity. Nitrogen, OC, and pH were within the sufficient range with 71.1, 72.2 and 60.0% of all selected farm areas, respectively.

Table 3.1: Estimated lower limit- (L_l), upper limit- (L_u) of the sufficiency range and nutritional index (NI) for soil properties

	pH	**OC**	**N**	**K**	**Ca**	**Mg**	**Av.P**	**S**	**Fe**	**Cu**	**Zn**	**Mn**
		%	**%**	**------- Cmol+kg^{-1} ---**			**------------------ mg kg^{-1}-----------------**					
L_l	6.12	2.53	0.25	0.15	24.51	6.81	10.94	19.91	185.10	0.53	0.19	2.09
L_u	6.75	4.37	0.43	0.47	39.55	9.23	51.00	36.64	277.80	1.65	0.44	3.63
	Nutritional Indices											
	N	**OC**	**pH**	**Fe**	**P**	**Zn**	**K**	**Mg**	**Ca**	**Cu**	**S**	**Mn**
	-3.06	**-3.04**	**-2.77**	**-2.76**	**-2.76**	**-2.76**	**-2.75**	**-2.72**	**-2.71**	**-2.67**	**-2.56**	**-2.37**

OC=Organic Carbon; N= Total Nitrogen; K= Potassium; Ca=Calcium; Mg=Magnesium; Av. P=available Phosphorous; Na= Sodium; S=Sulphur; Cu=Copper; Zn=Zinc; Mn=Manganese; Fe=Iron.

The major deficiencies were K > Mn > P = Zn > Cu in 40.3, 35.5, 33.9 and 32.3% of the low-yield areas, respectively (Fig. 3.1). In the low yield areas, K was most limiting nutrient, this is in line with earlier studies (van Asten *et al.*, 2004; Ndabamenye *et al.*, 2013; Ganeshamurthy *et al.*, 2011). K is taken up by banana crop like other primary nutrients are being exported off banana farms in large amount in the order K > P > N (Shand, 2007; Nyombi *et al.*, 2010; Taulya, 2015). The application of K sources and in a rate required is very low among farmers in the areas, who mostly use farmyard manure, mulch and crop residues, consequently minimal replacement of K which is removed in bulk by bunch harvest and its residues (leaves and pseudostem) and fed to livestock.

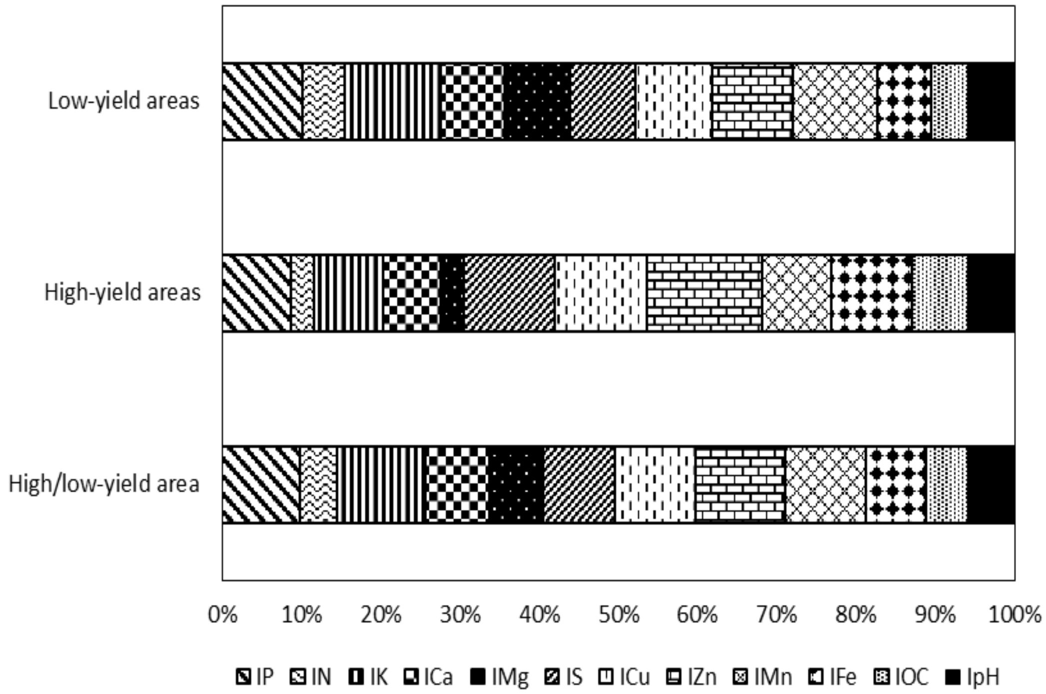

Fig 3.1: Limiting nutrients estimated and their corresponding proportions of farm areas (in %) in Rombo District

Figure 3.1 shows where nutrients are most limiting in the low-yield areas, high-yield areas and high&low yield areas (overall study area) in Rombo District.

3.3.2 Nutrient management and bunch weight across socio-economic classes

Resource-rich households possessed more land area under banana than the resource-medium and resource-poor households by 8% with no significant difference in the banana acreage (Table 3.2). This observation tallied with findings by Mwijage *et al*. (2009), where the resource rich (wealthy) owned more land (Kibanja) holding than the average and poor households. A different trend was observed with banana mat density where the resource-rich household had a lower mat density by about 20%. The lower mat density for resource-rich could be for better farm management and maintenance so as to obtain a banana high bunch weight harvest being intercropped with other crops. Overall, the resource-rich class had significantly (P≤0.05) higher banana bunch weight than the resource-medium and resource-poor by 23% and 8%, respectively.

Table 3.2: Variation in mat density, banana acreage and bunch weight (*Bwt*) across the household wealth classes

Wealth classes	**n**	**Mat density** (Mats ha^{-1})	**Banana acreage** (ha)	**Bwt** (kg)
		Mean ± se	Mean ± se	Mean ± se
L1	16	2427 ± 377ns	0.25 ± 0.05ns	25.21 ± 1.57ab
L2	36	2302 ± 238ns	0.25 ± 0.03ns	22.04 ± 0.96a
L3	34	1970 ± 223ns	0.27 ± 0.02ns	27.11 ± 1.29b

L1= resource-poor households; L2= the resource-medium households; L3= the resource-rich households; Different letters in the column signify significant differences at P≤0.05 Turkey HSD for the different classes.

In Table 3.3, for the resource-poor, mulch depth was significantly (P≤0.05) higher than resource-medium and resource-rich households by about 20%, and also a higher mulch cover by about 15% (no significant different). This indicated the crop residues and grasses are left on the farm as mulch since most of resource-poor have no livestock to feed these crop remains. Yet again in line with findings by Mwijage *et al*. (2009) suggested that mulch quantity and its application to home garden depicts a larger variation among the households based on resource use. Nonetheless, there was no significant difference in weed depth and weed cover across the wealth classes.

Table 3.3: Variation in mulch depth, mulch cover, weed depth and weed cover across the household wealth classes

Wealth classes	**n**	**Mulch depth (cm)**	**Weed depth**	**Mulch cover (%)**	**Weed cover**
		Mean ± se	Mean ± se	Mean ± se	Mean ± se
L1	16	4.04 ± 0.37a	15.32 ± 3.31a	56.17 ± 4.31a	11.03 ± 1.81a
L2	36	3.48 ± 0.16ab	13.25 ± 2.40a	48.60 ± 3.94a	9.14 ± 0.79a
L3	34	3.35 ± 0.16b	10.50 ± 2.60a	53.47 ± 3.99a	8.90± 0.95a

L1= resource-poor households; L2= the resource-medium households; L3= the resource-rich households; Different letters in column signify significant differences at $P \leq 0.05$ by Turkey HSD for the different classes.

3.4 Conclusion and Recommendation

Results obtained showed yield-limiting nutrient in the low-yield areas due to nutrient deficiencies were K > Mn > P = Zn > Cu in 40.3, 35.5, 33.9 and 32.3% of the areas, respectively. These nutrients were limiting in the low yielding areas of households that are resource-limited with poor nutrient management (low nutrient supply) that led to decline in yield.

Resource-rich household (L3) owned more land area under banana than the resource-medium and resource-poor households by 8% (no significant difference) and had significantly ($P \leq 0.05$) higher banana bunch weight. Additionally an integrated nutrient management especially for less resource households could be recommended in order to improve banana production.

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CHAPTER FOUR

4.0 PARTIAL NUTRIENT BUDGET FOR THE MOST LIMITING MAJOR NUTRIENTS

ABSTRACT

The use of organic fertiliser (manure) in replenishing nutrients in the home gardens has been a norm in banana farming systems, with poor nutrient management and low nutrient input, hence decline in banana crop yield in Rombo district. There are no adequate records indicating nutrient flow (fluxes) in farming systems in Rombo. Thus, this study was conducted so as to develop partial nutrient balances in home gardens. Agronomic survey was done and survey data used to categorise farmers into wealth and cattle ownership classes. Plant samples were collected and nutrient content analysed. Nutrient analysis and survey data were used to calculate partial nutrient balances in home gardens across the household classes. Large nutrient input observed was from farmyard manure and major nutrient loss by crops harvested and residues removed. Higher negative N and K balances were obtained in home gardens of less resource households (HHs) and those with few (≤ 2) cattle. Positive P balances were observed in home gardens across all HHs classes indicating less P-removal but P could be adsorbed or lost through erosion. Positive NPK balances were observed for HHs with more (>2) dairy cattle, but these HHs were few. Hence, there is need to explore and employ other nutrient sources especially in less resource HHS in order to supply more nutrients in the farms, so as to increase yield.

Keywords: *primary nutrients, nutrient budget, household classes*

4.1 Introduction

Decline in the productivity of banana farming systems is attributed to nutrient imbalances in the farms, leading to decline in crop yield (Baijukya and de Steenhuijsen Piters, 1998;

Baijukya, 2004; Ndabamenye *et al.*, 2013). Also, many smallholder farmers continuously cultivate banana on weathered farm land with low nutrient supply (Bekunda *et al.*, 2002; Baijukya *et al*., 2005). these farmers have limited resources (Maerere *et al*., 2008), and very few use inorganic fertiliser due to cost-restrains, poor availability and poor knowledge of their use (Ndabamenye *et al.*, 2013; Senkoro *et al.*, 2017). Nutrient removal from banana farming systems result into soil nutrient deficiencies and negative yield drifts (Baijukya, 2004; Nyombi *et al*., 2010).

Nutrient balances are useful indicators for improving crop productivity, management of nutrients and resources (Cobo *et al*., 2010). Nutrient budget is calculated by the difference between nutrient inputs and outputs of a system with defined spatial-temporal boundaries (Bindraban *et al*., 2000). A partial nutrient budget is simply the difference between the nutrient inputs into a farming system (mainly organic and/or inorganic fertilisers) and the nutrient outputs from the farming system (nutrients taken up crop and/or pasture) (Bekunda and Manzi, 2003; Zingore *et al*., 2007). Generally, it is expressed in amount of nutrient(s) per unit of area and time (kg ha^{-1} year^{-1}). Negative balance (i.e. removal exceeds use) indicates declining soil fertility, hence, reduced productivity once nutrient supplies drop below critical levels. Positive balance (i.e. use exceeds removal) defines increasing soil fertility but with risk of nutrient loss to the environment. Zero balance (i.e. use equals removal) describes soil fertility maintenance. Several studies have reported the use of the nutrient balance approach for improving soil fertility and crop productivity (Baijukya and de Steenhuijsen Piters, 1998; Færge and Magid, 2004; Cobo *et al.*, 2010; Wairegi and van Asten, 2011; Ndabamenye *et al.*, 2013).

In this study, data from nutrient analysis and from interview with farmers was used to develop partial balances of limiting nutrients NPK in banana farming systems in Rombo.

4.2 Materials and Methods

4.2.1 Description of the study area

The study was carried out in Rombo District (Fig. 2.1) in the Eastern Kilimanjaro Region. It is located between Latitudes 2° 52’ 48” S - 3° 23’ 60” S and Longitudes 37° 16’ 48” E - 37° 42’ 00” E. It lies within an altitude of 800 – 2 000 m a.m.s.l, with an area of 1 442 km². The rainfall pattern in Rombo District is bimodal, with long rains fall between March to June while short rains fall between October to December. Mean annual rainfall ranges from 500 mm to 1 750 mm (RDAICP, 2019). Soils are predominantly sandy loam and clay loam with soil types described as Andosols, originating from volcanic rocks, ash and lava. The upper southern slopes of Mt. Kilimanjaro are characterised by the densely populated Chagga farming system, with banana home garden and food production systems to the lower slopes and adjacent plains (Soini, 2002; Misana *et al*., 2012). Banana is cultivated in at least 70 % of the households as food and/or cash crop, with planted area per household about 0.4 to 1.5 ha (Kalyebara *et al*., 2007; MAFC, 2012).

4.2.2 Study design

A survey approach was employed, involving sample collection in farmers’ banana fields. Using probability sampling technique, six wards (namely: Aleni, Mamsera, Manda, Mengeni, Mengwe and Shimbi) were selected in a systematic random way based on banana production areas. Then from six wards, 90 farm sites were selected in a stratified random manner. The study area was divided into strata (0-89) and each stratum assigned 10 geo-points (a-j) from which a suitable site with a banana farming household was selected and geo-referenced.

4.2.2.1 Survey and data collection

An agronomic survey was done in the banana producing households to identify banana production constraints and agronomic management practices over the past 12 months. A questionnaire and direct measurements was used to obtain agronomic information. Information collected included farm size, number of years farm has existed, type of cropping system, banana cultivars, crop residue management, manure application (source, quantity and frequency), weeding frequency, inorganic fertiliser use, banana harvests, mat density, weed intensity, mulch thickness, pest and disease prevalence and pesticides used. Furthermore, demographics and other socioeconomic aspects about the selected banana farming households were taken.

4.2.2.2 Socioeconomic characterisation

Data from the field survey were used to describe socio-economic characteristics of the banana farmers in Rombo District. In describing soil fertility (nutrients) management, households were categorised into two; wealth classes and cattle ownership. The banana farm household were categorised based on their possessions and three household (HH) groups were identified: HHs with low resources (L1), medium resources (L2), and high resources (L3). Wealth indicators included domestic assets owned such as means of transport (automobile and bicycle), television and radio; livestock ownership and landholding. Household groups according to cattle ownership included those with no cattle (C1), with 1 to 2 cattle (C2) and those with 3-5 cattle (C3) where from the survey the highest number of cattle was 5. Different socio-economic wealth classes have almost different nutrient management practices, hence yield variations.

4.2.2.3 Plant sampling and nutrient analysis

Composite foliar samples of 5 cm by 5 cm were taken from both sides of the mid-rib in the midpoint of the lamina of the third-youngest fully expanded leaf of three randomly selected banana plants at flowering stage (Memon *et al.*, 2005), at the beginning of short rains. Also, plant samples were collected from the pseudo-stem, leaves, peduncle and fingers to determine the nutrient concentrations (N, P, K, Mg, and Ca) on the dry matter basis after harvest and further used to estimate the above ground biomass (ABG). Analysis for nutrients (N, P, K, Mg, and Ca) concentrations of the composite foliar samples was done at IITA soil laboratory in Dar es Salaam. Plant and foliar samples were oven dried at 60°C for 24-48 hours, ground, and then digested in a mixture of sulphuric acid and selenium. Nitrogen was determined by the micro-Kjedahl digestion procedure followed by distillation, P was determined using a spectrophotometer (Okalebo *et al*., 2002), whereas K, Ca and Mg were determined using Atomic Absorption Spectrophotometer (AAS) (Okalebo *et al*., 2002).

4.2.2.4 Partial nutrient budget

A partial nutrient budget is a simple input-output model of nutrient fluxes into/out of farms. These budget were developed based on quantitative and qualitative analyses from agronomic survey data and also the biophysical data. The nutrient fluxes from difficult to measure processes such as denitrification, soil erosion and leaching were not considered in the model. Partial nutrient balances (kg ha^{-1} year^{-1}) for NPK nutrients were calculated using input and output model involving inorganic (IN1) and organic fertiliser (IN2) as inputs, and harvested crops (OUT1) and crop residues (OUT2) as output (Bekunda and Manzi, 2003; Zingore *et al*., 2007; Wairegi and van Asten, 2010). Partial nutrient balances for most limiting selected nutrients were calculated as difference between inputs-outputs,

Eqn. 2: $\text{Partial balance} = (\text{IN1} + \text{IN2}) - (\text{OUT1} + \text{OUT2})$

Nutrient fluxes were calculated from the nutrient concentration in the inputs and outputs applied per hectare for a 30 cm soil depth.

4.2.3 Statistical analysis

Data from nutrient analysis and interview survey was arranged and sorted in Microsoft Office Excel 2013. Calculations and analyses involving yields and nutrient balances for major nutrients NPK were done in Microsoft Office Excel 2013 and R software 3.6.0 version.

4.3 Results and Discussion

4.3.1 Nutrient flows (input and output)

The nutrient inputs in banana homestead considered were inorganic fertilisers (IN1) and organic fertilisers (IN2). But the farmers in Rombo do not use of inorganic fertilisers in their farms, so IN1 was negligible. The major nutrient management practices observed were application of farmyard manure and grass mulch. Table 4.1 gives a summary of amount of manure used and crop harvested.

Table 4.1: Overall average nutrient input and output in Rombo District

Input/output		Amount	Nutrient Concentration (%)		
		(kg ha^{-1})	N	P	K
Manure (cattle)	*	3933.21	0.19	0.08	0.3
Banana	**				
Harvested		4235.91			
Consumed/bought		1270.77	1.59	0.15	1.38
Stem		2753.34	2.62	0.31	1.80
Leaves		211.80	2.23	0.21	1.17
Coffee	**				
Beans^{+}		86.51	2.28	0.23	2.26
Husks^{++}		63.10	2.01	0.20	2.77
Beans	**	25.24	4.24	0.58	1.71
Yam	**	40.39	0.56	0.18	1.22

N= Nitrogen; P=Phosphorous; K= Potassium; * Nutrient input (IN); **nutrient output (OUT1 and 2); $^{+}$55% of the coffee cherries; $^{++}$45% of the cherries

Farmyard manure was a notable organic nutrient input (IN2) especially for farms with cattle (both indigenous and improved cattle) in their home gardens. Whereas harvested crops (banana, coffee, beans, and yam) (OUT1) and residues (OUT2) contributed to the total nutrients output from home gardens. Harvests from banana and coffee accounted for the high K-loss while N-loss was more due to beans harvest (Baijukya and de Steenhuijsen Piters 1998; Baijukya *et al*., 2005; Senkoro *et al.*, 2017).

The nutrient input through farmyard manure across household (HH) classes in Fig. 9 depicts resource-rich HHs (L3) and HHs with 3 to 5 cattle (C3) applied significantly (P≤0.05) more farmyard manure in their home gardens than the less-resource households (L1) and HHs with less or no cattle (C1), respectively. This tallied with result of Baijukya and de Steenhuijsen Piters (1998), indicating negative nutrient balance for households with fewer or no cattle.

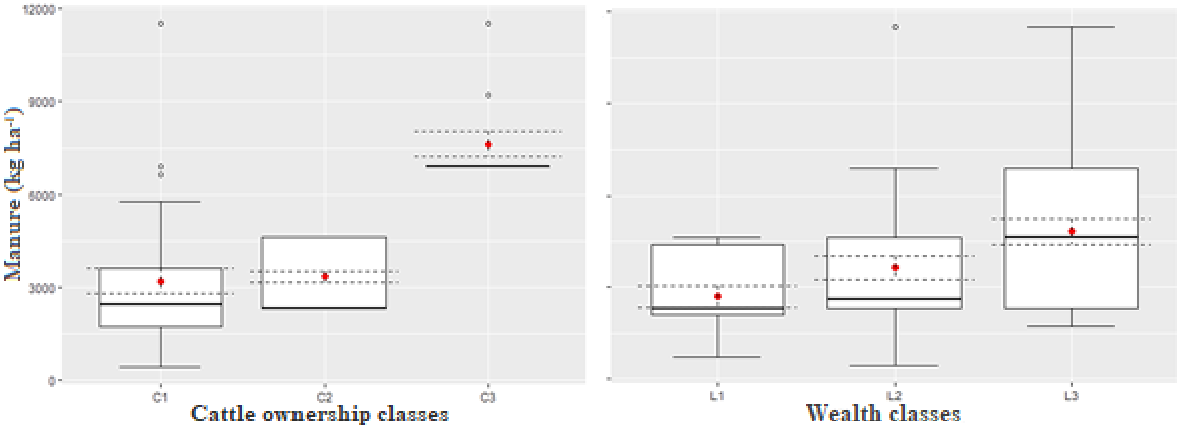

Figure 4.1: Manure application across the different household categories

The solid lines across boxes are medians and dotted lines bars are error bars. The boxes represent the interquartile range (25–75th percentile), circles represent outliers while bars represent the minimum and maximum observations.

4.3.2 Partial nutrient balance

Nutrient balances in home gardens of the different household classes was shown in Table 4.2 and Fig. 4.2. In the home gardens across the two household (HH) categories, P nutrient balances was positive implying there is adequate P added than removed. But in these home gardens, P could be adsorbed leading to the formation of insoluble P compounds not available for plant uptake or P could be removed via erosion, hence P as a limiting factor to banana production (Bekunda *et al.*, 2002).

Table 4.2: Farms nutrient balances across household classes in Rombo District

HH classes	n	Nutrient balances (kg ha^{-1} yr^{-1})		
		N	P	K
L1	16	-49.85a	10.89a	-19.88a
L2	36	-38.00a	18.04ab	-4.04a
L3	34	-24.61a	26.74b	-14.82a
C1	33	-57.61a	13.15a	-20.91a
C2	40	-43.00a	15.62a	-10.64a
C3	13	47.58b	51.85b	88.92b

N= Nitrogen; P= Phosphorous; K= Potassium; L1= resource-poor households; L2= resource-medium households; L3= resource-rich households; Different letters across the column per HH category signify significant differences at P≤0.05 according to Turkey HSD for the different categories

Nutrient balances were negative for N and K in home gardens across all HH wealth classes expect C3, although balances were more negative for home gardens of resource-poor households due to low input in their farms. This tallies with results from Zingore *et al.* (2009) that showed negative nutrient balance and low net income on poor farmers can be ascribed to poor productivity and lower nutrient added as a result of low inputs and low nutrient stocks in the soils. Potassium balances was less negative for resource-medium households (*L2*) than the resource-rich and resource-poor households. The resource-rich households having more negative balance could be due to some of *L3* households with few or no cattle, hence need to purchase manure which could as well be insufficient for banana density in their home gardens. Households with more (>2) cattle had positive balances for N, P and K indicating the contribution of manure from cattle to nutrient balances in home gardens with at least two dairy cattle and a relatively small size home gardens. This results agreed with report by Baijukya and de Steenhuijsen Piters (1998), indicating negative nutrient balance for households with no cattle.

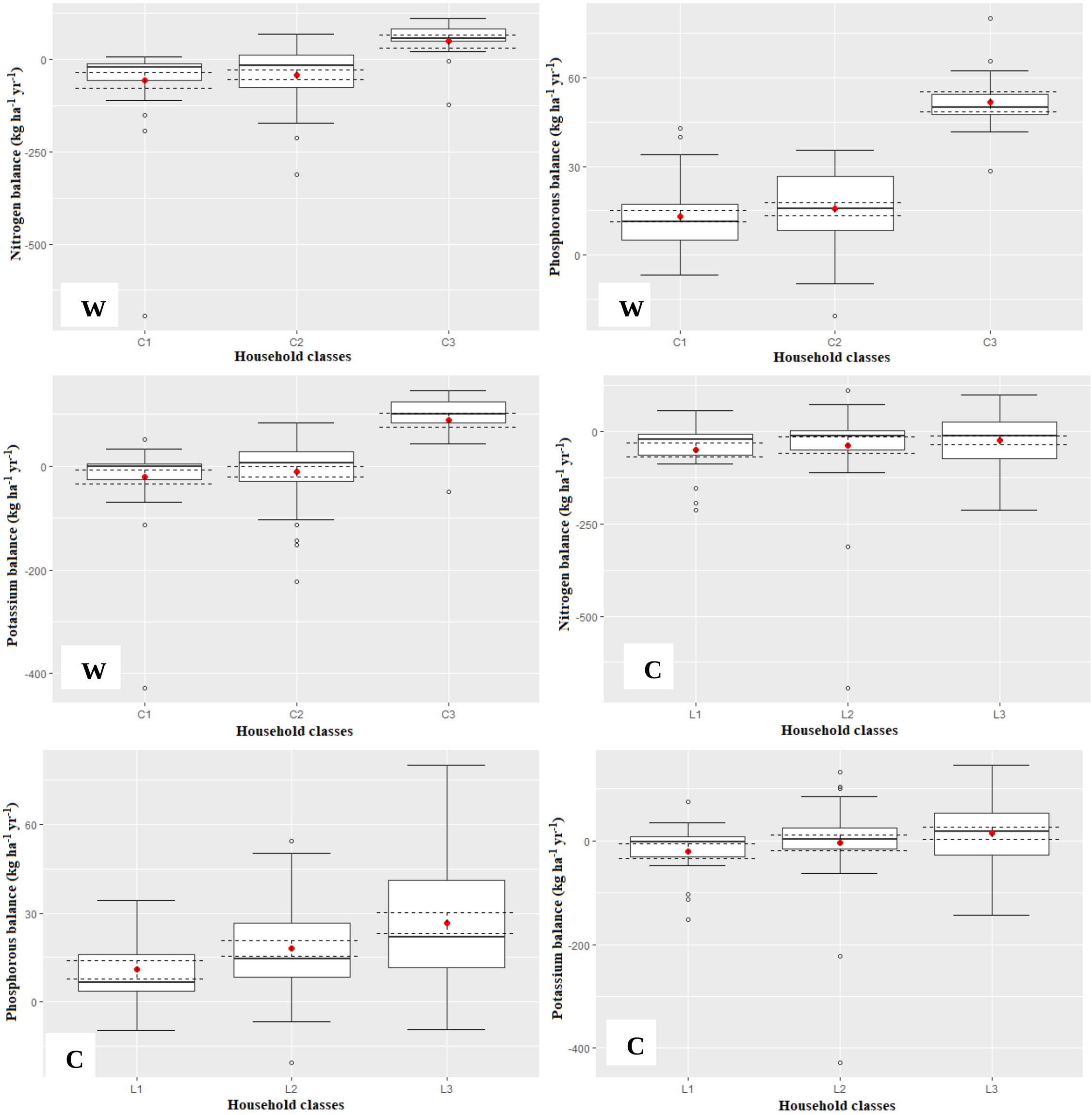

Figure 4.2: The boxplots showing nutrient balances for NPK for bananas farms across different household categories

W-wealth classes and C-cattle ownership classes. The solid lines across boxes are medians and dotted lines bars are error bars. The boxes represent the interquartile range (25–75th percentile), circles represent outliers while bars represent the minimum and maximum observations.

4.4 Conclusion and Recommendations

The resource-rich household (L3) and household with more (>2) cattle (C3) applied significantly ($P \leq 0.05$) more farmyard manure in their home gardens. Likewise, nutrient balances were negative for N and K in home gardens across all household classes expect those with more cattle (C3) and positive for all P balances. Generally, it was noted in this study that nutrient fluxes in the home gardens was dependent on the farmers' resources, access and use of organic inputs.

Few farms had positive nutrient balances as a result of large application of farmyard manure. Therefore, more nutrient sources should be explored that will enable positive nutrient balance in farms and increase in yield. Furthermore, employing integrated nutrient management and exploring other sources of nutrient inputs at a farm level. Also the need to make adequate use of crop residues and household waste so as to increase nutrient inputs for a balanced nutrient flow.

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CHAPTER FIVE

5.0 GENERAL CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

i. Descriptive statistics of soil properties, showed that P>Cu>K>Zn>Mn>S varied more markedly with high coefficient of variation (>50%) in the selected areas in Rombo. The variation in mean nutrients concentrations was well displayed in the nutrient spatial distribution maps showing how nutrients were spatially distributed and their variation among the points sampled.

ii. Results obtained showed yield-limiting nutrient in the low-yield areas due to nutrient deficiencies were K > Mn > P = Zn > Cu in 40.3, 35.5, 33.9 and 32.3% of the areas, respectively. These nutrients were limiting in the low yielding areas of households that are resource-limited with poor nutrient management (low nutrient supply) that led to decline in yield.

iii. The resource-rich household (L3) and household with more (>2) cattle (C3) applied significantly ($P \leq 0.05$) more farmyard manure in their home gardens. Likewise, nutrient balances were negative for N and K in home gardens across all household classes expect those with more cattle (C3) and positive for all P balances. Generally, it was noted in this study that nutrient fluxes in the home gardens was dependent on the farmers' resources, access and use of organic inputs.

6.2 Recommendations

i. For proper nutrient management need to consider the variations and specific nutrient status in order to improve banana productivity. From the observation, localized nutrient management practices can be optimally carried out to replenish nutrient that are deficient and site specific recommendations given in future studies.

ii. Resource-rich household (L3) owned more land area under banana than the resource-medium and resource-poor households by 8% (no significant difference) and had significantly ($P \leq 0.05$) higher banana bunch weight. Additionally an integrated nutrient management especially for less resource households could be recommended in order to improve banana production.

iii. Few farms had positive nutrient balances as a result of large application of farmyard manure. Therefore, more nutrient sources should be explored that will enable positive nutrient balance in farms and increase in yield. Furthermore, employing integrated nutrient management and exploring other sources of nutrient inputs at a farm level. Also the need to make adequate use of crop residues and household waste so as to increase nutrient inputs for a balanced nutrient flow.

APPENDICES

Appendix 1: Soil nutrient concentration and physicochemical properties

Ward	HHid	pH	OC	P	N	Ca	Mg	K	Na	S	Cu	Zn	Mn	Fe	Txtr	CL	SI	SA
			%	mg/kg	%	-------- Cmol+/kg ----------				------------------- mg/kg --------------						%	%	%
aleni	1a	6.33	2.69	44.50	0.28	33.08	8.88	0.16	0.24	30.15	0.64	0.42	2.81	246.88	C	45	29	26
aleni	3a	6.43	2.49	63.00	0.25	38.72	8.35	0.07	0.22	9.59	1.11	0.38	3.15	293.75	C	50	31	19
aleni	17a	6.40	2.47	48.00	0.21	32.05	7.16	0.20	0.18	20.56	0.60	0.27	5.28	253.13	C	58	27	15
aleni	18a	6.88	4.19	11.00	0.44	28.97	7.00	0.09	0.22	24.68	1.83	0.53	1.03	359.38	CL	33	30	37
aleni	29a	6.34	3.91	71.50	0.49	37.69	8.14	0.27	0.21	23.30	1.62	0.51	2.50	340.63	SCL	39	54	7
aleni	30a	6.22	4.09	3.60	0.47	14.62	5.32	0.08	0.16	17.81	0.39	0.10	0.94	156.25	CL	29	28	43
aleni	32a	5.99	2.54	4.30	0.26	21.03	6.52	0.26	0.07	21.93	0.58	0.20	1.64	206.25	CL	36	26	38
aleni	44a	6.60	3.71	88.00	0.33	34.87	9.07	0.28	0.19	43.86	1.99	0.36	4.21	196.88	SiC	46	42	12
aleni	56a	6.24	3.02	39.50	0.31	19.10	6.74	0.11	0.18	13.70	0.25	0.13	3.05	309.38	C	46	37	17
aleni	59a	6.61	3.33	1.50	0.29	25.13	7.43	0.13	0.20	24.68	3.21	0.15	4.04	156.25	SiC	50	41	9
aleni	62a	6.98	4.32	34.30	0.34	45.64	10.00	0.15	0.17	42.49	0.23	0.11	5.97	231.25	SiC	45	42	13
aleni	63a	6.76	3.00	12.00	0.27	33.59	7.54	0.23	0.17	27.41	0.69	0.13	4.56	221.88	C	49	39	12
aleni	81a	6.78	3.79	9.60	0.43	34.87	8.51	0.44	0.33	24.68	0.99	0.38	3.33	212.50	C	47	30	23
aleni	85a	5.20	5.56	56.50	0.50	13.97	4.95	0.11	0.23	60.30	2.36	0.34	1.34	331.25	CL	35	36	29
aleni	89a	5.94	4.01	40.50	0.44	20.13	6.04	0.11	0.32	28.79	3.17	0.25	1.33	112.50	CL	39	32	29
mamsera	0a	6.43	4.01	114.50	0.34	51.15	9.45	0.53	0.25	28.79	0.28	0.57	3.20	243.80	C	48	32	20
mamsera	2a	4.97	4.98	2.30	0.40	51.41	9.92	0.58	0.17	46.60	0.78	0.18	1.58	209.38	CL	35	37	28
mamsera	9a	6.12	2.29	11.30	0.23	22.18	6.55	0.13	0.21	41.11	0.60	0.06	3.54	212.50	C	41	21	38
mamsera	13a	6.64	3.22	65.50	0.29	34.74	7.45	0.53	0.22	23.30	2.03	0.46	4.59	231.25	C	51	29	20
mamsera	21a	7.00	2.01	5.70	0.17	38.46	3.08	0.24	0.18	10.96	0.33	0.19	3.08	268.75	CL	39	26	35

mamsera	22a	6.73	3.00	47.50	0.29	31.54	8.29	0.37	0.12	32.89	1.21	0.44	3.59	206.25	C	52	28	20
mamsera	23a	6.59	3.51	39.00	0.35	34.87	9.69	0.30	0.19	32.89	4.25	0.44	2.31	190.63	C	43	34	23
mamsera	38a	6.58	5.05	33.50	0.37	46.28	8.71	0.16	0.31	49.34	3.25	0.50	0.98	246.88	CL	22	30	48
mamsera	43a	6.20	1.94	3.10	0.19	16.28	10.92	0.09	0.18	12.34	0.32	0.19	3.35	309.38	C	48	27	25
mamsera	47a	6.41	4.23	28.00	0.43	37.31	7.56	0.19	0.18	45.23	2.26	0.46	1.73	178.13	CL	32	28	40
mamsera	60a	6.81	3.76	13.20	0.42	41.41	9.21	0.61	0.20	32.89	2.20	0.16	4.36	228.13	C	44	35	21
mamsera	61a	7.01	3.80	21.50	0.42	32.18	8.20	0.52	0.19	47.98	1.16	0.21	4.81	231.25	SiC	46	41	13
mamsera	74a	6.35	3.57	8.50	0.32	19.74	7.95	0.19	0.20	5.49	0.31	0.31	4.51	206.25	C	53	32	15
mamsera	83a	6.80	2.95	4.20	0.26	32.44	11.43	0.77	0.33	15.08	0.77	0.32	4.12	256.25	CL	33	30	37
mamsera	84a	6.56	4.10	34.70	0.39	39.49	8.10	0.34	0.30	26.04	3.09	0.58	2.87	237.50	CL	37	30	33
mamsera	86a	7.19	3.53	24.10	0.36	40.64	9.03	0.85	0.28	41.11	0.91	0.47	3.97	293.75	C	47	32	21
manda	6a	6.48	2.00	2.50	0.19	22.31	7.64	0.08	0.23	13.70	0.16	0.03	3.30	190.63	C	65	27	8
manda	10a	6.69	2.64	35.50	0.25	44.23	10.38	0.81	0.23	32.89	0.97	0.16	2.01	275.00	L	38	20	42
manda	11a	5.94	3.91	4.20	0.39	25.38	6.80	0.09	0.21	49.34	0.32	0.16	0.47	146.88	L	25	29	46
manda	12a	6.02	3.71	1.80	0.42	29.10	8.80	0.12	0.23	30.15	0.55	0.32	1.34	275.00	CL	39	31	30
manda	14a	6.52	2.29	32.50	0.28	32.44	8.99	0.18	0.18	21.93	0.66	0.28	3.89	203.13	C	59	31	10
manda	26a	6.60	2.77	131.50	0.35	38.21	8.99	0.22	0.20	38.38	1.17	0.52	2.17	225.00	CL	37	30	33
manda	31a	6.57	2.59	15.50	0.24	24.87	6.70	0.13	0.17	2.74	0.81	0.28	3.57	187.50	C	55	32	13
manda	33a	6.48	2.76	29.50	0.25	32.31	7.57	0.17	0.15	4.11	0.97	0.35	2.35	243.75	CL	32	36	32
manda	34a	6.27	3.80	39.00	0.35	31.54	6.55	0.10	0.15	24.68	2.15	0.51	2.79	203.13	CL	38	34	28
manda	39a	6.66	2.72	62.00	0.24	31.28	5.79	0.37	0.32	6.85	1.94	0.48	2.43	200.00	CL	42	36	22
manda	45a	6.81	2.93	15.60	0.26	26.92	7.34	0.19	0.18	20.56	0.57	0.28	4.52	178.13	C	52	34	14
manda	54a	6.79	3.84	14.20	0.35	48.46	8.99	0.76	0.22	39.75	1.21	0.58	3.09	240.63	CL	32	30	38
manda	55a	6.70	3.41	4.30	0.30	30.13	7.52	0.24	0.19	41.11	0.62	0.19	3.06	262.50	CL	34	38	28
manda	70a	6.84	3.11	9.90	0.31	36.15	8.96	0.30	0.21	41.11	1.96	0.43	4.45	215.63	SiL	49	28	23
manda	72a	6.31	2.12	26.50	0.34	21.79	7.20	0.09	0.19	13.70	0.22	0.12	2.96	181.25	C	53	34	13
manda	73a	6.40	3.09	8.50	0.30	30.38	10.76	0.20	0.20	28.79	0.37	0.16	2.59	246.88	C	43	32	25

manda	75a	6.18	3.53	10.00	0.22	13.59	5.30	0.09	0.25	16.45	0.18	0.10	0.66	131.25	CL	35	26	39
manda	77a	6.22	3.10	1.50	0.24	31.25	9.18	0.91	0.13	15.08	0.28	0.43	0.91	137.74	C	56	23	22
mengeni	7a	6.48	2.13	14.00	0.23	32.31	8.26	0.19	0.20	9.59	0.55	0.26	3.42	228.13	C	55	31	14
mengeni	8a	6.92	2.41	46.00	0.28	63.72	11.44	1.25	0.21	53.45	0.46	0.16	1.75	240.63	C	66	21	13
mengeni	15a	6.52	2.69	19.50	0.30	30.00	9.49	0.20	0.19	16.45	0.63	0.30	3.85	228.13	C	57	26	16
mengeni	16a	6.57	2.69	134.00	0.30	45.26	7.49	0.30	0.17	31.53	0.61	0.38	2.93	425.00	C	44	30	26
mengeni	20a	6.97	2.29	12.50	0.25	28.85	7.01	0.10	0.18	42.49	0.31	0.13	3.76	225.00	C	57	26	17
mengeni	24a	6.00	3.92	2.30	0.37	25.13	9.38	0.16	0.21	24.68	0.40	0.22	1.98	318.75	CL	38	32	30
mengeni	25a	6.68	2.77	9.50	0.27	32.44	11.67	0.37	0.21	31.53	0.98	0.29	2.44	362.50	SC	35	18	47
mengeni	27a	6.37	2.00	11.50	0.19	13.85	7.58	0.08	0.17	41.11	0.19	0.11	4.90	225.00	C	65	6	29
mengeni	28a	6.48	2.51	28.00	0.22	30.51	7.62	0.36	0.18	10.96	1.13	0.45	3.51	371.88	C	48	25	27
mengeni	35a	6.43	3.54	35.00	0.34	31.28	7.67	0.35	0.20	39.75	0.81	0.32	2.76	234.38	CL	36	32	32
mengeni	37a	6.75	3.28	34.00	0.27	32.82	7.92	0.37	0.04	26.04	1.06	0.49	3.77	250.00	CL	40	30	30
mengeni	40a	6.63	2.67	83.00	0.26	33.97	6.83	0.53	0.18	17.81	0.88	0.41	4.18	256.25	CL	36	36	28
mengeni	41a	4.91	5.35	2.20	0.49	7.05	2.55	0.10	0.17	21.93	0.14	0.03	0.84	146.88	CL	18	30	52
mengeni	42a	6.39	3.45	77.00	0.29	46.28	7.79	0.65	0.20	31.53	2.52	0.52	2.64	265.63	CL	32	32	36
mengeni	46a	6.01	3.31	35.00	0.30	24.36	6.83	0.18	0.18	38.38	0.58	0.54	6.09	275.00	C	45	31	24
mengeni	48a	5.56	3.36	2.80	0.29	13.97	3.99	0.08	0.18	10.96	0.45	0.10	1.87	171.88	CL	36	30	34
mengeni	49a	5.95	4.40	6.20	0.42	25.13	5.45	0.12	0.19	30.15	1.00	0.14	0.69	140.63	L	26	30	44
mengeni	52a	6.40	3.54	4.50	0.33	25.00	8.29	0.09	0.20	12.34	0.59	0.17	1.60	237.50	CL	28	34	38
mengeni	57a	5.17	3.63	2.00	0.39	16.28	9.18	0.13	0.18	47.98	0.40	0.31	1.72	181.25	CL	38	31	31
mengeni	58a	6.55	3.50	18.80	0.35	43.72	8.67	0.38	0.17	20.56	2.96	0.14	2.14	250.00	CL	38	27	35
mengeni	65a	6.68	2.25	50.50	0.23	24.36	8.82	0.20	0.18	8.23	0.35	0.09	3.94	215.63	C	51	34	15
mengeni	67a	6.51	2.69	11.70	0.26	36.15	8.37	0.37	0.18	20.56	0.98	0.10	3.00	284.38	CL	39	27	34
mengeni	71a	5.35	3.79	33.50	0.35	12.69	3.13	0.16	0.19	57.56	0.35	0.53	1.01	156.25	CL	31	28	41
mengeni	78a	6.50	2.20	18.50	0.22	26.67	9.01	0.10	0.25	16.45	0.32	0.15	1.07	268.75	CL	35	26	39
mengeni	79a	6.09	3.84	29.50	0.34	20.00	7.01	0.12	0.28	35.64	0.81	0.35	2.38	206.25	C	35	39	26

mengeni	82a	6.67	2.91	4.50	0.28	32.44	10.33	0.15	0.32	8.23	1.53	0.41	3.17	246.88	C	55	32	13
mengwe	4a	6.51	3.37	53.50	0.34	45.26	9.75	0.30	0.26	35.64	1.59	0.46	5.20	415.63	C	53	27	20
mengwe	5a	7.30	3.21	138.50	0.36	48.72	9.76	0.61	0.24	27.41	1.69	0.42	5.41	290.63	C	55	23	22
mengwe	19a	6.42	3.23	80.00	0.34	57.82	9.34	0.28	0.22	12.34	0.48	0.49	2.75	228.13	CL	35	30	35
mengwe	36a	6.53	2.98	41.00	0.28	32.18	6.96	0.35	0.20	46.60	0.73	0.51	4.21	159.38	CL	38	36	26
mengwe	50a	6.93	2.89	24.00	0.30	34.74	10.45	0.54	0.23	37.00	1.18	0.30	3.82	225.00	C	44	20	36
mengwe	51a	7.12	3.75	152.50	0.35	41.67	7.51	0.92	0.21	20.56	0.40	0.58	3.79	246.88	CL	38	38	24
mengwe	53a	6.65	3.41	26.80	0.34	35.13	7.29	0.26	0.17	21.93	0.41	0.56	4.15	259.38	SiC	40	40	20
mengwe	64a	7.00	2.55	4.80	0.27	21.54	8.91	0.11	0.16	20.56	0.33	0.02	2.85	181.25	C	47	36	17
mengwe	68a	7.14	5.01	26.30	0.43	51.79	10.08	0.83	0.20	30.15	4.36	0.18	3.27	190.36	CL	35	34	31
mengwe	76a	6.26	1.94	11.50	0.21	15.77	6.23	0.05	0.22	5.49	0.14	0.12	4.59	287.50	C	55	36	9
mengwe	80a	6.94	3.84	31.30	0.36	43.21	9.04	0.50	0.32	24.68	1.52	0.55	4.01	309.38	CL	37	30	33
mengwe	87a	7.07	3.00	25.10	0.32	37.05	7.83	0.63	0.32	31.53	1.08	0.52	5.16	259.38	C	47	32	21
mengwe	88a	7.06	2.65	43.50	0.26	30.26	10.37	0.40	0.24	65.79	1.53	0.18	3.77	196.88	C	51	28	21
shimbi	66a	6.24	3.75	2.40	0.37	46.93	9.52	0.83	0.11	31.53	0.39	0.96	0.80	179.25	C	45	31	24
shimbi	69a	6.37	3.80	6.00	0.44	16.67	6.40	0.32	0.18	23.30	0.51	0.29	1.37	178.13	CL	33	28	39
shimbi	90a	5.31	8.88	25.50	0.86	15.64	3.92	0.06	0.26	19.19	0.77	0.10	0.54	87.50	SL	13	28	59
shimbi	94a	6.18	5.03	3.90	0.52	28.59	8.21	0.13	0.26	41.11	1.01	0.09	0.56	121.88	SL	17	30	53
shimbi	95a	6.50	3.17	14.90	0.32	39.10	8.67	0.23	0.24	12.34	3.51	0.17	0.32	359.38	C	45	37	18
shimbi	98a	6.51	3.17	4.60	0.33	30.90	8.38	0.27	0.26	13.70	1.90	0.47	1.69	190.63	CL	37	29	34
shimbi	99a	6.45	4.94	11.20	0.51	36.92	8.30	0.15	0.23	27.41	1.12	0.38	0.71	162.50	L	25	32	43
shimbi	100a	6.55	4.79	6.50	0.44	34.87	8.50	0.33	0.31	35.64	1.90	0.29	0.71	143.75	L	23	32	45
shimbi	102a	7.01	2.95	2.00	0.27	44.77	9.06	0.66	0.20	21.93	0.92	0.64	0.85	81.13	C	61	35	4
shimbi	103a	6.08	7.98	5.00	0.81	70.23	9.12	0.50	0.12	45.23	0.69	0.12	1.73	75.47	SL	16	25	59
shimbi	104a	6.02	6.52	1.90	0.61	46.82	8.83	0.66	0.10	42.49	0.61	0.55	0.28	75.66	L	22	29	49
shimbi	105a	6.57	3.17	3.20	0.33	27.31	6.98	0.42	0.19	37.00	0.87	0.14	4.13	318.75	C	51	33	16