THE VARIABILITY OF SOIL CARBON AND OTHER SELECTED SOIL PROPERTIES AS INDICATORS OF SUSTAINABLE LAND MANAGEMENT UNDER TOMATO PRODUCTION AT MOOKETSI ZZ2 FARM IN LIMPOPO, SOUTH AFRICA

By

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Declaration

I declare that the mini-dissertation hereby submitted to the University of Limpopo, for the degree of Master of Science in Agriculture (Soil Science) has not previously been submitted by me for a degree at this or any other university; that it is my work in design and in execution, and that all material contained herein has been duly acknowledged.

Ledwaba KD (Miss) 04/04/2023

Dedication

I dedicate this dissertation to my lovely family, my parents Mrs. Sophia Mokgaetji and the late Mr. Thaloki James Ledwaba, and my siblings Happy, Florance, Harry, Jackson, Moshekoa, and the late Francis Ledwaba.

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Abstract

The soil is the most important component in sustainable land management that varies spatially due to the combined effect of biological, physical, and chemical processes that occur over time. Although there has been extensive research on some of the soil characteristics and their effects on different crop yields, the interactive effect of various management practices and soil properties on carbon as well as the main factor or factors controlling soil C under short-term continuous tomato production are not yet fully understood. The objectives of the study were (i) to determine the spatial variation of soil carbon (C) and other selected soil properties within the tomato production field and (ii) to investigate the inter-relationship between soil C and the selected soil properties within the tomato production field at Mooketsi ZZ2 Farm. To achieve these objectives, a detailed soil survey was conducted, whereby a systematic soil sampling strategy was carried out where one sample was collected every 40 m using an auger at depth of 0-15 cm on a 23-hectare farm. The total number of samples collected were 132. A handheld Global Positioning System (GPS) was used to record the geographical coordinates, the latitude, and the longitude of where each sample was taken, this was used to create spatial variability maps. A handheld cone penetrometer was used to determine the penetrative resistance of the soil before soil samples were collected. The collected soil samples were analysed for physical and chemical soil properties such as particle size distribution, aggregate stability, soil organic carbon (SOC), soil pH, electrical conductivity (EC), and soil extractable phosphorus. The soil colour was also determined for the collected soil samples. The coefficient of variation (CV) showed that high variation exists in SOC with a CV of 38.72%, clay content with CV of 43.48%, silt content with CV of 50.70% and EC with CV of 59.60%. Semivariograms which are important for spatial analysis showed variation of soil properties within Mooketsi ZZ2 farm. Spatial dependency, which is the nugget/sill ratio, showed that extractable P had a weak spatial dependence with 1.00 nugget/sill ratio. Soil pH (KCl), EC, MWD, clay, silt and sand had moderate spatial dependence with the following nugget/sill ratios: 0.60; 0.44; 0.38; 0.48; 0.41 and 0.41 respectively. The SOC and PR both had 0 nugget/sill ratio which is a strong spatial dependence. The correlation results showed that SOC had weak correlation with the silt, sand and clay content having correlation coefficients of 0.30, -0.27 and 0.2, respectively. This means that texture does not influence the spatial variation of SOC across the tomato field.

Mean weight diameter (MWD) was positively correlated with sand (r= 0.50) and negatively correlated with silt content (r = -0.46) and clay content (r= -0.51) showing that there was weak aggregation in the Glenrosa soil. The electrical conductivity had relatively weaker positive correlation with both clay content (r= 0.33) and silt content (r= 0.29) and it was negatively correlated with sand content (r= -0.32). The positive relationship between clay content and silt content with EC might be because; finer particles have more negatively charged sites that can hold onto the cations. The negative relationship between EC and sand content might be because; sandy soils tend to have low organic matter levels, which is important in binding soil particles. The low correlations between soil properties might be because, the Glenrosa soil has low clay content which means less surface area to hold cations and soil particles is available. This leads to poor soil structure and poor nutrient holding capacity of the soil. Overall, the results revealed that there was wide spatial variation within the soil properties of the study area. The RMSE values showed that kriging is reliable to characterize pH, MWD, SOC, P, PR, clay, silt, and sand with moderate to good accuracy, but it is less reliable when it comes to EC. From the inter-relationship results, it can be concluded that there is no soil property that has strong influence on SOC for the case considered. This indicates that none of these properties could serve as a proxy for predicting soil C or as parameters that can assist in soil C management options. The observed spatial variation could have an implication in the optimization of tomato yield in the study area. This bids for the adoption of site-specific soil nutrient management in the area in order to optimize tomato production because over and under fertilisation would be costly for the farm.

Keywords: spatial variation, spatial dependence, soil organic carbon, soil properties.

CHAPTER 1

GENERAL INTRODUCTION

1.1 Background

In many developing countries like South Africa, agricultural production contributes more to the economy. As a result, much attention has been given to the issue of sustainability, particularly with soils, land, and agriculture mainly because an increasing population is competing for limited natural resources, which may result in land degradation. Soil is a natural resource that consists of chemical, physical, biological, and mineralogical properties that vary with land management (Buol *et al.*, 2011). Various definitions exist for sustainable land management but, here it refers to the combination of production and conservation of the natural resources on which the production depends (Smyth *et al*., 1993).

The soil is the most important component in sustainable land management that varies across different spatial areas due to the combined effect of biological, physical, and chemical processes that occur over time (Santra *et al.*, 2008). These properties vary spatially and temporally from subfield to subfield and from one field to the next. Spatial variability of soil properties determines the change of a soil property's magnitude in each space. The change can be observed at different spatial locations on the land surface (Chesworth, 2007; Mulla and McBratney, 2002). Variability is affected by soil-forming factors, which can be called intrinsic such as parent material, topography, organisms, and extrinsic factors such as crop rotation and land-use change (Denton *et al*., 2017).

South Africa is one of the leading producers of tomato in the Southern region of Africa. Limpopo Province is one of the largest producers of tomato in South Africa, it produces about 66% of the tomatoes in the country (NDA, 2009). The soils on the farms producing tomatoes must be assessed to get a better understanding of the spatial variation of the soil properties and how the variation affects crop yields. This is done to ensure that farmers get optimal yields, and the soil quality does not decline (Dorais, 2007). In recent times, there has been growing interest in better soil management on lands producing agricultural products such as tomatoes. The management of soil resources should be done to prevent land degradation. As degraded soils are less productive due to nutrient losses, consequently, crop yields decrease, and producers cannot recover costs of production (Shah and Wu, 2019).

1.2 Problem statement

Tomato farming is the major land use in the Mooketsi region of Limpopo Province, South Africa. However, concern has arisen in recent years about soil carbon (C) depletion that is possibly occurring under the annually tilled soils for tomato production. Circumstantial evidence for this includes poor plant growth and damaged soil structure that cannot hold efficient nutrients for the plant (Brearley and Thomas, 2015). As a result, tomato fields are now temporarily used to grow temperate grasses for animal feed production after each harvesting season. This management strategy was adopted mainly because the short-term introduction of perennial crops like grassland has been reported to increase C levels in the soil (Guo and Gifford, 2002) due to the very large inputs of organic matter, particularly as root turnover, but also as above-ground litter and animal dung, which occur under grazed pasture (Milne and Haynes, 2004). However, the magnitude and direction of these management-induced changes are soil and site-specific (Guo and Gifford, 2002). Variability in the soil can occur due to land-use change, cultivation, erosion, salination, and mismanagement of the soil. Spatial variability of the soil properties is also affected by land degradation processes including water and wind erosion, as the soil will be unprotected from the heavy rains and strong winds (Behera *et al*., 2018). The variability of soil properties is inherent but, introducing change through land-use conversion from cropland to perennial grasses can cause more variation in the soil properties such as pH, colour, organic C, bulk density, porosity, phosphorus, and nitrogen content of the soil due to excretion and animal movements. This might happen because of introducing livestock to pastoral land with prior land use being crop production (Soupir *et al*., 2006).

1.3 Rationale

The soil quality of agricultural land has been typically equated with soil organic matter (SOM) or its associated derivative, organic carbon (OC). Recent literature evidence increasingly suggests that land use management may be important in controlling OC content, stabilisation, and storage (Wiesmeier *et al*., 2019; Dlamini *et al*., 2019). For example, a study conducted by Blanco-Canqui and Lal (2004) showed that the inclusion of perennial grasses in crop rotations increases soil aggregation and OC content. Studies have shown that crop rotation of tomato (*Solanum lycoversicum* L.) and legumes such as alfalfa, beans, peas, and peanuts, will restore soil nutrients such as OC that have been depleted by crops such as tomatoes. A two-year tomato rotation with any of the legumes, helps with tomato-related diseases to die-off before planting tomatoes in the same field and the soil C to be replenished (Kumar *et al*., 2018). A study by Tautges *et al*. (2019) has shown that maize-tomato rotations help to increase OC in the soil by 12.6%. The rotation is beneficial to tomatoes as maize has large root mass that returns significant organic matter to the soil, thus increasing soil OC. In south-central Texas, Wright and Hons (2005) found that soils under grain sorghum and legume rotations sequester more OC than those under continuous monoculture. Havlin *et al.* (2016) also affirmed these results under subsistence agriculture. Although there has been extensive research on some of the soil characteristics and their effects on different crop yields, the interactive effect of various management practices and soil properties on SOC as well as the main factor or factors controlling the soil C under short-term (< 2 years) continuous tomato production are not yet fully understood (Johnston *et al*., 2017). Generally, perennial grasses or legumes improve soil organic carbon (SOC) levels whereas annual row cropping often leads to soil structural degradation, mainly due to loss of ground cover and organic matter when the soil is disturbed by cultivation (Conant *et al.,* 2001; Bronick and Lal, 2005; Johnston *et al*., 2017).

1.4 Purpose of the study

1.4.1 Aim

This study aims to investigate the spatial variability of soil C and other selected soil properties as indicators of sustainable land management in the tomato field at Mooketsi ZZ2 Farm.

1.4.2 Objectives

i. To determine the spatial variation of soil C and other selected soil properties within the tomato production field at Mooketsi ZZ2 Farm.
ii. To investigate the inter-relationship between soil C and the selected soil properties within the tomato production field at Mooketsi ZZ2 Farm.

1.4.3 Hypotheses

i. There is no spatial variation of soil C and other selected soil properties in the tomato field at Mooketsi ZZ2 Farm.

ii. There is no any inter-relationship between soil C and the selected soil properties within the tomato production field at Mooketsi ZZ2 Farm.

1.4.4 Dissertation structure

Note on the modification of the study from the original design

The study was initially going to investigate the spatial variability of soil carbon (C) and other selected soil properties after a short-term integration of livestock into the tomato field. The farm practices fallowing and livestock integration in the tomato field as a way of improving sustainability. Due to Covid-19 the implementation of the plan was hampered and constrained by study time limit. For this reason, the objectives of the study had changed to focus on the inherent variability of soil properties within the field. I want to acknowledge that it had created a bit of a deviation in the alignment of the title and objectives,

This dissertation is organized into four chapters, with chapter 1 providing a background of sustainable land management, soil variability, and the approaches used to ensure land sustainability. The chapter also includes the objectives of the study, the aim, and the hypotheses. Chapter 2 provides a detailed literature review on the causes and effects of soil variability on the physical and chemical properties of the soil. Chapter 3 addresses the two hypotheses of the study with the first hypothesis describing spatial variation of the soil carbon and other selected soil properties and the second hypothesis describing the inter-relationship between soil C and the selected soil properties within the tomato production field. The chapter also includes a discussion of the research findings. Chapter 4 provides a summary and conclusion of the findings of the study.

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CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Most arable land in South Africa has been cultivated for many years, as a result, the soil fertility is severely depleted. This problem of depleted soil fertility has led to decreasing crop yields (Lal, 2015). The decrease in crop yields can be counteracted by improving the overall fertility of the land by avoiding practices such as monoculture and land mismanagement. These practices are aggravated by factors of variability in the soil which causes erosion and land degradation in the inherently variable soil (Lal, 2015). Soil variation refers to the extent to which the soil varies, and spatial variability of soil properties determines the change in soil property's magnitude with change in space (Chesworth, 2007).

2.2 Variability of soil properties and their causes.

Soil properties vary spatially even within similar layers because of deposition and post-deposition processes that cause variation in properties (Lacasse and Nadim, 1996). Knowledge of the variation of soil properties within agricultural production is essential in determining production limitations related to soil nutrients. Spatial variability assessment using the grid sampling method is a viable option to identify critical nutrient deficiency zones. This enables farmers to strategize site-specific nutrient management based on soil and crop requirements. The spatial variability of soil properties can be recorded also by using the interpolation method (Cambardella and Karlen, 1999).

Inherently, the soil biochemical properties have high spatial variability and in converted lands, these might exceed the land-use change effects on soil nutrient levels (Parkin, 1993). The spatial variation requires that it be quantified both between and within fields so that changes in the spatial distribution of the soil properties can be attributed to changes in management (Glendell *et al*., 2014). The characterization and mapping of soil properties are very important as they provide helpful information on spatial variability of the agricultural fields, grasslands, and forests. A soil characterization study is therefore a major building block for understanding and classifying soil and getting the best understanding of the environment (Esu, 2005).

The understanding of variation creates an opportunity for a precision agriculture approach. As it is a farming management concept based upon observing, measuring, and responding to inter and intra-field variability in crops, or to aspects of animal rearing (Das *et al*., 2018). This approach can be used to manage the inputs so that the farm resources are not wasted by applying inputs where they are not needed. Therefore, over or under-application of inputs on variable fields can be avoided and reduced as the use of technology helps farmers to spot sites that need more nutrients than others. With the application of precision agriculture, environmental degradation will be reduced (Das *et al*., 2018).

2.3 Sources of soil variation

Although, many factors cause variation within the soil, some of which are of microscopic scale such as biological activities, soil salinity, soil electrical conductivity (EC), uneven fertilizer, and manure application, the main drivers for soil heterogeneity are initial variations in parent material properties, topography, and biota (Augusto *et al*., 2017). Landscape, weathering of parent material, and erosion because of tillage act over a larger distance (Minasny *et al*., 2015). Variation in the weathering parent material leads to differences in soil texture or clay concentration and may explain variation in the soil organic carbon (SOC) accumulation rate and C sequestration (McLauchlan, 2006). The difference in parent material is often the reason for crop productivity differences experienced on fields (Phillips, 2017).

2.3.1 Topography

Within fields, topography influences crop yields and the availability of plant nutrients. The noticeable effect is the thickness of the A-horizon (Adhikari *et al*., 2018). Excessive rainfall at ridge tops, hilltops, and upper slopes does not have time to infiltrate into the soil except in the sandy-textured soils. These soils loose some of the precipitation due to surface runoff, resulting in less organic matter (OM) accumulation and crop growth. The upper landscape positions are also subject to stronger oxidizing conditions compared to those in lower positions. In addition to influencing the OM levels in the A-horizon, internal water flow in landscapes affects the accumulation, cycling, and availability of nutrients (Jendoubi *et al*., 2019).

2.3.1.1 Landscape

According to Amundson *et al*. (2015) variations in hydraulic properties, as caused by spatially variable development of soil structure, texture, and soil organic carbon will influence patterns of surface runoff and subsurface flow and hence the mass redistribution across the landscape. Spatially varying soil development will lead to variations in edaphic factors such as water and nutrient availability or their excess, which will cause heterogeneity of the natural vegetation and its biomass production and subsequently cause heterogeneity of OM inputs to the soil (Amundson *et al*., 2015).

According to Franzen (2018), topography influences nutrient levels as water moves through a landscape continually due to gravity and inherent soil flow-through directions. Hilltops and upper slopes generally contain less moisture due to leaching depth at higher landscape positions and runoff during periods of more intense rainfall. Soils with a high leaching potential tend to be of loamy or sandy texture, on higher landscape positions. The presence or absence of lime in response to landscape and internal water movement affects soil pH and the availability of iron (Franzen, 2018; Kanianska, 2016).

Wysocki *et al*. (2000) found that in a landscape, the natural development of available phosphorus (P), potassium (K), and other nutrients are greatest where there is more moisture. Therefore, plants growing at higher landscape positions do not accumulate as much P and K as crops growing in more favourable moisture conditions such as at the foot-slope. Soil P in the higher organic matter soils is relatively low, whereas P in the sandy soils is often very high due to lower crop productivity combined with decades of high, uniform P applications. A management zone approach would involve separating the field into landscape positions, to be able to get optimal yields from the different positions (Schaetzl and Thompson, 2015).

2.3.2 Tillage

Topsoil displacement during cultivation leads to variation within the field (Meena *et al*., 2020). In recent years, tillage erosion or the downslope movement of soil by ploughing has become prevalent in intensively farmed areas (Thaler *et al*., 2021). In natural areas with a dense vegetation cover, mass decomposition processes are the main source of deposition to rivers and cause spatial variability in soil thickness and properties (Ebabu *et al*, 2020). While soil erosion is a geological process, it is greatly accelerated by human impact. With the loss of topsoil, crops often have a greater reliance on fertilizers and tillage to maintain and increase production. Problems such as crusting and susceptibility to drought and adverse weather fluctuations have increased these problems.

The productivity at top slopes is low compared to that of lower slope positions, mostly due to the lack of topsoil as the soil from top slopes is deposited at lower positions (Chaves *et al*., 2002). This results in increased soil crusting, lower water holding capacity in top slopes, and high amounts of water and nutrients will be deposited at the lower positions because of downward movement (Chaves *et al*., 2002). The implementation of reduced tillage systems and cover crops can be used to improve overall soil health and reduce soil nutrient losses (Dozier *et al*., 2017).

2.3.3 Erosion

Variations in erodibility caused by differences in soil texture and SOC content during soil formation influences the spatial variation and extent of erosion processes (van Noordwijk *et al*., 1997; Van Oost *et al*., 2007). One of the most important processes shaping the surface of the earth and the soils beneath is the lateral transport of soil by erosion. The rates and spatial patterns of erosion and deposition strongly depend on the type of erosion process. On agricultural land, water and wind erosion has been dominant since historic times, thus leading to variation within the field (Troeh *et al*., 2004; Montgomery, 2007, Brevik and Hartemink, 2010). Water erosion is a major factor impacting long-term land sustainability. Nutrients from the higher landscape positions accumulate in the lower landscape positions, which often results in higher soil nutrient availability in depositional areas than in eroded zones (Bashagaluke *et al*., 2018).

2.3.4 Fertilizer and manure application

Franzen (2018) found that the application of fertilizers and manures can result in systematic variability. Systematic variability is non-natural soil variability caused by human activities. Application of fertilizers higher in dust such as powdered fertilizer forms can be blown away by wind and spread unevenly across the field. The different sizes of fertilizer granules can also result in uneven application patterns leading to systematic variability. Soil properties particularly affected long-term by systematic variability are P, K, and soil pH. Systematic variability is a long-term problem in fields fertilized with high fertilizer rates during nutrient build-up applications (Kitchen and Clay, 2018).

2.3.5 Soil electrical conductivity (EC)

EC has been used as an agricultural means of measuring soil salinity. It has been used to establish spatial variability of several soil physicochemical properties that influence the measurement of EC (Corwin and Lesch, 2005). Soil clay content, moisture content, nutrient levels, and soluble salts contribute to different EC readings (Sudduth *et al*., 2005). Assessing soil salinity is complex due to its spatially variable nature. Moreover, soil salinity is dynamic due to the influences of varying soil, crop, and irrigation management practices, water table depth, soil permeability, evaporation and transpiration rates, rainfall amount and distribution, and salinity of groundwater (Rhoades, 1993).

2.4 Role of soil management on sustainable agriculture

Soil management systems play a central role in sustainable agriculture and the quality of the environment. Soil management systems and land-use changes have a great effect on the physical and chemical properties of the soil (Hulugalle *et al*., 1997). Alterations of an area from the natural environment to cultivated land may be the reason for soil degradation and a decrease in soil quality. The most important consequence of soil cultivation is that it decreases cation exchange capacity (CEC) which is credited with the reduction of SOM (Paz-Gonzalez *et al.*, 2000). Soil cultivation systems lead to increasing soil pH, base saturation, and extractable phosphorus because of application of lime and fertilizers. This is because lime contains a carbonate component that reacts with hydrogen ions in soil solution to raise soil pH, as soil acidity is reduced, phosphorus can be unlocked and available to plants (Paz-Gonzalez *et al.*, 2000). Application of phosphate fertilizers increases the amount of phosphorus that can be accessible to the plants (Kisinyo *et al*., 2015). Soil organic carbon (SOC) and total nitrogen tend to decrease in cultivated soils compared to pasture, because cultivated soil is aerated and the C in the soil is exposed to oxygen, and it burns off into the atmosphere. Nitrogen can be lost in cultivated land because of soil erosion and surface runoff, this in turn decreases the amount of nitrogen available to plants (Cameron *et al*., 2013).

Studies by Chan and Hulugalle (1999), found that a greater percentage of mechanically dispersible clay, lower pH, and electrical conductivity were found in cultivated soils compared to pasture. This might be because cultivated soils have lower SOC as organic matter decreases when the soil is aerated during cultivation. The lower pH may be attributed to rainfall, leaching and nitrification of ammonia. Soil organic carbon tends to be higher in no-tillage soils compared with minimum tillage (Lopez-Fando and Pardo, 2011). Some researchers reported that the highest organic matter (OM) content was found in pastures compared to agricultural fields (Riezebos and Loerts, 1998; Chan and Hulugalle, 1999; Paz-Gonzalez *et al*., 2000; Jaiyeoba, 2003). The depletion of organic matter in the cultivated fields can be associated with severe tillage and the removal of plant residues. The conversion of no-tilled soils to plough-tilled increased soil pH in the soil. This might be because of application of lime to plough tilled soils (Chatterjee and Lal, 2009). The soil quality of the cultivated fields decreases over time even though fertilizer additions are made. The electrical conductivity (EC) which is the measure of the amount of salts in the soil varies with the concentration of dissolved salts (Bohn *et al*., 1985). Additionally, soil pH decreases when the salt concentration increases (Seatz and Peterson, 1965). The soils under various types of agricultural uses have less cation exchange capacity (CEC) than the soils under natural grassland (Jaiyeoba, 1995; Unger, 1997). Land use and its changes have a major impact on the pH level found in soil, soil organic matter, phosphorus and nitrogen contents, soil salinity, and base saturations.

2.5 Soil carbon and its inter-relationship with other soil properties

Soil organic carbon (SOC) is the carbon stored within the soil and it makes up approximately 60% of the soil organic matter (SOM). SOC is the basis of sustainable agriculture because the more C is stored in the soil, there will be less amount of carbon dioxide in the atmosphere. Increasing the amount of organic matter by manure and plant residues increases the amount of C stored in the soil which in turn improves the soil health (Chan *et al*., 2010). Food production affects the amount of soil C as harvesting removes C from the agricultural system. The depletion of soil C has an impact on crop yields as they will significantly decrease. Planting of perennial grasses provides a constant C input in the soil, therefore, rotations involving the perennial species will help return the C to the soil (Chan *et al*., 2010).

Soils under arable crops are annually cultivated and most of the above-ground biomass is harvested, compared to soils under permanent vegetative cover, which have no such disturbance and benefit from increased perennial inputs of C (Chapman *et al.*, 2013; Wiesmeier *et al.*, 2012). The total amount of C accumulated in the soil will depend on the length of the grassland period, nitrogen inputs, crops in the rotation, and soil cultivation methods (Johnston *et al.,* 2017). Over the long term, higher SOM contents are seen under grass/ley-arable rotations compared with continuous arable cropping (Haynes, 1999; Soussana *et al*., 2004; Katterer *et al*., 2012; Christensen *et al.*, 2009; Johnston *et al*., 2017).

The finer soils that have high clay content tend to have higher SOC because clay binds to the organic matter. This decreases the rate of decomposition as the organic matter is protected from the microbial attack by being clay bound. Coarse textured soils like sandy soils tend to have low SOC. This is because the organic matter in these soils decomposes faster and the released OC becomes quickly used-up by plants. The high amount of organic matter and clay content in the soil is beneficial because soil aggregates become more stable, and the soil structure improves. The improvement is due to the binding effects of clay and hyphae from the microorganisms which tie soil particles together (Reijneveld *et al*., 2009). The soils with higher clay content have high electrical conductivity than those that have low clay content because of more negatively charged sites on the clay that can hold onto cations in the soil. Low EC levels indicate low available nutrients, and high EC levels indicate an excess of nutrients (Sumner and Miller, 1996). As organic matter improves soil nutrient holding capacity, the supply of nutrients such as nitrogen, phosphorus and potassium improves, and crop yields increase. The lower levels of OC in the soil makes the soil highly susceptible to compaction (Wortmann and Jasa, 2003). This happens because organic matter acts like a sponge that keeps the soil from compacting, so low organic matter in soils makes it easily compacted. High soil acidity can help with accumulation of organic matter which in turn increases the SOC as microbial activities are reduced because microorganisms cannot thrive in very acidic conditions (Averill and Waring, 2018).

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CHAPTER 3

THE SPATIAL VARIABILITY OF SOIL CARBON AND OTHER SELECTED SOIL PROPERTIES

Abstract

The information about spatial distribution of soil properties is of great importance especially in site-specific and sustainable land management. As variation of soil properties occurs spatially and temporally from subfield to subfield and from one field to the next. Loss of soil nutrients due to land mismanagement is costly for farmers as crop yields decrease. The objective of the study was to determine the spatial variation of soil C and other selected soil properties within a tomato production field at Mooketsi ZZ2 farm, Limpopo Province in South Africa. Spatial variation maps of soil pH, SOC, mean weight diameter (MWD), electrical conductivity (EC), extractable phosphorus (P), clay, silt, sand, and penetrative resistance (PR) were created by ordinary Kriging. There was high variation in SOC with CV value of 38.72%, EC with CV of 59.60% followed by silt with CV of 50.70% and the least variation was observed in PR with CV of 5.27% and pH (KCl) with CV of 6.93%. Spatial dependence, which is the ratio of nugget to sill, showed that extractable P had a weak spatial dependence with 1.00 nugget/sill ratio. Soil pH (KCl), EC, MWD, clay, silt and sand had moderate spatial dependence with the following nugget/sill ratios: 0.60; 0.44; 0.38; 0.48; 0.41 and 0.41 respectively. SOC and PR both had 0 nugget/sill ratio which has a strong spatial dependence. Strong spatial dependence means that observed variation can be explained by distance, as two samples next to each other will have similar values compared to the ones far away for that soil property. Moderate spatial dependence means that to some extent distance can explain the observed variation of the soil property. Weak spatial dependence means that the observed variation of the soil property is not a function of distance. The samples next to each other might have different values within a short distance as they are not affected by distance. The SOC had a positive relationship with silt (r= 0.30) and a negative relationship with sand (r= -0.27). The finer soil particles like silt can store and hold onto cations as they are less porous than sand. These results show that wide variation exists within the field.

Keywords: spatial variation, soil organic carbon, nugget/sill ratio, soil properties.

3.1 Introduction

Soil properties vary spatially even within similar layers because of deposition and post-deposition processes that cause variation in properties (Lacasse and Nadim, 1996). The spatial variation requires that it be quantified both between and within fields so that changes in the spatial distribution of the soil properties can be attributed to changes in management (Glendell *et al*., 2014). Variations of soil organic carbon (SOC) because of land use changes have caught much attention worldwide as a critically important issue for agricultural management, ecosystem restoration and environmental conservation (Jiao *et al.*, 2020). This is because soil organic matter is an effective indicator of soil resource condition that reflects functional traits such as soil aggregate stability, water holding capacity, and microbial activity (Jiao *et al.*, 2020). Research reveals that many studies have measured the spatial variability of soil properties (Campbell, 1978; Vauclin *et al*., 1983; Ovalles and Collins, 1988; Cambardella *et al*., 1994; Shukla *et al*., 2004; Worsham *et al*., 2010). This study looks at the spatial variation of soil carbon and other selected soil properties within the tomato production field. This is because soil physical and chemical properties such as aggregate stability, particle size distribution, soil pH, and organic carbon play an important role in tomato production. Determining how these soil properties influence each other and plant growth will be valuable information for farmers and crop production.

3.2 Methodology

3.2.1 Site description

The study was conducted at Mooketsi ZZ2 farm, in Limpopo Province (23° 65’ 17’’ S, 30° 06’ 89’’ E, and 772 m above sea level) (Figure 3.1). The area is characterized by a subtropical climate, with average annual temperature and precipitation ranges of 15°C to 27°C and 800 mm - 1000 mm, respectively (Nzanza, 2012). The field is dominated by Glenrosa soil form of 1.1.10 soil family and the dominant geology is granite. The dominating soil that is found there is shallow lithic, with predominantly sandy loam and loamy sand texture.

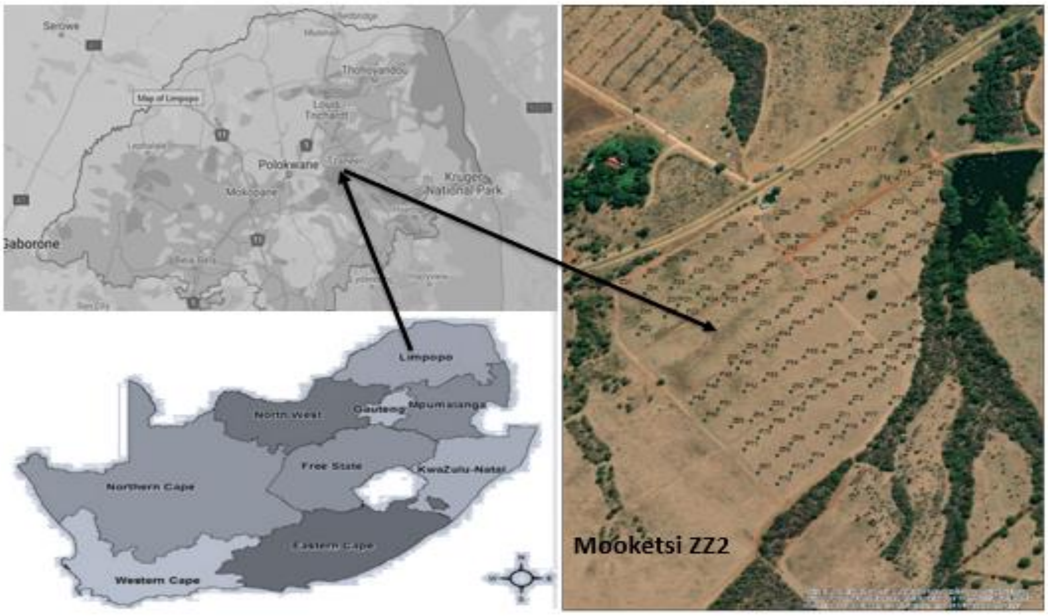

Figure 3.1: Map of study site Mooketsi ZZ2 farm

3.2.2 Experimental design and sampling in the field

As a practice of ensuring sustainability, land used for tomato production is left fallow up to 7 years where natural grass will grow. The land at the study site was cultivated for the past 5 to 10 years. After years of declined crop yields, the land has now been fallowed for about 3 years. Soil survey was conducted in the field to assess spatial variation at Mooketsi ZZ2 farm. A handheld cone penetrometer was used to determine the penetrative resistance of the soil before soil samples were collected. Systematic soil sampling was carried out, where one sample was collected every 40 m using an auger. Soil samples were collected on a 23-hectare field at depth of 0-15 cm and analysed in the laboratory to assess the spatial variation. A handheld Global Positioning System (GPS) was used to record the geographical coordinates, the latitude and longitude of where each sample was taken. The overall total of bulk soil samples collected was 132. Three pits were dug to a limiting layer and soil classification was done and master horizons were demarcated (Figure 3.2).

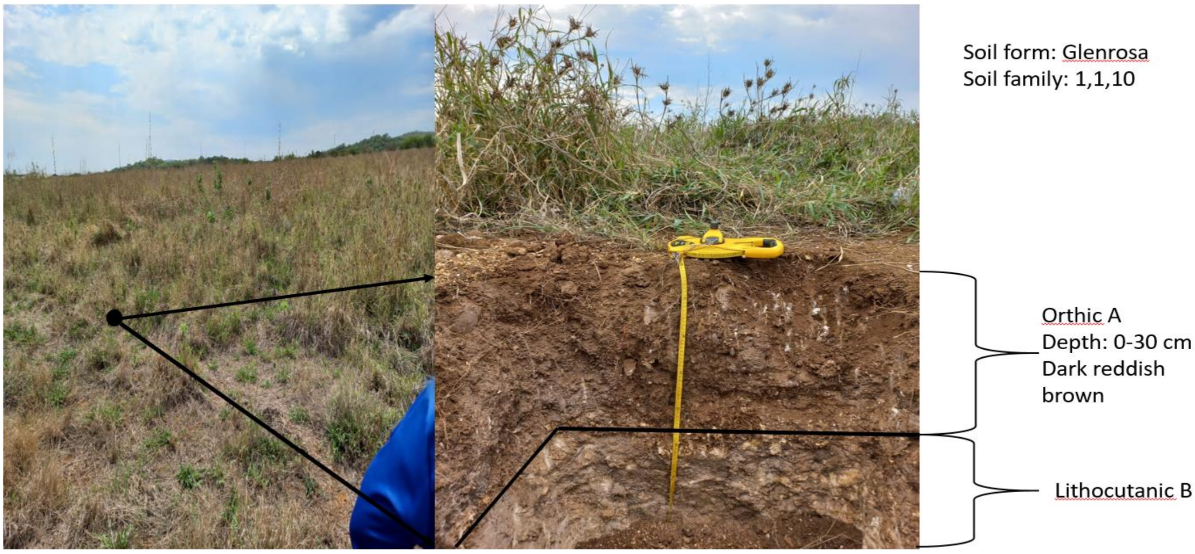

Figure 3.2: Soil profile at Mooketsi ZZ2 farm

3.3 Laboratory analysis

3.3.1 Determination of soil physical properties

Particle size distribution was determined using the hydrometer method (Gee and Bauder, 1986). Soil colour was determined using the Munsell soil colour chart (Munsell Colour Company Incorporation, 1988). Penetrative resistance was determined using a handheld cone penetrometer (Herrick and Jones, 2002). Soil aggregate stability was determined using the wet sieving procedure of Elliott (1986) where air dried soil was wet-sieved and separated into four aggregate size classes through a series of three sieves. These aggregate size classes are as follows: large macro aggregates (LM; > 2000 µm), small macro aggregates (SM; 2000-250 µm), micro aggregates (MI; 250-53 µm) and silt and clay (S+C; <53). The air-dried soil of 100 grams was evenly spread in the 2000 µm sieve, immersed in deionized water at room temperature, resulting in slaking of the soil. The soil was afterwards sieved to separate water-stable aggregates by moving the sieve in an up-and-down motion with 50 repetitions over a period of 2 min. The remaining soil in the 2000 µm sieve was transferred into a beaker for drying. Soil plus water that passed through the sieve was poured into the next smaller-sized sieve, the sieving procedure was repeated, and this was done for all the sieve-sizes. All aggregate classes separated were then oven dried for 48 hours at 40°C and weighed. Mean weight diameter (MWD) was calculated using the equation below:

$$MWD = (2*LM/m) + (1.106*SM/m) + (0.131*MI/m) + (0.025*(S + C)/m) \quad (1)$$

Where: LM is the large macro-aggregates (>2000 μm); SM is the small macro-aggregates (2000-250 μm); MI is the micro-aggregates (250-53 μm); S+C is the silt and clay (<53 μm), and m is the mass= 100 g.

3.3.2 Determination of soil chemical properties

Soil pH and EC were determined using the electrometric method (ASTM, 1995). Soil organic carbon was determined using Walkley-Black method (Nelson and Sommers, 1982). Soil available phosphorus was determined by Bray No. 1 extraction method (Bray and Kurtz, 1945).

3.4 Statistical analysis

Descriptive statistics (minimum, maximum, mean, median, standard deviation, standard error and % coefficient of variation (%CV)) were computed following Webster (2001). The CV was categorized into low (CV<15%), medium (CV= 15-35%) and high (CV>35%) classes (Wilding, 1985). The correlation table was created using Genstat 20th edition to determine the strength of relationships between the measured soil properties. Geo-statistical analysis was performed using GIS software ArcMap version 10.6. By using the Geostatistical Analyst tool, an ordinary Kriging interpolation method was used to create maps of the measured soil properties. Semivariograms which are important to spatial analysis were computed to spatial structure of measured soil properties within the field. The semivariograms and parameters such as nugget, range, partial sill, and nugget/sill ratio were all computed by simple kriging using ArcGIS. The cross validation was done to obtain prediction errors such as root mean square error that reveals the accuracy of the kriging prediction. Cross validation uses all the data to estimate the trend and autocorrelation models. It removes each data location one at a time and predicts the associated value. The predicted and actual values at a location of the omitted point are compared. The procedure is done for all data points. For all the points, cross validation compares how far away is the predicted value to the measured value. Cross validation helps to make an informed decision on which model provides the best predictions (Howard *et al*., 2008).

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(P_i - Oi)^2}{n}} \quad (2)$$

where Σ is the sum, P_i is the predicted value for the i^{th} value in the data set, O_i is the observed value i^{th} in the data set and n is the sample size.

3.5 Results

3.5.1 The morphological characteristics of Glenrosa soil profile.

Table 3.1 below shows that the Glenrosa soil form classified at the site was characterized by a topsoil of dark reddish-brown colour (2.5YR 3/4) Orthic A horizon with thickness of 0.30 m, underlain by 0.30 m thick Lithocutanic B horizon in the 3 soil profiles (Figure 3.2). The total soil depth (TSD) was 0.6 m, and the effective rooting depth (ERD) was 300 mm. The soil was shallow lithic with a slope class of 0-3% and a permeability of 1-3 seconds for the 3 soil profiles. Profile 1 had a dominating soil textural class of sandy loam with the following particle size distribution (16.16% clay, 21.28% silt and 62.56% sand). Profile 2 had a dominating soil textural class of loamy sand with the following particle size distribution (10% clay, 18% silt and 72% sand). Profile 3 had a dominating soil textural class of sandy loam with the following particle size distribution (14.16% clay, 17.28% silt and 68.56% sand).

Table 3.1: Morphological characteristics of Glenrosa soil profile.

Profile	Horizons	Depth (cm)	TSD (m)	ERD (mm)	Soil colour		Slope (%)	Permeability (s)	Clay (%)	Silt (%)	Sand (%)	Textural class
1	Orthic A	0-30	0.6	200-300	2.5YR3/4	Dark reddish brown	0-3	1-3	16.16	21.28	62.56	Sandy loam
	Lithocutanic B	30-60										
2	Orthic A	0-30	0.6	200-300	2.5YR3/4	Dark reddish brown	0-3	1-3	10	18	72	Loamy sand
	Lithocutanic B	30-60										
3	Orthic A	0-30	0.6	200-300	2.5YR3/4	Dark reddish brown	0-3	1-3	14.16	17,28	68.56	Sandy loam
	Lithocutanic B	30-60										

3.5.2 Descriptive statistics of soil properties

The summary statistics for the 132 soil samples at Mooketsi ZZ2 farm is provided in Table 3.2. The standard error shows mean accuracy. This can be divided into three classes: high, moderate, and low mean accuracy. The results showed that, there was high mean accuracy in pH (0.09), MWD (0.06), SOC (0.12), P (0.10) and PR (0.18). This means that, the mean accuracy of these soil properties was closest to the population mean they were meant to measure. Soil texture had moderate mean accuracy where, clay content had (1.05), silt content (1.83) and sand content (2.73). This means that, the mean accuracy of these soil properties was close to the population mean they were meant to measure. The lowest mean accuracy was observed in EC (36.20), this means that the sample mean of EC was further from the population mean it was meant to measure. The skewness of soil properties which is a measure of symmetry or asymmetry was as follows: pH (1.96), EC (4.00) and PR (-1.40) these soil properties had highly skewed distribution. The soil properties with moderately skewed distribution were P (0.56), silt content (0.51) and sand content (-0.54). Fairly symmetrical soil properties were: MWD (0.01), clay content (0.36) and SOC (-0.25). Kurtosis of soil properties were as follows: pH (3.76), EC (25.7) and PR (4.75) distribution was too peaked, and P (0.06), MWD (-0.84), SOC (-0.41), clay content (-0.07), silt content (-0.41) and sand content (-0.17) distribution was too flat.

Table 3.2: Descriptive statistics of measured soil properties at a depth of 0-15 cm

Variable	pH (KCl)	EC (µS/cm)	MWD (mm)	SOC (%)	P (mg/kg)	Clay (%)	Silt (%)	Sand (%)	PR (kg/cm^2)
Minimum	5.73	127.2	0.57	0.11	0.37	2	1.28	34	21.80
Maximum	8.06	1649	1.87	3.17	3.24	28	40	96.56	31.64
Mean	6.38	297.17	1.20	1.56	1.66	11.8	17.7	70.5	28.70
Median	6.25	247.2	1.20	1.64	1.58	10.16	16.64	72.56	28.70
Variance	0.20	31396	0.09	0.37	0.26	26.32	80.12	178.69	2.28
SD	0.44	177.2	0.31	0.61	0.51	5.13	8.95	13.37	1.51
Skewness	1.96	4.00	0.01	-0.25	0.56	0.36	0.51	-0.54	-1.40
Kurtosis	3.76	25.7	-0.84	-0.41	0.06	-0.07	-0.41	-0.17	4.75
CV (%)	6.93	59.60	25.76	38.72	30.60	43.48	50.70	18.95	5.27
SE	0.09	36.20	0.06	0.12	0.10	1.05	1.83	2.73	0.18

SD= Standard deviation, CV= Coefficient of variation (%), SE= Standard error, EC= Electrical conductivity (µS/cm), MWD= Mean weight diameter (mm), SOC= % of Soil organic carbon, P= Phosphorus (mg/kg), Clay= Clay content (%), Silt= Silt content (%), Sand= Sand content (%), PR= Penetrative resistance (kg/cm^2)

3.5.3 Spatial variation of soil physical and chemical properties

Figure 3.3 shows the spatial variation of soil pH within the tomato field, the lowest value was 5.73 and the highest value was 8.06. The north-eastern part of the field had soil pH values with the following ranges: 6.07-6.17; 6.17-6.28 and 6.28-6.38. Soil pH values with the following ranges: 6.17-6.28; 6.28-6.38 and 6.38-6.49 were the most spatially distributed along the field and covered most part of the field (Appendix 3A and 3B). The south-western part of the field had soil pH values with the following ranges: 6.49-6.59; 6.59-6.70; 6.70-6.80, 6.80-6.91 and 6.91-7.01. The soil pH (KCl) was the least variable with CV of 6.93% (Table 3.2).

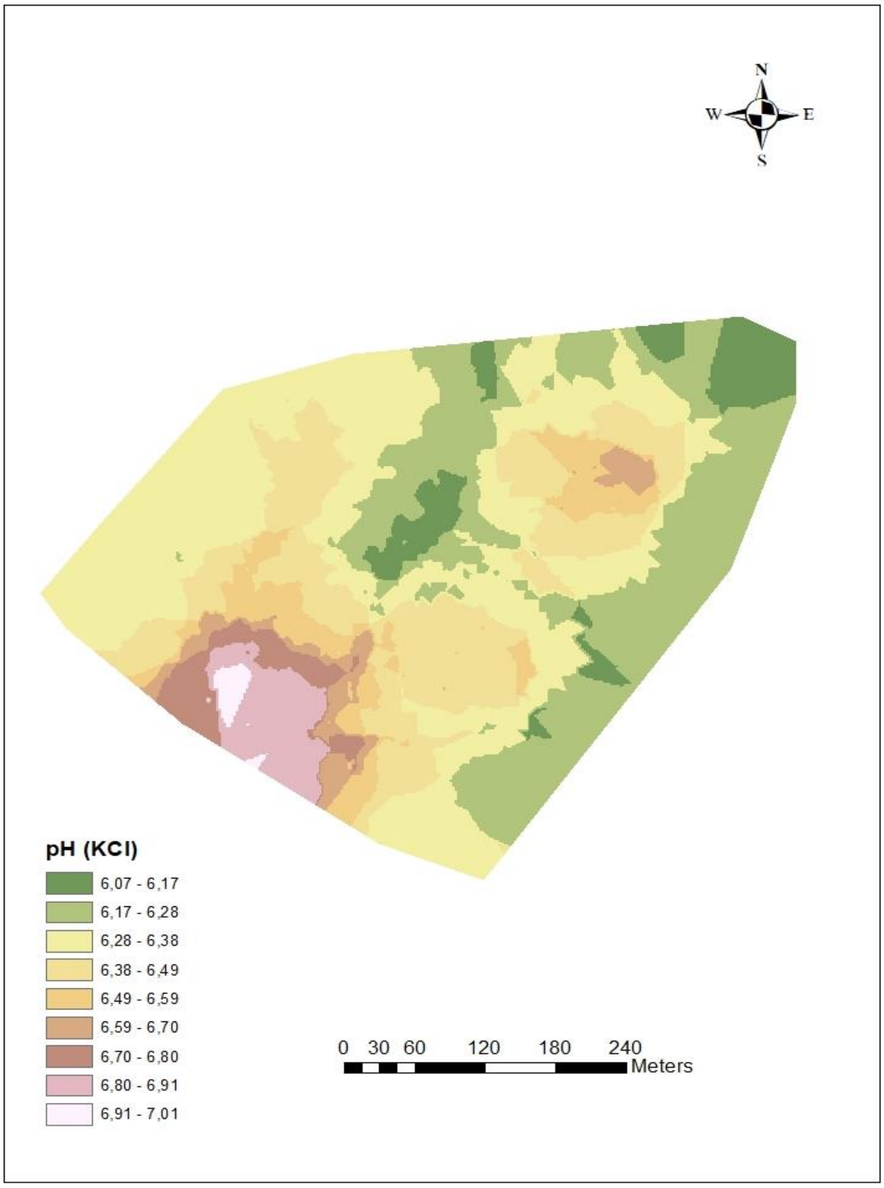

Figure 3.3: Map showing spatial variation of pH (KCl) at Mooketsi ZZ2 farm at a depth of 0-15 cm using ordinary kriging technique

Figure 3.4 below shows spatial variation of EC (µS/cm) within the field. The lowest EC was 127.2 µS/cm while the highest was 1649 µS/cm (Table 3.2). The north-western side of the field had EC values falling in the range of 158.25-197.60 µS/cm and 197.60-243.50 µS/cm (Appendix 3A and 3B). The north-eastern side of the field had soil EC ranging from 243.50-287.21 µS/cm and 333.11-379.01 µS/cm; these were most spatially distributed along the field and covered most part of the field. The EC values with a range of 379.01-429.28 µS/cm; 429.28-488.30 µS/cm; 488.30-562.61 µS/cm and 562.61-715.61 μS/cm were mostly found in the southern part of the field. Soil EC had the highest variation with CV of 59.60%.

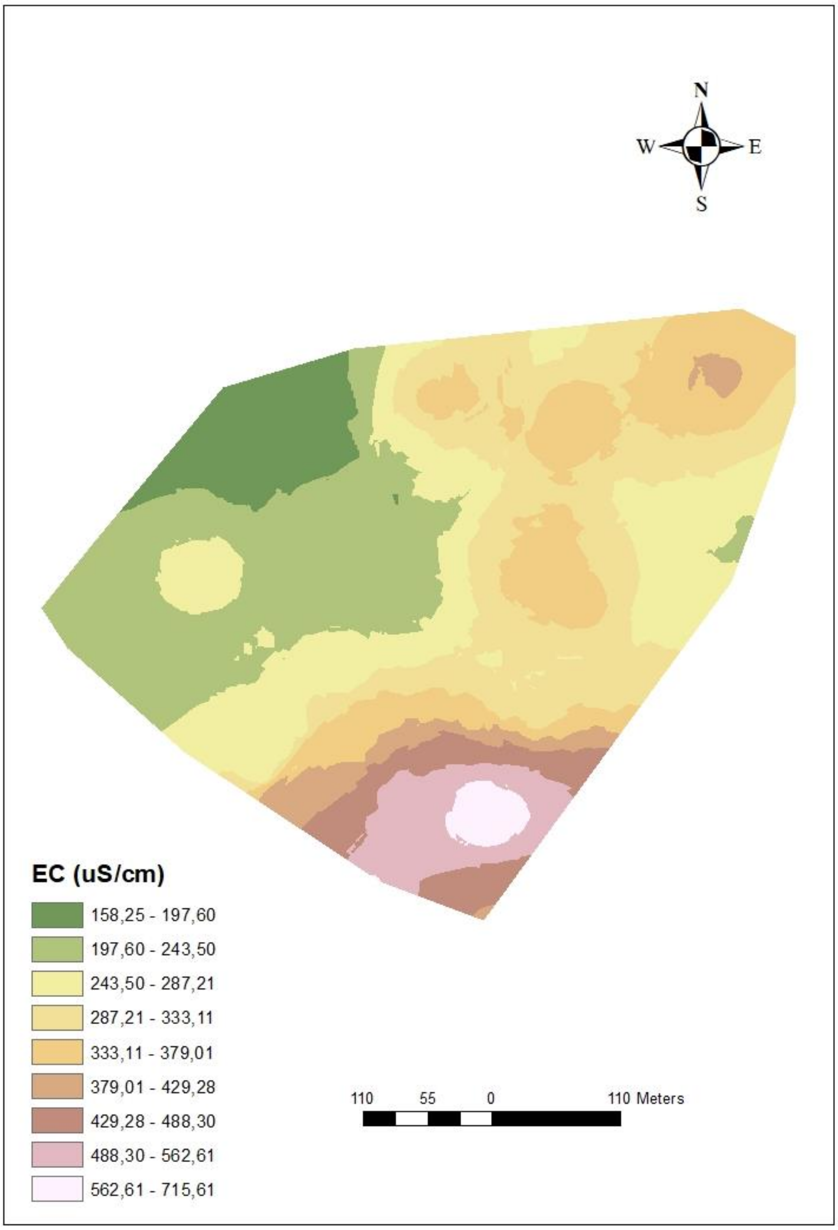

Figure 3.4: Map showing spatial variation of EC (μS/cm) at Mooketsi ZZ2 farm at a depth of 0-15 cm using ordinary kriging technique

Figure 3.5 below shows the spatial variation of MWD, the lowest value was 0.57 mm whereas the highest value was 1.87 mm. The eastern side of the field had mean weight diameter with the following ranges 0.57-0.71 mm and 0.71-0.85 mm. Mean weight diameter with the following ranges were the most spatially distributed and covered most part of the field: 0.85-1.00 mm; 1.00-1.14 mm; 1.14-1.28 mm; 1.28-1.42 mm, 1.42-1.57 mm, and 1.57-1.71 mm (Appendix 4). Mean weight diameter with ranges of 1.28-1.42 mm; 1.42-1.57 mm; 1.57-1.71 mm and 1.71-1.85 mm were mostly found on the western and south-eastern part of the field. Mean weight diameter had a medium CV of 25.76%.

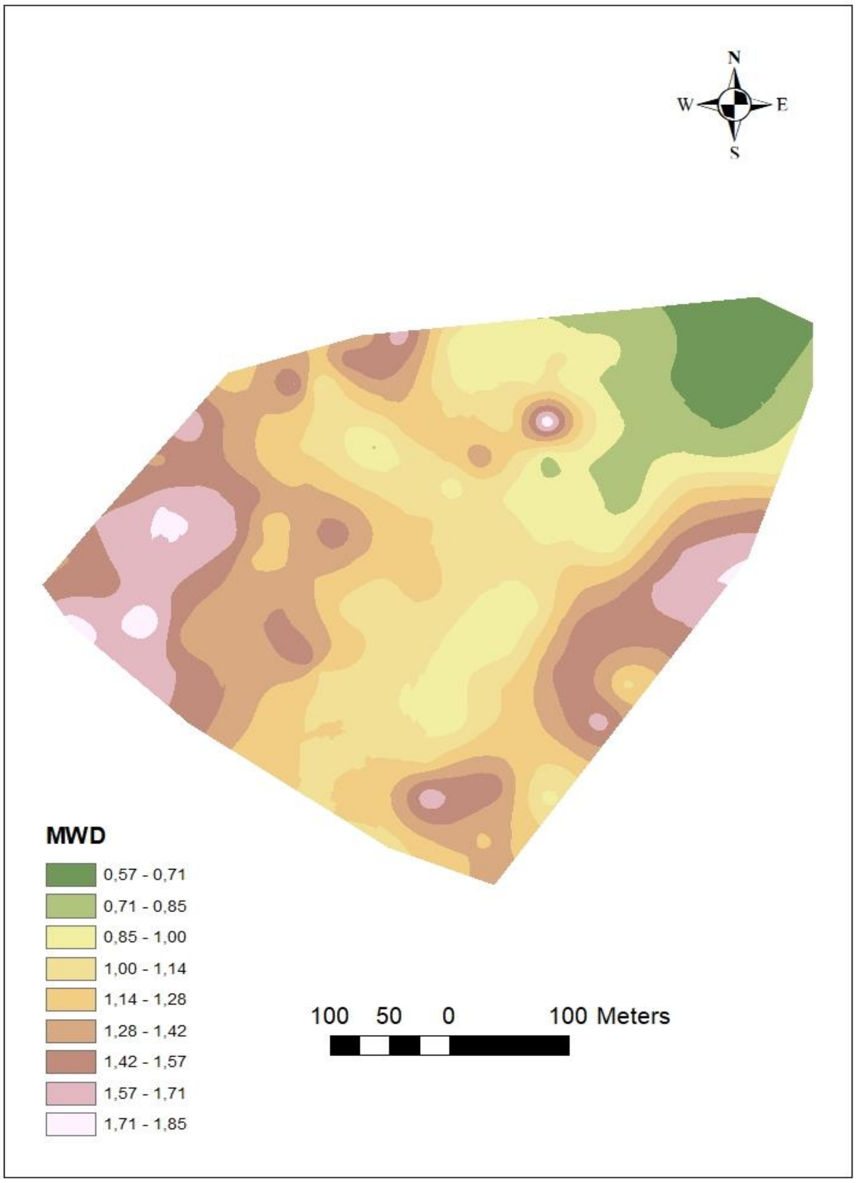

Figure 3.5: Map showing spatial variation of mean weight diameter (MWD) in mm at Mooketsi ZZ2 farm at a depth of 0-15 cm using ordinary kriging technique

Figure 3.6 below shows the spatial variation of SOC (%) within the field. The lowest SOC value was 0.11% and the highest was 3.17%. The south-eastern side of the field had SOC with the following ranges 1.65-1.79% and 1.79-1.93%. The SOC with the following ranges were the most spatially distributed and covered most of the field:

1.24-1.38%; 1.38-1.52% and 1.52-1.65% (Appendix 1). The SOC values falling in the range of 0.96-1.10% were mostly found on the northern part of the field, while SOC with ranges of 1.93-2.07% and 2.07-2.21% were mostly found in the southern part of the field. The SOC had high variation with CV of 38.72%.

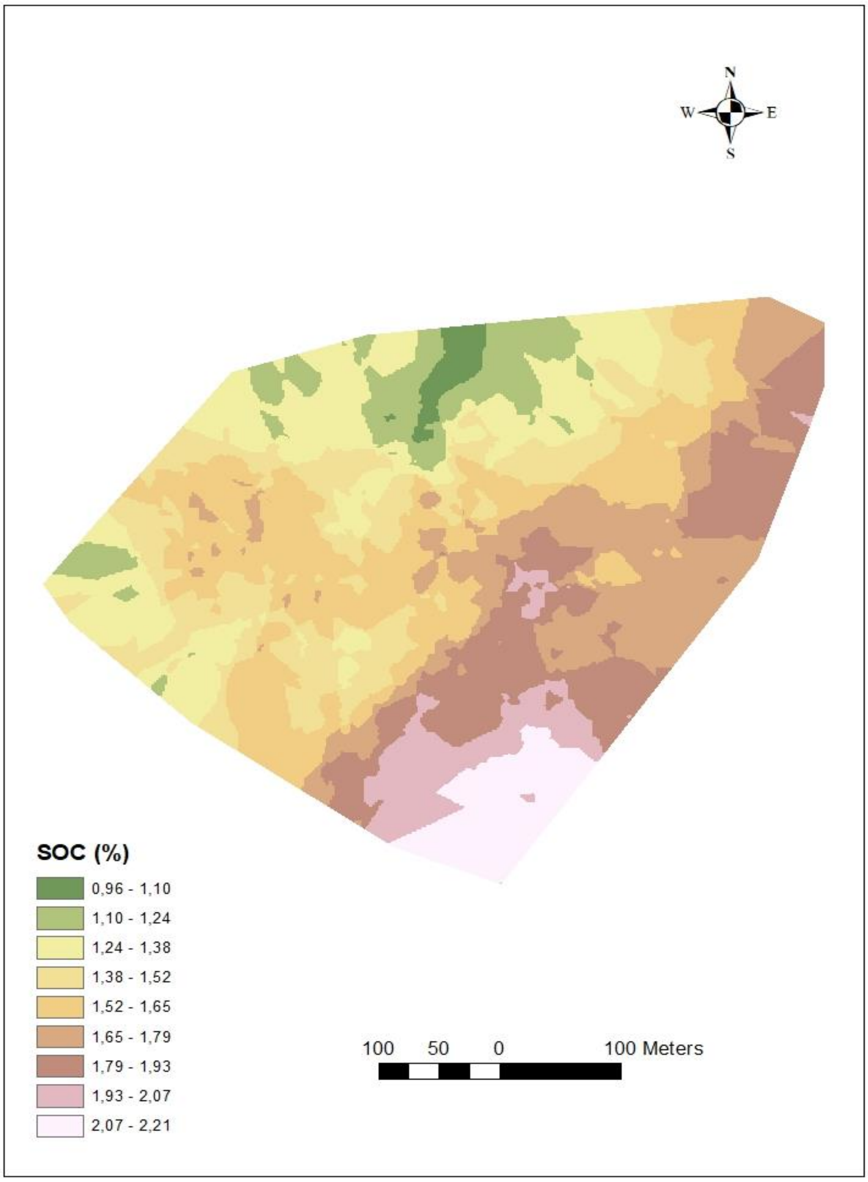

Figure 3.6: Map showing spatial variation of soil organic carbon (SOC) in % at Mooketsi ZZ2 farm at a depth of 0-15 cm using ordinary kriging technique

Figure 3.7 below shows the spatial variation of extractable phosphorus (P) in mg/kg. The lowest value was 0.37 mg/kg, and the highest value was 3.24 mg/kg. The north-eastern side of the field had soil extractable phosphorus with the following ranges 1.14-1.25 mg/kg, 1.25-1.36 mg/kg, and 1.36-1.47 mg/kg. Soil extractable phosphorus with the following ranges were the most distributed along the field and covered most of the field 1.36-1.47 mg/kg; 1.47-1.59 mg/kg; 1.59-1.70 mg/kg and 1.70-1.81 mg/kg (Appendix 5). The following values of extractable phosphorus ranges :1.81-1.93 mg/kg; 1.93-2.047 mg/kg and 2.04-2.15 mg/kg were mostly found in the southwestern part of the field. Soil extractable phosphorus had medium variation with CV of 30.60%.

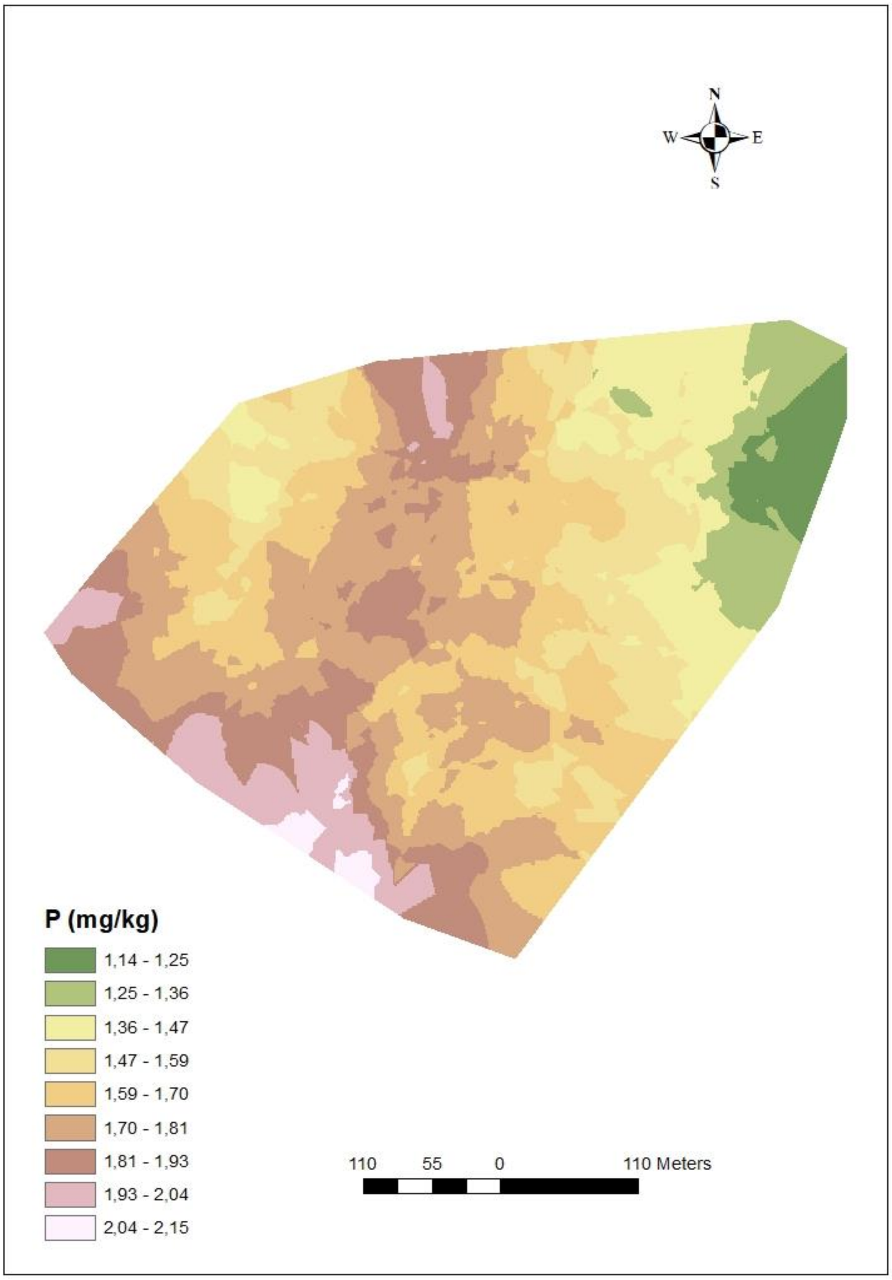

Figure 3.7: Map showing spatial variation of extractable (P) phosphorus (mg/kg) at Mooketsi ZZ2 farm at a depth of 0-15 cm using ordinary kriging technique

Figure 3.8 below shows the spatial variation of clay content (%) within the field. The lowest value of clay content was 2% and the highest value was 28% (Appendix 2A and 2B). The eastern and southern part of the field had clay content with the following ranges dominant 11.42-13.04%, 13.04-14.66%; 14.66-16.28%, 16.28-17.90% and 17.90-19.52%. Clay percentage with the following ranges 4.94-6.56% and 6.56-8.18% were mostly distributed in the eastern and western part of the field. The clay percentage with a range of 8.18-9.80% and 9.80-11.42% were the most distributed along the field and covered most part of the field. Clay content had high variation within the field with CV of 43.48%.

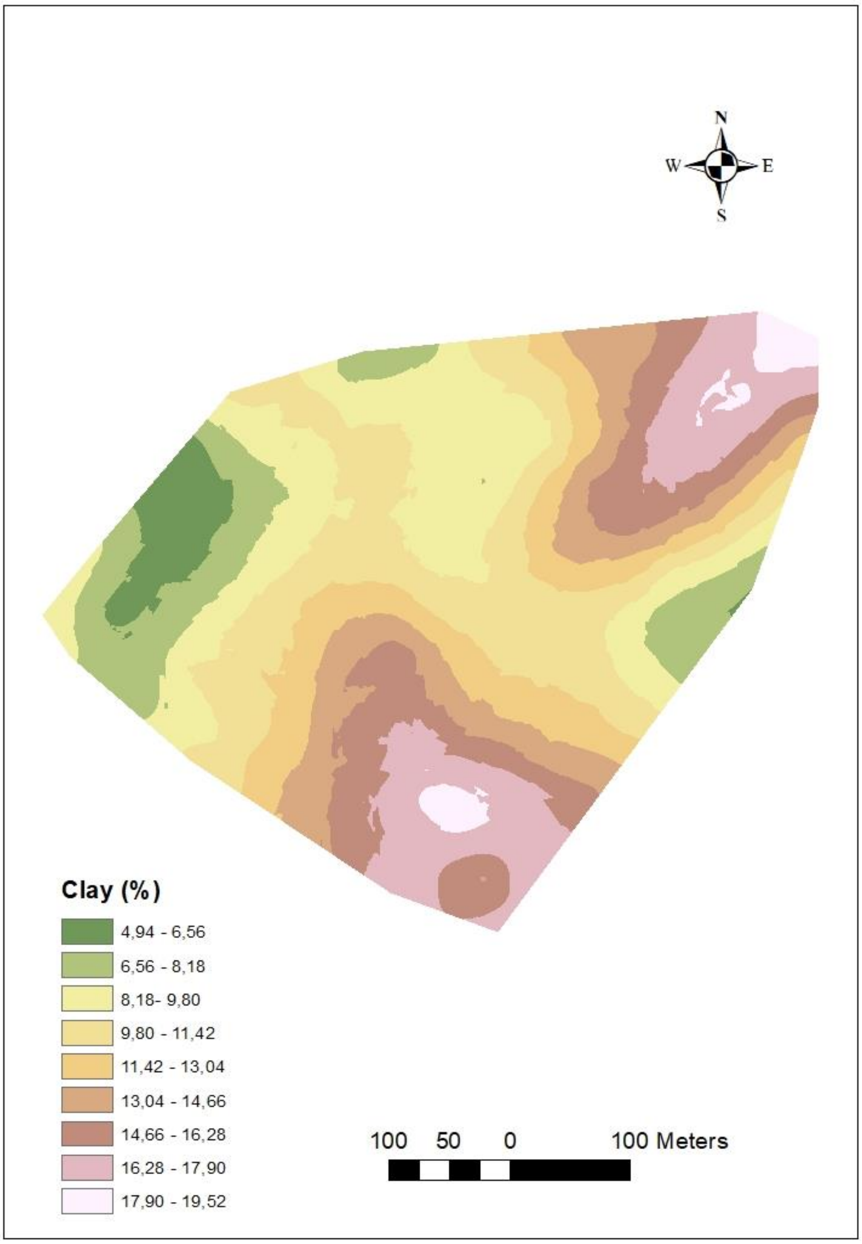

Figure 3.8: Map showing spatial variation in clay content (%) at Mooketsi ZZ2 farm at a depth of 0-15 cm using ordinary kriging technique

Figure 3.9 below shows the spatial variation of silt content (%) within the field. The lowest silt content value was 1.28% and the highest value was 40% (Appendix 2A and 2C). The western part of the field had silt content values with the following ranges: 4.89-8.04%; 8.04-11.39% and 11.39-14.74%. The silt content with the following ranges: 18.09-21.44%, 21.44-24.79%; 24.79-28.14%, 28.14-31.50% and 31.50-34.85% were mostly distributed in the eastern and southern part of the field. The silt percentage with a range of 11.39-14.74% and 14.74-18.09% were the most distributed along the field and covered most part of the field. Silt had higher variation within field with CV of 50.70%.

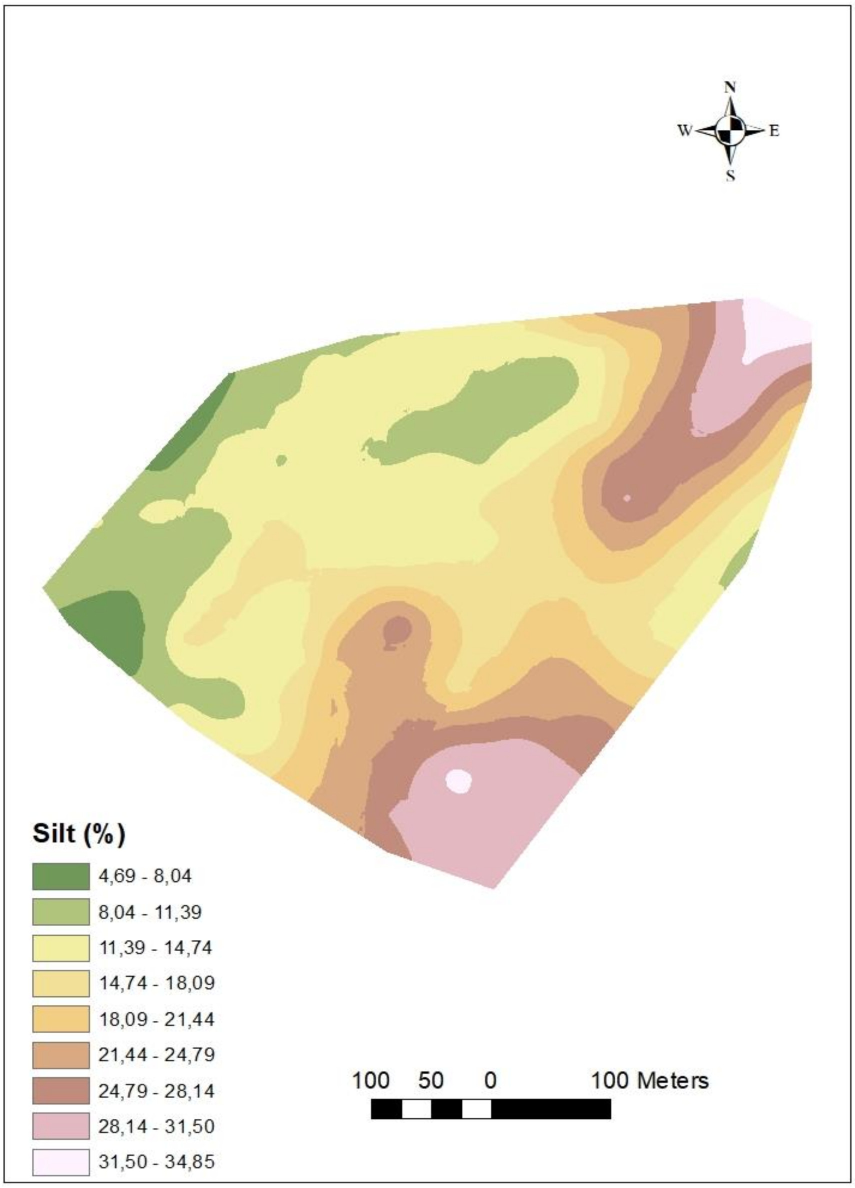

Figure 3.9: Map showing spatial variation in the silt content (%) at Mooketsi ZZ2 farm at a depth of 0-15 cm using ordinary kriging technique

Figure 3.10 below shows the spatial variation of sand content (%) within the field. The lowest value was 34% and the highest was 96.56% (Appendix 2A and 2C). The eastern and southern part of the field had sand content values with the ranges of 44.94-49.90%; 49.90-54.86%; 54.86-59.82%; 59.82-64.78% and 64.78-69.74%. The sand content with the following ranges: 74.70-79.67% and 79.67-84.63% were mostly distributed in the north-western and south-eastern part of the field. The sand percentage with a range of 84.63-89.59% were distributed in the western part of the field. The sand content with 69.74-74.70% were the most distributed along the field and covered most part of the field. Sand content had medium variation within the field with CV of 18.95%.

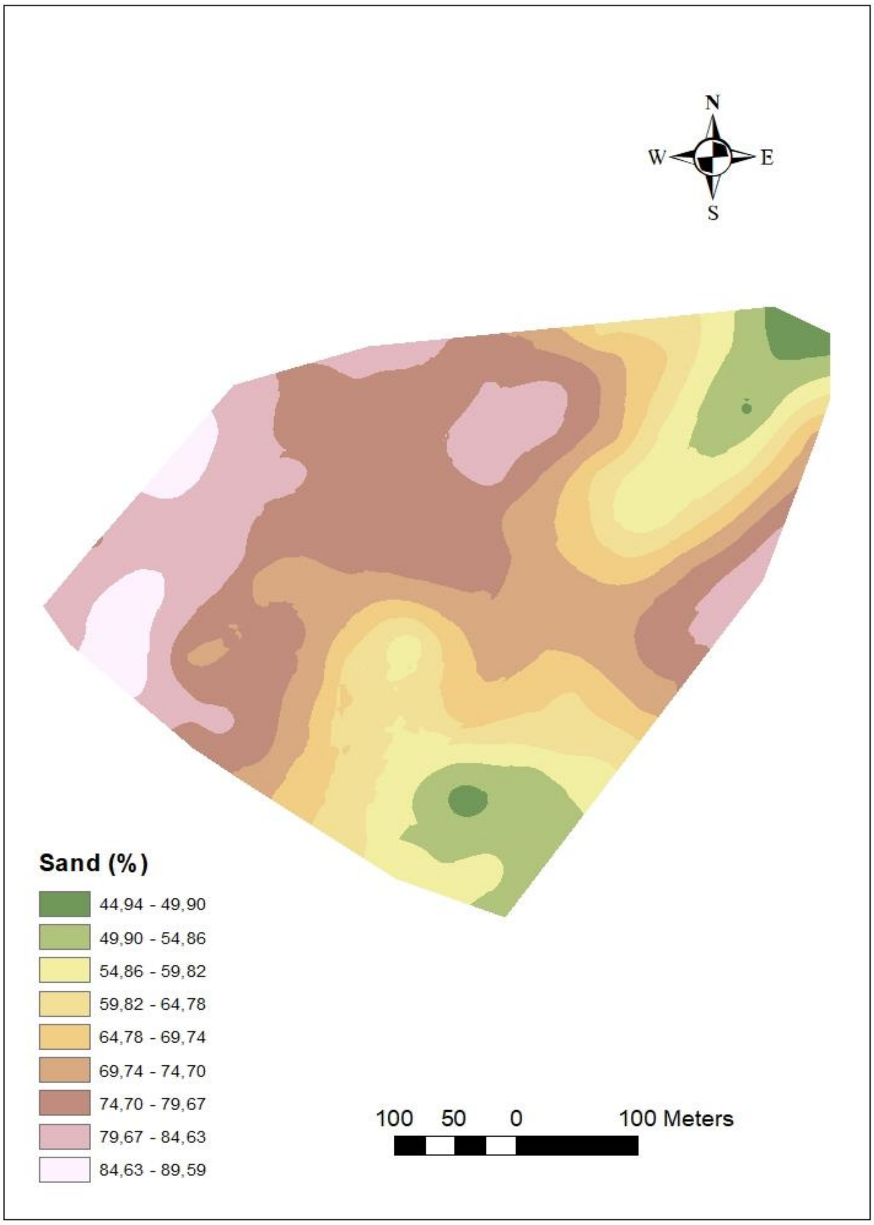

Figure 3.10: Map showing spatial variation in the sand content (%) at Mooketsi ZZ2 farm at a depth of 0-15 cm using ordinary kriging technique

Figure 3.11 below shows the spatial variation of penetrative resistance (PR) in the field. The lowest value was 21.80 kg/cm^2 and the highest value was 31.64 kg/cm^2 (Appendix 6A and B). The following ranges of penetrative resistance: 27.28-27.56 kg/cm^2; 27.56-27.84 kg/cm^2 and 27.84-28.12 kg/cm^2 were mostly distributed in the north-eastern part of the field. The eastern and western part of the field had PR ranges of 28.68-28.95 kg/cm^2; 28.95-29.23 kg/cm^2; 29.23-29.51 kg/cm^2 and 29.51-29.79 kg/cm^2. The PR ranges of 27.84-28.12 kg/cm^2 and 28.40-28.68 kg/cm^2 were mostly distributed in the southern part of the field. The PR values with the following ranges: 27.84-28.12 kg/cm^2; 28.12-28.40 kg/cm^2; 28.40-28.68 kg/cm^2 and 28.68-28.95 kg/cm^2 were the most distributed along the field and covered most part of the field. Penetrative resistance had the lowest variation within the field with CV of 5.27%.

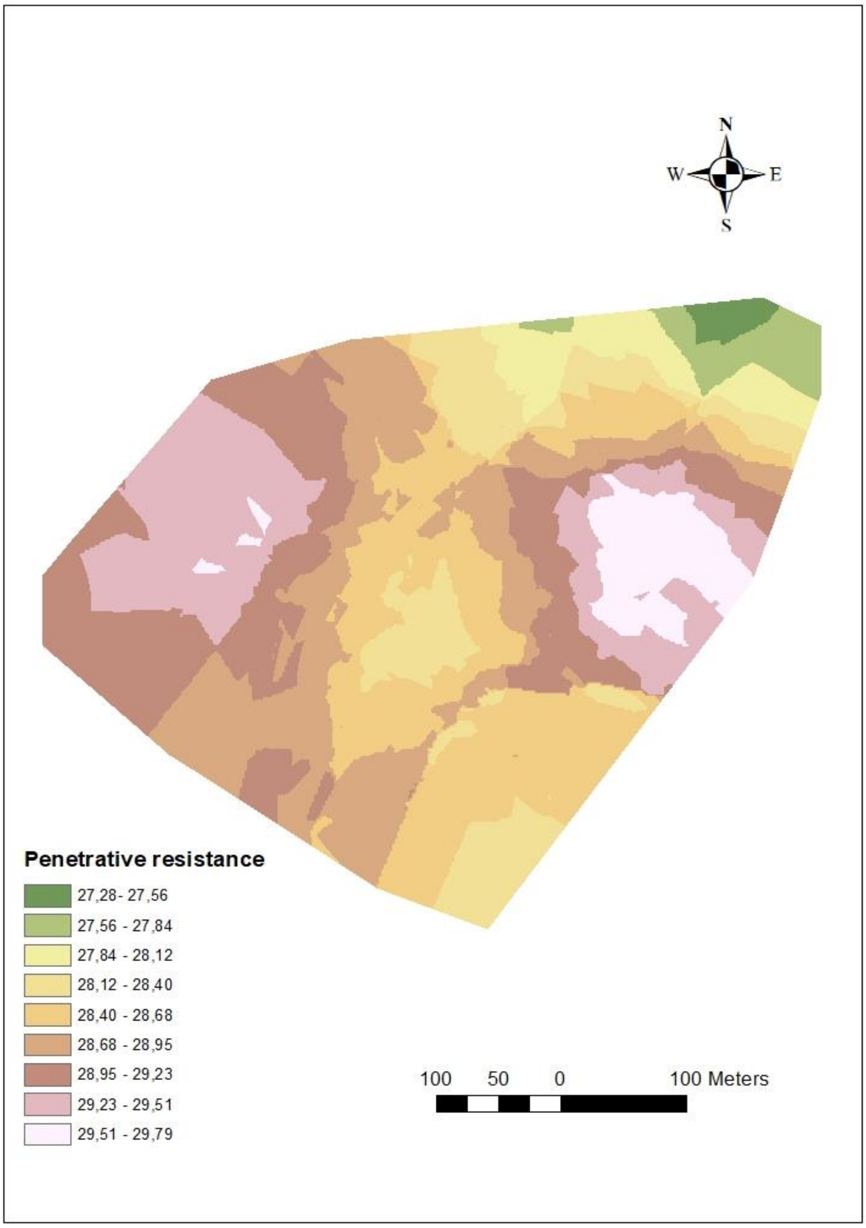

Figure 3.11: Map showing spatial variation of penetrative resistance (kg/cm^2) at Mooketsi ZZ2 farm at a depth of 0-15 cm using ordinary kriging technique

3.5.4 Semivariograms and spatial dependency of soil properties

The semivariograms which are important for spatial analysis showed variation of soil properties within the tomato field. The semivariograms of measured soil properties are shown in Figure 3.12 to Figure 3.20. Spatial dependency, which is the ratio of nugget to sill (partial sill plus nugget), was used to categorize the spatial dependence of the variable. The following categories were used: when the ratio is <25% the variable has strong spatial dependence, 25-75% = moderate spatial dependence and >75% = weak spatial dependence (Cambardella *et al*., 1994). Soil pH (KCl) had nugget of 0.73, partial sill of 0.48, with a range of 135.29 m, a nugget/sill ratio of 0.60 and RMSE of 0.40. The nugget and partial sill of electrical conductivity (EC) were 0.57 and 0.74 respectively, with a range of 375.68 m and nugget/sill ratio of 0.44 and root mean square error (RMSE) of 160.49 μS/cm. The nugget and sill of MWD were 0.38 and 0.62 respectively, with a range of 312.29 m and nugget/sill ratio of 0.38 and RMSE of 0.20 mm. The nugget and partial sill of SOC were 0 and 1.12 respectively, with a range of 383.06 m and nugget/sill ratio of 0 and RMSE of 0.58%. The nugget and partial sill of extractable P were 0.90 and 0 respectively, with a range of 67.16 m and nugget/sill ratio of 1 and RMSE of 0.50 mg/kg. The nugget and partial sill of clay content was 0.53 and 0.58 respectively, with a range of 344.19 m and nugget/sill ratio of 0.48 and RMSE of 3.89%. The nugget and partial sill of silt content 0.48 and 0.68 respectively, with a range of 354.39 m and nugget/sill ratio of 0.41 and RMSE of 6.09%. The nugget and partial sill of sand content were 0.43 and 0.63 respectively, with a range of 340.86 m and nugget/sill ratio of 0.41 and RMSE of 8.92%. The nugget and partial sill of PR were 0 and 0.99 respectively, with a range of 64.84 m and nugget/sill ratio of 0 and RMSE of 1.44 kg/cm^2. The soil properties showed differences in spatial dependence as reflected by the nugget/sill ratio and could be grouped into three. The pH (KCl), EC, MWD, clay, silt and sand percentages showed moderate spatial dependence. Whereas SOC and PR had strong spatial dependence while P showed weak spatial dependence. The RMSE values showed the accuracy of ordinary kriging where pH, MWD, SOC, P, PR, and clay had good accuracy. Silt and sand content had moderate accuracy, whereas EC had less accuracy (Table 3.3).

Table 3.3: Semivariogram parameters for measured soil properties

Variable	Nugget	Range	Partial sill	Nugget/sill ratio	RSME
pH (KCl)	0,73	135,29	0,48	0.60	0,40
EC (µS/cm)	0,57	375,68	0,74	0.44	160,49
MWD (mm)	0,38	312,29	0,62	0.38	0,20
SOC (%)	0	383,06	1,12	0.00	0,58
P (mg/kg)	0,90	67,16	0	1.00	0,50
Clay (%)	0,53	344,19	0,58	0.48	3,89
Silt (%)	0,48	354,39	0,68	0.41	6,09
Sand (%)	0,43	340,86	0,63	0.41	8,92
PR (kg/cm^2)	0	64,84	0,99	0.00	1,44

RSME= Root mean square error, EC= Electrical conductivity, MWD= Mean weight diameter, SOC= Soil organic carbon, P= Phosphorus, Clay= Clay content, Silt= Silt content, Sand= Sand content, PR= Penetrative resistance

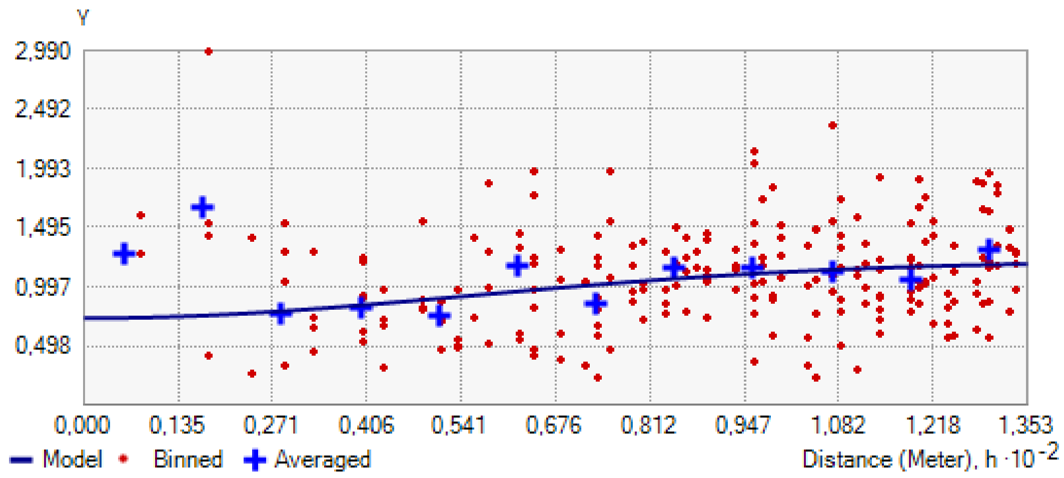

Figure 3.12: Semivariogram of pH (KCl)

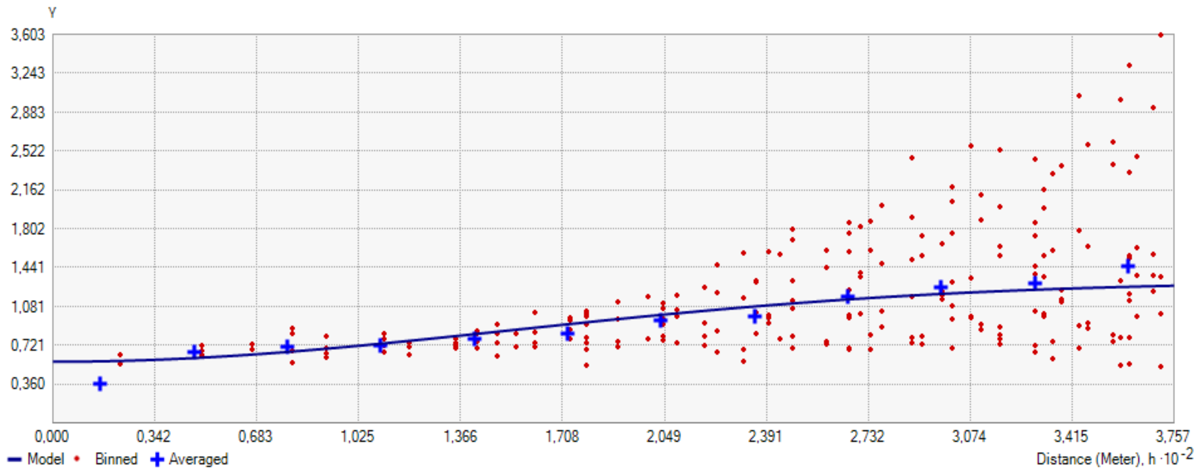

Figure 3.13: Semivariogram of electrical conductivity (EC) in µS/cm

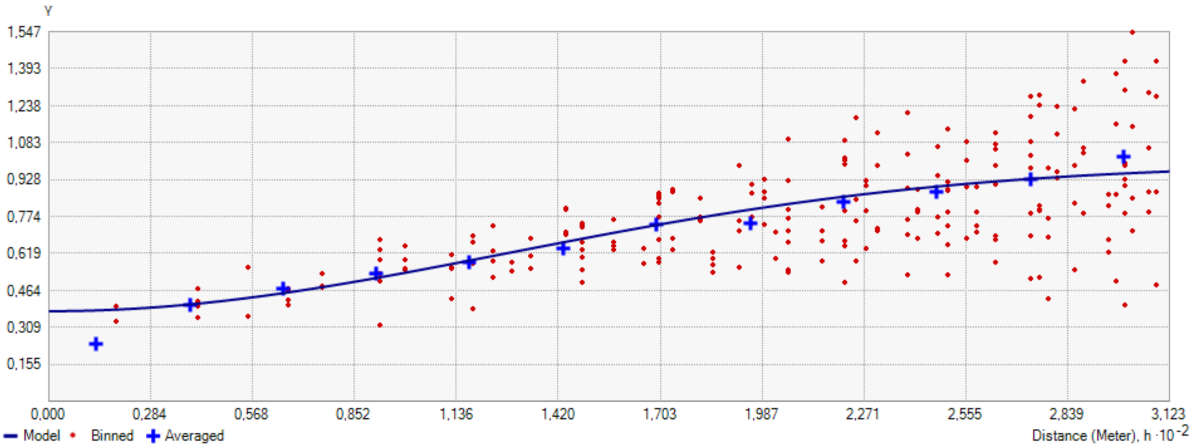

Figure 3.14: Semivariogram of mean weight diameter (MWD) in mm

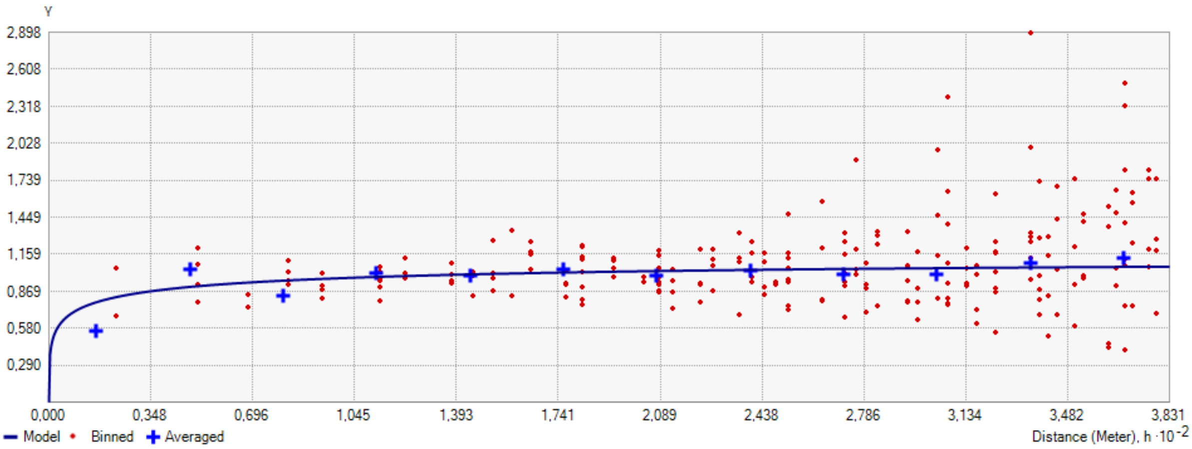

Figure 3.15: Semivariogram of soil organic carbon (%)

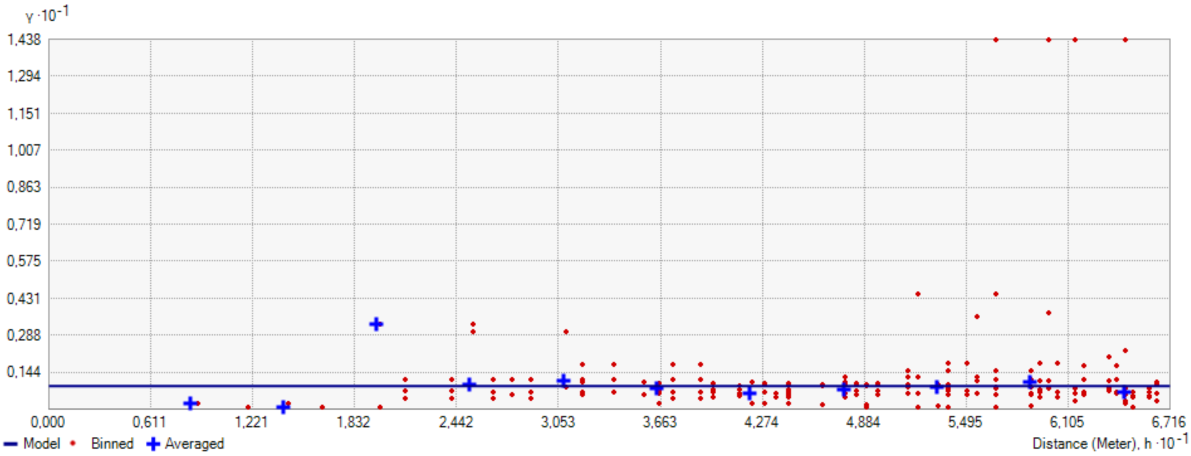

Figure 3.16: Semivariogram of extractable phosphorus (P) in (mg/kg)

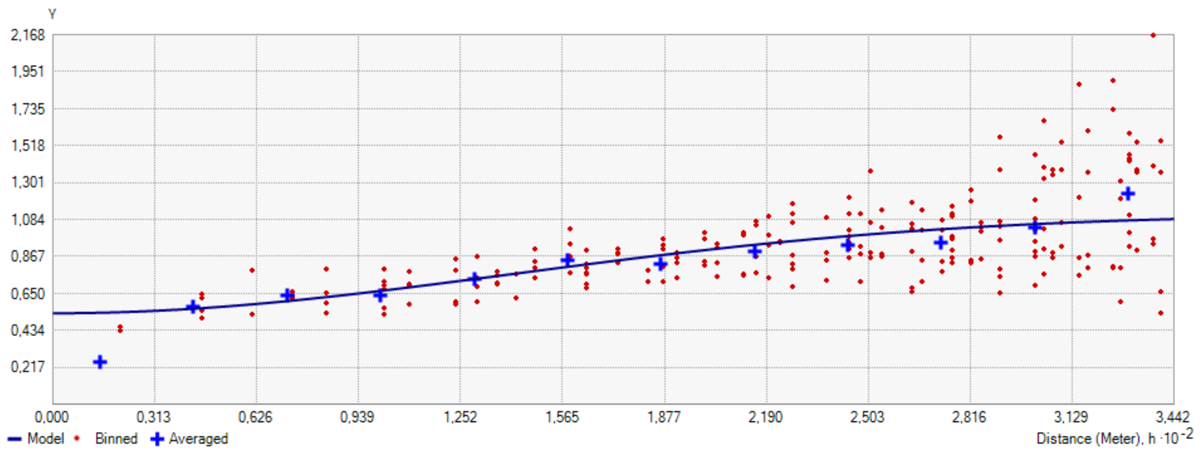

Figure 3.17: Semivariogram of clay content (%)

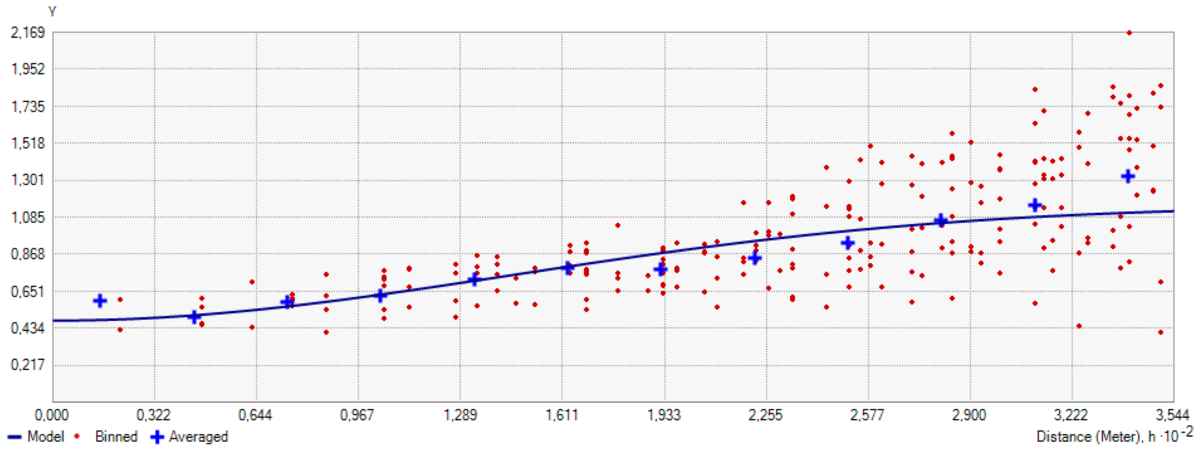

Figure 3.18: Semivariogram of silt content (%)

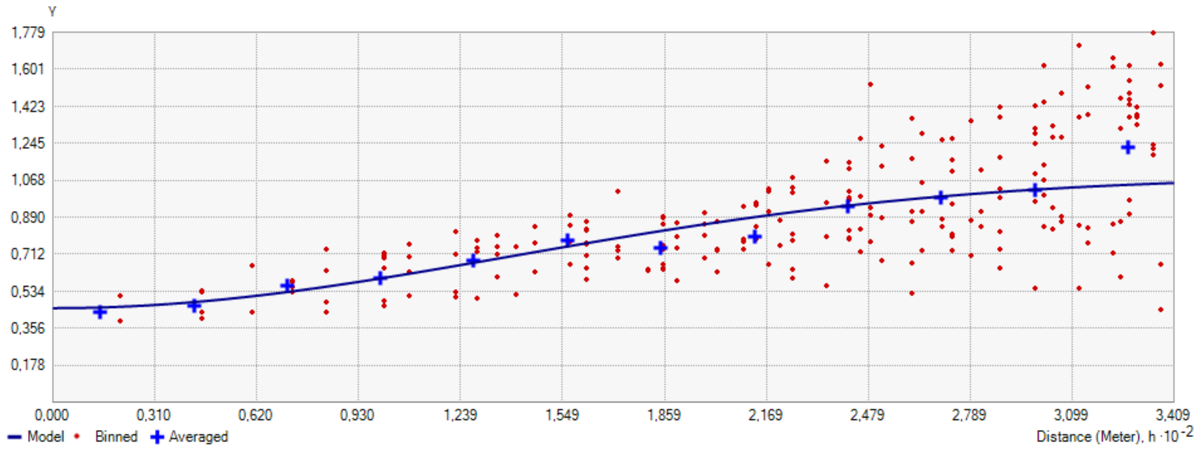

Figure 3.19: Semivariogram of sand content (%)

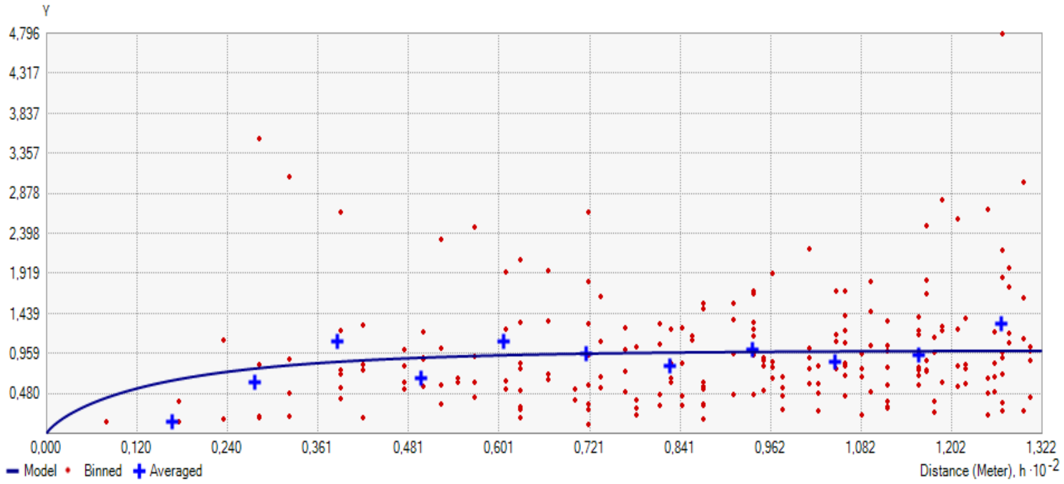

Figure 3.20: Semivariogram of penetrative resistance (PR) in (kg/cm^2)

3.5.5 Correlations between soil properties

Table 3.4 below shows the correlation among soil organic carbon, clay, silt, sand, MWD, and EC. Soil organic carbon was positively correlated with silt content (r= 0.30) and negatively correlated with sand content (r= -0.27). There was no significant correlation found between soil organic carbon and clay content of the soil. This means that clay content does not influence the spatial variation of SOC across the tomato field, yet in theory we have been told that clay content positively influences SOC (Singh *et al*., 2018). For the Glenrosa soil type, this is not the case probably because it does not have a high clay content in the topsoil (0-15 cm). Clay was positively correlated with silt content (r= 0.81) and negatively correlated with sand content (r= -0.93). Silt was negatively correlated with sand content (r= -0.97). Mean weight diameter was negatively correlated with clay content (r= -0.51), silt content (r = -0.46), and it was positively correlated with sand content (r= 0.50). The EC was positively correlated with clay content (r= 0.33), silt (r= 0.29), and it was negatively correlated with sand (r= -0.32).

Table 3.4: Correlations of measured soil properties

Variable	pH (KCl)	EC	MWD	SOC	P	Clay	Silt	Sand	PR
pH (KCl)	1								
EC (µS/cm)	-0.02	1							
MWD (mm)	0.2	-0.02	1						
SOC (%)	-0.19	0.15	-0.06	1					
P (mg/kg)	-0.1	-0.03	0.22	-0.06	1				
Clay (%)	0	**0.33**	**-0.51**	0.2	-0.01	1			
Silt (%)	-0.02	**0.29**	**-0.46**	**0.30**	0.09	**0.81**	1		
Sand (%)	0.01	**-0.32**	**0.50**	**-0.27**	-0.05	**-0.93**	**-0.97**	1	
PR (kg/cm^2)	0.2	-0.01	0.13	-0.11	0.13	-0.21	-0.09	0.14	1

Correlations in bold were significant at P (<0.05). EC= Electrical conductivity (µS/cm), MWD= Mean weight diameter (mm), SOC= Soil organic carbon (%), P= Phosphorus (mg/kg), Clay= Clay content (%), Silt= Silt content (%), Sand= Sand content (%), PR= Penetrative resistance (kg/cm^2)

3.6 Discussion

3.6.1 Spatial variation of soil properties

Soil properties were variable across the field, they had different coefficients of variation (CV). Soil is inherently variable because of different soil forming factors such as parent material, climate, topography, and organisms present in the area (Denton *et al*., 2017). The results in this study showed that there was high variation of SOC with CV of 38.72%, clay content with CV of 43.48%, silt content with CV of 50.70% and EC with CV of 59.60%. Since these properties influence other soil properties that leads to spatial variation within the field. The high variation of SOC may be attributed to the different clay percentages observed across the tomato field, because clay has good nutrient holding capacity. Clay content and silt content variation may be attributed to the weathering parent material which is granite and the high temperatures of the study area. This is because finer particles may be carried to different subfields. Since the subfields are different from each other, this leads to high variation with the tomato field (Pieper and Barrett, 2009).

The variation in EC of the study area may be attributed to the high rainfall and temperatures in the area, the amount of fertilizers used during tomato production and the soil texture. This is because soil clay content, nutrient levels affect the EC levels in the soil. The higher the EC, the more negatively charged sites (clay and organic particles) there will be in the soil, and therefore more cations will be held in the soil (Sumner and Miller, 1996; McCauley *et al*., 2009). Therefore, this causes variation in the soil properties as finer soils thus have a much better ability to store and hold onto cations, and the loss of nutrients would be much less so than in sandy soils (Sollins, 1998).

The soil property that had the least variation in this study was penetrative resistance with CV of 5.27% and pH (KCl) with CV of 6.93%. The low variability of soil pH can be attributed to sandy loam texture, mineral content, and the weathering parent material which is granite, and the weathering processes that acted on it such as climate, topography. A study by Bogunovic *et al*. (2014) found that content of soil organic matter and pH had lower variability ranging from 1.26% to 2.66% and from 3.75 to 7.13, respectively. The results from basic statistics showed that soil pH had a low variation. The factors driving the variation of soil organic matter and pH were mineral content, soil formation processes such as weathering of parent material and the sandy loam texture (Catoni *et al*., 2016). Other researchers (Castrignano *et al*., 2000; Chung *et al*., 1995; Fu *et al*., 2010; McBratney and Webster, 1983, and Parfitt *et al*., 2009) also report relatively small variations of pH of the surface layer with CV value from 2.22% to 8.1%.

The variability in soil properties is attributed to combined effect of Glenrosa soil as it has low clay content and poor nutrient holding capacity, climatic conditions, and management practices such as fallowing and crop rotations which influence the variation of tomato yields (Mallarino *et al*., 1999; Foroughifar *et al*., 2013). Some CV values for selected soil properties in this study were lower than those reported in other references, indicating probably to the homogenizing effect of the long-term cultivation and crop rotations management on topsoil (Ayoubi *et al*., 2007). This finding is also in accordance with Paz-Gonzalez *et al*. (2000). Many studies have revealed that soil properties vary across agricultural fields, causing spatial variability in crop yields (Stein *et al*., 1997; Rockstrom *et al*., 1999; Gaston *et al*., 2001; Mzuku *et al*., 2005). Factors such as clay mineralogy, texture, soil pH can influence the spatial variability at each unique site. Quantifying variation across agricultural fields is also helpful in making better management decisions for precision farming (Mzuku *et al*., 2005).

Spatial dependence which is the nugget/sill ratio shows how the variable is spatially dependent. In this study, spatial dependence results showed that extractable P had a weak spatial dependence which was >75%, whereas pH, EC, MWD, clay, silt and sand had moderate spatial dependence which were between 25-75%, and SOC and PR had a strong spatial dependence which were <25%. In this study, SOC had a strong spatial dependence with nugget/sill ratio value of 0. The strong spatial dependence means that high SOC variation observed can be explained by distance, as two samples next to each other will have similar values compared to the ones far away. This might be because of the intrinsic variation in the soil characteristics such as texture and mineralogy. Study by Behera *et al*. (2018) which found that SOC had 0 nugget/sill ratio. Khan *et al*. (2019) found that the soil OM had strong spatial dependence with the value of 16.52% (0.1652). In this study, extractable P had a nugget/sill ratio of 1.00 which has a weak spatial dependence. Weak spatial dependence means that low variation of P observed is not a function of distance. The samples next to each other might have different values within a short distance as they are not affected by distance. The variability of weak spatial dependence in phosphorus may be attributed to extrinsic variations such as fertilizer application and tillage during tomato production. Study in Ethiopia by Laekemariam *et al*. (2018) found that P had weak spatial dependence. In this study, clay had 0.48 nugget/sill ratio which has moderate spatial dependence. Moderate spatial dependence means that to some extent, distance can explain variation of the clay content. This might be attributed to both the intrinsic and extrinsic variations such as texture, clay mineralogy and tillage (Cambardella *et al*., 1994). A study conducted by Lopez-Granados *et al*. (2002) found that clay had nugget/sill ratio within the 0-10 cm depth. In this study, soil pH had 0.60 nugget/sill ratio which has moderate spatial dependence. Moderate spatial dependence means that to some extent, distance can explain the observed variation of the soil pH. This might be attributed to both the intrinsic and extrinsic variations such as texture, clay mineralogy and fertilizer and manure application. A study by Cambardella and Karlen (1999) found that pH in the 5-10 cm and 20-30 cm had 56.1% and 60.7% nugget/sill ratios which had moderate spatial dependence. Another study by Lopez-Granados *et al*. (2002) found that pH had a moderate spatial dependence with a nugget/sill ratio of 0.30 in the 0-10 cm depth.

In this study, both silt and sand content had a nugget/sill ratio value of 0.41 which has moderate spatial dependence. Moderate spatial dependence means that to some extent, distance can explain the observed variation of the silt and sand content. This might be attributed to both the intrinsic and extrinsic variations such as texture, clay mineralogy and tillage. A study by Lopez-Granados *et al*. (2002) found a similar trend as both silt and sand content had moderate spatial dependence where sand had 46% and silt had 57% spatial dependence respectively. Managing spatial variability which is popularly known as precision farming is essential for serving the dual purpose of enhancing productivity and reducing ecological degradation. The focus of precision farming is to optimize the crop production and reduce soil fertility losses. The first step in site-specific management is measuring the spatial variability of soil property using map generation (Zandi *et al*., 2011). The spatial variation maps demonstrated variability of soil properties in the study area and these maps could be utilized for site-specific soil nutrient management in the tomato field. An understanding of the distributions of soil properties at the field scale is important for refining agricultural management practices and assessing the effects of agriculture on environmental quality (Cambardella *et al*., 1994). There are many factors affecting the soil that create variation within the soils. Spatial variation in tomato yields is affected by factors such as climate, soil texture, soil pH. Understanding of spatial variability of soil properties is important for site-specific management (Havlin *et al*., 2016). Analysis of spatial variation of soil properties is fundamental to sustainable agriculture (Turmel *et al*., 2015).

3.6.2 Relationships of soil properties and how they influence each other

Soil properties influence each other one way or the other, with some properties influencing behaviour of more than one variable. In this study, SOC was positively correlated with silt content (r= 0.30) meaning that as SOC increased the percentage of silt increased, and SOC was negatively correlated with sand content (r= -0.27) meaning that as SOC increase the percentage of sand decreased. The relationship between SOC and silt content and SOC and sand content is also shown in (Figure 3.6 and 3.9) and (Figure 3.6 and 3.10) respectively. This is because finer particles like silt can store and hold onto cations as they are less porous. However, sandy soils tend to lose nutrients due to being porous and having a lack of binding particles. This is because soils which have fewer binding agents such as sandy soils, results in less stable aggregates which lose essential soil nutrients due to surface runoff and this will lead to erosion of soils (Colazo and Buschiazzo, 2010). Clay content was positively correlated with silt content (r= 0.81) meaning that as clay increased the silt content also increased and it was negatively correlated with sand content (r= -0.93) meaning that as clay increased the sand content decreased. The relationship between clay and silt, and clay and sand are also shown in (Figure 3.8 and 3.9) and (Figure 3.8 and 3.10). Silt content was negatively correlated with sand content (r= -0.97) meaning that as silt increased the sand content decreased. The relationship between silt and sand is also shown in (Figure 3.9 and 3.10). This is because literature suggests that soils which have fewer binding agents such as sandy soils, results in less stable aggregates which lose essential soil nutrients due to surface runoff and this will lead to erosion of soils (Colazo and Buschiazzo, 2010).

In this study, EC (μS/cm) was positively correlated with both clay content (r= 0.33) and silt content (r= 0.29) meaning as both clay and silt percentages increase EC increases. Electrical conductivity was negatively correlated with sand (r= -0.32) meaning that as the percentage of sand decreases EC increases (Table 3.4). The relationship of EC and clay content is also shown in (Figure 3.4 and 3.8), the one for EC and silt content is shown in (Figure 3.4 and 3.9), and for EC and sand content the relationship is also shown in (Figure 3.4 and 3.10). This might be because finer particles such as clay and silt have better capacity to store and hold onto cations, and the loss of nutrients would be much less than in sandy soils. In sandy soils, improving the organic matter levels can lead to an improvement in the ability of the soil to hold cations, in so doing improving the EC levels of the soil (Scotti *et al*., 2015; Glinski and Lipiec, 2018). The EC which is the measure of the amount of salts in the soil varies with the concentration of dissolved salts (Bohn *et al*., 1985). Soil EC is used as a measure to differentiate soil types for site-specific management. This is because soil EC indirectly measures many soil properties influencing soil fertility and crop yield (Corwin and Lesch, 2005). A study by Bronson *et al*. (2005) found that a positive correlation between EC and clay content was observed at four of six sites in southern high plains of Texas. Many studies have shown correlation of EC with soil properties important for plant growth and crop yields including soil compaction, soil water content, soil texture, drainage, total carbon, soluble salts, extractable P, and soil pH (Jung *et al*., 2005; Corwin and Lesch, 2005; and Sudduth *et al*., 2003). Drier and coarser soils are less electrically conductive than wetter and finer soils (Inman *et al*., 2002). A study by Sudduth *et al*. (2005) found that correlations of EC with other soil properties including silt and organic C were lower and more variable for the fields across North-central USA. Areas affected by high EC can be improved by implementing a management method which can improve water infiltration and conservation, or by planting more drought tolerant crops such as soybean or sorghum as, tomatoes cannot survive under high salinity because seed germination is adversely affected (Machado and Serralheiro, 2017). Management options for areas with low EC are associated with areas of excessive water in the early growing season (Kitchen *et al*., 1999). In this study MWD had a moderate positive relationship with sand (r= 0.50) meaning that as MWD increased the percentage of sand increased. MWD had a negative relationship with silt content (r = -0.46) and clay content (r= -0.51) meaning that as MWD increased both silt and clay percentages decreased (Table 3.4). The relationship between MWD and sand content is also shown in (Figure 3.5 and 3.10). The negative relationship between MWD and silt content and MWD and clay content are also shown in (Figure 3.5 and 3.9) and (Figure 3.5 and 3.8), respectively. This means there is weak aggregation in the soil as the clay percentage is low and sand percentage is high. Tisdall and Oades (1982) and Hassink (1997) proposed the concept that organic matter addition to soils results first in the formation of SOM associations with clay and silt particles and with micro-aggregates and that macro-aggregates formation starts if the SOM binding capacity of the clay and silt fraction is saturate. Hassink (1997) examined the relationship between SOM fractions and soil texture and found a relationship between the silt and clay-associated C and soil texture, no correlation was found between sand and amount of C. Based on these findings, he defined the capacity of soil to preserve C by its association with silt and clay particles. Sand-associated C accounted for the majority of total soil C. Given this dominance of sand-associated C and its greater sensitivity to cultivation than silt and clay associated C (Cambardella and Elliott, 1992), in which C is transported from the sand fraction to the silt and clay fractions during decomposition (Guggenberger *et al*., 1994), a loss of silt and clay associated C upon cultivation is likely to be minimal. Cultivation causes the release of C by breaking up the aggregate structure, thus increasing availability of C for the tomato crop. More specifically, cultivation leads to a loss of C-rich macro-aggregates and an increase of C-depleted micro-aggregates (Elliott, 1986; Six *et al*., 2000). The enhanced protection of SOM by aggregates in less disturbed soil results in an accumulation of more labile C than would be maintained in a disturbed soil (Crews and Rumsey, 2017).

In this study, penetrative resistance (PR) ranged from 21.80-31.64 kg/cm^2. This might be because of heavy machinery used during tomato production and the soil compaction inhibits root growth, which in turn reduces tomato production (Abu-Hamdeh, 2003). Soil compaction is mostly caused by natural processes and the use of heavy equipment during soil cultivation (Grzesiak, 2009). Compaction refers to pressed soil particles caused by applied forces, reducing the pore space, and increasing the soil density (Odey, 2018). A study by Souza *et al*. (2021) found average PR values between 28.55-142.76 kg/cm^2 in the cultivated soil caused by heavy machinery and equipment used during cultivation.

3.7 Conclusion

This study investigated the spatial variation of soil C and other selected soil properties and the inter-relationship between soil C and other selected soil properties within the tomato production field. It can be concluded that there was wide spatial variation in the soil properties of the study area. Furthermore, from the inter-relationship results, it could be deduced that none of the considered soil properties had significant effect on soil C. This indicates that none of these properties could serve as a proxy for predicting soil C or as parameters that can assist in soil C management options. The observed spatial variation could have an implication in the optimization of tomato yield in the study area. This bids for the adoption of site-specific soil nutrient management in the area in order to optimize tomato production because over and under fertilisation would be costly for the farm. The success of this recommendation is contingent upon the ability of the farm management to measure, interpret and predict soil properties and establish their relationships to crop productivity.

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CHAPTER 4

SUMMARY AND CONCLUSIONS

This mini dissertation aimed at investigating the spatial variability of soil carbon and other selected soil properties as indicators of sustainable land management in the tomato field. The first chapter provided a general introduction with the background, problem statement, and rationale information relating to variability and sustainable land management. The second chapter provided a detailed literature review on the variability of soils properties, sources of variation, role of soil management on sustainable agriculture and soil carbon and its inter-relationship with other soil properties. The third chapter looked at the spatial variability of the soil properties and how they influence each other at Mooketsi ZZ2 farm in Limpopo Province, South Africa. The objectives of the study were (i) to determine the spatial variation of soil carbon (C) and other selected soil properties within tomato production field and (ii) to investigate the inter-relationship between soil C and the selected soil properties within the tomato production field. To achieve these objectives, a detailed soil survey was conducted, whereby systematic soil sampling strategy was carried out where one sample was collected every 40 m using an auger. A handheld Global Positioning System (GPS) was used to record the geographical coordinates, the latitude, and the longitude of where each sample was taken, this was used to create spatial variability maps. A handheld cone penetrometer was used to determine the penetrative resistance (PR) of the soil before soil samples were collected. Soil samples were collected on a 23-hectare field and the total number of samples collected was 132. Three pits were dug to a limiting layer and soil classification was done and master horizons demarcated. The collected soil samples were analysed for physical and chemical soil properties such as particle size distribution, aggregate stability, soil pH, electrical conductivity, soil organic carbon and soil extractable phosphorus. Soil colour was also determined for the collected soil samples. The relationship between soil properties was determined by correlation and the results showed that SOC had a positive relationship with silt content and a negative relationship with sand content, this is because finer particles like silt can store and hold onto cations as they are less porous. However, sandy soils tend to lose nutrients due to being porous and having lack of binding particles. In this study there was no significant correlation between SOC and clay content because Glenrosa soil type has low clay content in the topsoil. The positive relationship between clay content and silt content with EC might be because, finer particles have more negatively charged sites that can hold onto the cations. The negative relationship between EC and sand content might be because, sandy soils tend to have low organic matter levels. MWD had positive relationship with sand and a negative relationship with both silt and clay, and this is in correspondence with the Glenrosa soil type found within the field as it has weak soil aggregates to support crop productivity. Spatial variability maps and semivariograms were created, and they showed wide variation in soil properties. These maps showed that EC had the highest variation, followed by silt, clay, SOC, and extractable P and the least variation was in the PR, pH (KCl) and sand. The spatial dependence results showed that pH (KCl), EC and clay had weak spatial dependence, MWD, silt, and sand had moderate spatial dependence, SOC, extractable P and PR all had a strong spatial dependence. It can be concluded that there was wide spatial variation in the soil properties of the study area. Furthermore, from the inter-relationship results, it could be deduced that none of the considered soil properties had significant effect on soil C. This indicates that none of these properties could serve as a proxy for predicting soil C or as parameters that can assist in soil C management options. The observed spatial variation could have an implication in the optimization of tomato yield in the study area. This bids for the adoption of site-specific soil nutrient management in the area to optimize tomato production because over and under fertilisation would be costly for the farm.

APPENDICES

Appendix 1: Results of soil organic carbon (SOC) content %

Sample	%SOC	Sample	%SOC	Sample	%SOC	Sample	%SOC	Sample	%SOC
Z01	1,17	Z28	2,11	Z55	2,06	P28	1,45	P55	3,17
Z02	2,34	Z29	2,02	Z56	1,36	P29	0,89	P56	0,66
Z03	2,59	Z30	2,17	Z57	1,77	P30	0,30	P57	1,34
Z04	2,34	Z31	1,66	Z58	1,30	P31	0,98	P58	1,23
Z05	2,59	Z32	1,93	Z59	0,81	P32	1,15	P59	0,23
Z06	0,58	Z33	1,81	Z60	1,74	P33	1,62	P60	1,08
Z07	0,60	Z34	2,02	Z61	2,02	P34	0,66	P61	0,81
Z08	2,02	Z35	2,51	Z62	2,02	P35	0,81	P62	0,98
Z09	1,96	Z36	2,28	Z63	1,28	P36	1,32	P63	1,57
Z10	2,04	Z37	2,40	Z64	2,36	P37	0,45	P64	1,11
Z11	1,83	Z38	2,49	Z65	1,83	P38	1,17	P65	0,94
Z12	1,64	Z39	1,94	Z67	0,66	P39	0,19	P66	1,25
Z13	1,60	Z40	2,17	Z68	2,38	P40	1,00	P67	2,21
Z14	2,11	Z41	1,79	Z69	2,10	P41	1,85	P68	0,66
Z15	2,27	Z42	1,87	Z70	2,36	P42	1,40	P69	0,11
Z16	2,15	Z43	1,96	Z71	2,02	P43	0,76	P70	0,92
Z17	2,15	Z44	1,70	Z72	1,64	P44	0,70	P71	0,62
Z18	2,02	Z45	1,74	Z73	1,66	P45	0,81	P72	1,40
Z19	1,76	Z46	1,81	Z74	1,47	P46	1,06	P73	0,94
Z20	1,40	Z47	1,76	Z75	1,81	P47	1,13	P74	1,04
Z21	1,45	Z48	2,40	P21	1,45	P48	1,09	P75	1,17
Z22	1,64	Z49	2,61	P22	1,89	P49	1,57	P76	1,32
Z23	1,96	Z50	2,11	P23	1,64	P50	1,42	P77	1,08
Z24	1,26	Z51	2,42	P24	1,93	P51	1,93	P78	0,28
Z25	1,93	Z52	1,59	P25	1,04	P52	1,08		
Z26	2,02	Z53	1,83	P26	1,49	P53	1,83		
Z27	1,74	Z54	2,25	P27	1,76	P54	1,19		

Appendix 2A: Particle size distribution results in percentage (clay, silt and sand)

Sample	%Clay	%Silt	%Sand	Sample	%Clay	%Silt	%Sand
Z01	20	28	52	Z28	10	18	72
Z02	20	30	50	Z29	10	18	72
Z03	18	32	50	Z30	14	28	58
Z04	16	28	56	Z31	10	20	70
Z05	14	28	58	Z32	18	34	48
Z06	10	18	72	Z33	18	28	54
Z07	8	12	80	Z34	4	34	62
Z08	4	16	80	Z35	18	28	54
Z09	6	16	78	Z36	14	28	58
Z10	16	22	62	Z37	28	38	34
Z11	18	30	52	Z38	16	28	56
Z12	24	38	38	Z39	14	20	66
Z13	18	34	48	Z40	12	18	70
Z14	20	40	40	Z41	10	20	70
Z15	24	38	38	Z42	10	16	74
Z16	16	22	62	Z43	12	20	68
Z17	6	12	82	Z44	10	28	62
Z18	8	16	76	Z45	14	8	78
Z19	8	10	82	Z46	12	10	78
Z20	4	8	88	Z47	6	12	82
Z21	16	28	56	Z48	14	16	70
Z22	16	28	56	Z49	12	20	68
Z23	18	24	58	Z50	10	12	78
Z24	18	28	54	Z51	8	14	78
Z25	14	28	58	Z52	10	16	74
Z26	20	36	44	Z53	22	38	40
Z27	14	24	62	Z54	18	28	54

Appendix 2B: Particle size distribution results in percentage (clay, silt and sand)

Sample	%Clay	%Silt	%Sand	Sample	%Clay	%Silt	%Sand
Z55	16	22	62	P28	14,16	17,28	68,56
Z56	6	10	84	P29	12,16	19,28	68,56
Z57	8	18	74	P30	14,16	17,28	68,56
Z58	8	14	78	P31	18,16	23,28	58,56
Z59	8	12	80	P32	12,16	9,28	78,56
Z60	8	16	76	P33	16,16	21,28	62,56
Z61	10	18	72	P34	14,16	17,28	68,56
Z62	12	24	64	P35	16,16	21,28	62,56
Z63	10	18	72	P36	20,16	27,28	52,56
Z64	16	24	60	P37	10,16	7,28	82,56
Z65	6	10	84	P38	8,16	7,28	84,56
Z67	12	8	80	P39	8,16	9,28	82,56
Z68	2	8	90	P40	4,16	7,28	88,56
Z69	2	8	90	P41	10,16	17,28	72,56
Z70	8	16	76	P42	6,16	13,28	80,56
Z71	4	14	82	P43	12,16	11,28	76,56
Z72	8	18	74	P44	14,16	17,28	68,56
Z73	8	12	80	P45	12,16	17,28	70,56
Z74	8	8	84	P46	10,16	9,28	80,56
Z75	8	12	80	P47	10,16	17,28	72,56
P21	20,16	29,28	50,56	P48	14,16	9,28	76,56
P22	16,16	27,28	56,56	P49	10,16	17,28	72,56
P23	20,16	29,28	50,56	P50	14,16	19,28	66,56
P24	18,16	27,28	54,56	P51	6,16	1,28	92,56
P25	10,16	7,28	82,56	P52	12,16	15,28	72,56
P26	12,16	17,28	70,56	P53	8,16	7,28	84,56
P27	10,16	15,28	74,56	P54	14,16	15,28	70,56

Appendix 2C: Particle size distribution results in percentage (clay, silt and sand)

Sample	%Clay	%Silt	%Sand	Sample	%Clay	%Silt	%Sand
P55	10,16	11,28	78,56	P67	4,16	5,28	90,56
P56	10,16	13,28	76,56	P68	6,16	7,28	86,56
P57	16,16	9,28	74,56	P69	8,16	7,28	84,56
P58	10,16	9,28	80,56	P70	8,16	7,28	84,56
P59	10,16	13,28	76,56	P71	2,16	1,28	96,56
P60	10,16	15,28	74,56	P72	10,16	9,28	80,56
P61	6,16	9,28	84,56	P73	10,16	11,28	78,56
P62	6,16	9,28	84,56	P74	12,16	13,28	74,56
P63	16,16	17,28	66,56	P75	8,16	11,28	80,56
P64	12,16	13,28	74,56	P76	2,16	1,28	96,56
P65	6,16	7,28	86,56	P77	2,16	1,28	96,56
P66	8,16	11,28	80,56	P78	16,16	7,28	76,56

Appendix 3A: Soil pH and EC (µS/cm) results

Sample	**KCl**	**H_2O**	**EC (µS/cm)**	**Sample**	**KCl**	**H_2O**	**EC (µS/cm)**	**Sample**
Z01	6,24	5,83	353,4	Z27	6,19	5,31	271,2	Z53
Z02	6,24	5,89	265,0	Z28	6,20	5,38	604,1	Z54
Z03	6,21	5,51	533,2	Z29	6,21	5,79	217,7	Z55
Z04	6,23	5,49	508,6	Z30	6,22	5,62	220,2	Z56
Z05	6,24	5,42	673,1	Z31	6,14	5,37	223,6	Z57
Z06	6,22	5,48	210,6	Z32	6,26	5,84	416,1	Z58
Z07	6,22	5,79	347,2	Z33	6,22	5,49	1649,0	Z59
Z08	6,22	5,37	152,6	Z34	6,21	5,80	331,5	Z60
Z09	6,25	5,36	250,2	Z35	6,22	5,41	379,6	Z61
Z10	6,30	5,66	297,9	Z36	6,23	5,43	371,0	Z62
Z11	6,29	5,76	271,3	Z37	6,27	5,94	354,1	Z63
Z12	6,23	5,41	437,5	Z38	6,20	5,41	313,3	Z64
Z13	6,18	5,83	516,0	Z39	6,25	5,93	449,4	Z65
Z14	5,73	5,87	342,9	Z40	5,75	5,77	259,9	Z67
Z15	6,22	5,75	423,2	Z41	6,20	6,07	243,2	Z68
Z16	6,20	5,40	205,2	Z42	6,20	5,78	422,5	Z69
Z17	6,20	5,67	275,7	Z43	6,23	5,73	328,3	Z70
Z18	6,10	5,88	205,9	Z44	6,22	5,86	364,6	Z71
Z19	6,25	5,82	220,8	Z45	5,73	5,65	195,7	Z72
Z20	6,06	5,81	246,3	Z46	6,22	5,58	658,4	Z73
Z21	6,20	5,82	243,0	Z47	6,21	5,71	573,3	Z74
Z22	6,25	5,44	385,7	Z48	6,25	5,66	233,6	Z75
Z23	6,30	5,88	455,4	Z49	6,27	5,99	345,9	
Z24	6,18	5,41	240,1	Z50	6,21	5,75	460,0	
Z25	6,26	5,28	187,2	Z51	5,76	5,44	173,2	
Z26	6,21	5,47	286,4	Z52	6,21	5,77	182,6	

Appendix 3B: Soil pH and EC (μS/cm) results

Sample	KCl	H_2O	EC (μS/cm)	Sample	KCl	H_2O	EC (μS/cm)
Z53	6,23	5,63	235,2	P21	7,33	8,15	368,0
Z54	6,21	5,55	259,4	P22	8,06	8,45	778
Z55	6,22	5,69	411,2	P23	5,98	8,38	634
Z56	6,22	5,41	188,9	P24	5,97	8,12	452
Z57	6,43	5,89	171,7	P25	7,66	8,36	359
Z58	6,35	5,43	198,5	P26	7,27	8,10	327
Z59	6,38	5,96	157,2	P27	7,58	8,47	306
Z60	6,31	5,93	215,8	P28	6,02	8,25	371
Z61	6,35	5,95	193,9	P29	7,54	8,19	280
Z62	6,40	5,60	219,9	P30	7,58	8,42	398
Z63	6,42	6,03	159,7	P31	7,17	8,03	311
Z64	6,46	5,85	285,6	P32	7,39	7,98	440
Z65	6,28	6,02	158,7	P33	7,14	7,91	314
Z67	6,35	5,46	243,4	P34	6,01	8,14	261
Z68	6,18	5,82	211,8	P35	6,02	8,36	338
Z69	6,18	5,60	175,5	P36	6,04	8,00	228
Z70	6,27	5,44	260,0	P37	5,98	8,35	181
Z71	5,76	5,76	193,1	P38	6,00	8,20	188
Z72	6,38	5,86	176,2	P39	6,04	8,79	176,0
Z73	6,50	5,92	149,4	P40	5,98	8,23	127.2
Z74	6,51	5,55	156,4				
Z75	6,27	5,91	179,9				

Appendix 3C: Soil pH and EC (µS/cm) results

Sample	KCl	H_2O	EC (µS/cm)	Sample	KCl	H_2O	EC (µS/cm)
P41	6,00	7,76	223,8	P61	6,38	5,90	176,2
P42	5,94	8,05	191,8	P62	6,23	5,93	149,4
P43	6,05	8,27	190,5	P63	6,22	5,91	175,0
P44	6,02	7,95	276,9	P64	6,37	5,86	150,8
P45	6,08	8,20	248,1	P65	6,50	5,80	238,7
P46	7,27	7,92	240,9	P66	6,38	5,92	138,5
P47	7,28	8,19	260,5	P67	6,33	5,88	312,4
P48	7,10	8,03	225,0	P68	6,31	5,92	474,3
P49	7,25	7,85	333,7	P69	6,41	5,50	205,4
P50	6,55	5,96	281,1	P70	6,31	5,92	153,6
P51	8,01	8,60	352,0	P71	6,15	5,92	180,5
P52	6,42	5,98	172,3	P72	6,40	5,93	206,5
P53	7,63	8,32	267,1	P73	6,40	5,85	217,4
P54	6,45	5,90	175,6	P74	6,52	5,93	224,8
P55	6,51	5,88	207,5	P75	6,33	5,84	150,6
P56	6,37	5,94	240,2	P76	6,44	5,86	175,4
P57	6,55	5,95	248,2	P77	6,40	5,94	130,0
P58	6,34	6,01	145,3	P78	6,36	5,94	165,6
P59	6,40	5,88	794,2				
P60	6,43	5,95	312,6				

Appendix 4: Aggregate stability results by mean weight diameter (mm)

Sample	MWD	Sample	MWD	Sample	MWD	Sample	MWD	Sample	MWD
Z01	1,34	Z28	1,29	Z55	1,12	P28	0,95	P54	1,29
Z02	1,27	Z29	1,56	Z56	1,66	P29	0,81	P55	1,53
Z03	0,94	Z30	1,49	Z57	1,49	P30	0,99	P56	1,25
Z04	1,17	Z31	1,34	Z58	1,07	P31	0,87	P57	0,84
Z05	1,65	Z32	1,17	Z59	1,04	P32	0,97	P58	1,28
Z06	1,09	Z33	1,52	Z60	1,29	P33	0,78	P59	1,06
Z07	1,50	Z34	1,27	Z61	1,22	P34	0,82	P60	0,91
Z08	1,57	Z35	1,22	Z62	1,25	P35	0,68	P61	1,27
Z09	1,54	Z36	1,68	Z63	1,40	P36	0,78	P62	1,52
Z10	1,22	Z37	1,38	Z64	1,32	P37	1,04	P63	0,97
Z11	0,76	Z38	1,15	Z65	1,57	P38	0,99	P64	1,20
Z12	0,64	Z39	1,06	Z67	1,77	P39	1,05	P65	1,15
Z13	0,57	Z40	0,94	Z68	1,48	P40	1,40	P66	1,48
Z14	0,62	Z41	0,95	Z69	1,70	P41	0,93	P67	1,67
Z15	0,70	Z42	1,21	Z70	1,73	P42	1,16	P68	1,60
Z16	0,81	Z43	0,94	Z71	1,51	P43	1,15	P69	1,54
Z17	0,86	Z44	0,74	Z72	1,39	P44	1,12	P70	1,82
Z18	0,97	Z45	0,93	Z73	1,29	P45	1,08	P71	1,65
Z19	1,43	Z46	0,86	Z74	1,58	P46	1,50	P72	1,42
Z20	1,71	Z47	1,87	Z75	1,24	P47	1,20	P73	1,42
Z21	0,64	Z48	0,79	P21	1,41	P48	1,27	P74	1,57
Z22	0,58	Z49	0,98	P22	1,03	P49	1,29	P75	1,45
Z23	0,68	Z50	1,11	P23	1,09	P50	1,52	P76	1,40
Z24	0,82	Z51	1,09	P24	0,92	P51	1,46	P77	1,70
Z25	0,81	Z52	1,20	P25	0,95	P52	1,39	P78	1,13
Z26	0,76	Z53	1,10	P26	0,93	P53	1,43		
Z27	0,95	Z54	1,22	P27	0,90				

Appendix 5: Results of extractable phosphorus in (mg/kg)

Sample	Extractable P (mg/kg)	Sample	Extractable P (mg/kg)	Sample	Extractable P (mg/kg)	Sample	Extractable P (mg/kg)	Sample	Extractable P (mg/kg)
Z01	1,60	Z28	0,99	Z55	1,19	P28	1,62	P55	1,98
Z02	1,62	Z29	1,47	Z56	1,34	P29	2,25	P56	2,60
Z03	1,57	Z30	1,05	Z57	1,27	P30	2,25	P57	1,86
Z04	1,38	Z31	1,58	Z58	1,82	P31	2,40	P58	2,30
Z05	1,50	Z32	2,57	Z59	1,13	P32	1,63	P59	1,82
Z06	1,77	Z33	1,44	Z60	1,40	P33	1,09	P60	3,24
Z07	1,93	Z34	2,00	Z61	1,27	P34	2,26	P61	2,57
Z08	1,39	Z35	1,82	Z62	1,41	P35	2,40	P62	1,99
Z09	1,43	Z36	1,88	Z63	1,33	P36	1,35	P63	2,28
Z10	1,33	Z37	1,34	Z64	1,23	P37	0,95	P64	1,13
Z11	1,29	Z38	1,28	Z65	1,69	P38	1,11	P65	1,57
Z12	1,49	Z39	1,25	Z67	1,61	P39	1,76	P66	1,95
Z13	1,33	Z40	1,85	Z68	1,90	P40	1,28	P67	1,74
Z14	1,32	Z41	2,37	Z69	1,60	P41	2,01	P68	1,73
Z15	1,25	Z42	1,19	Z70	1,37	P42	1,83	P69	1,49
Z16	0,96	Z43	1,15	Z71	1,43	P43	1,68	P70	1,83
Z17	0,93	Z44	0,91	Z72	1,84	P44	1,39	P71	2,50
Z18	0,85	Z45	1,61	Z73	1,36	P45	2,26	P72	2,39
Z19	1,35	Z46	1,56	Z74	1,08	P46	1,36	P73	1,83
Z20	1,43	Z47	1,42	Z75	1,05	P47	2,42	P74	2,18
Z21	1,09	Z48	1,35	P21	2,68	P48	2,41	P75	2,75
Z22	1,17	Z49	1,87	P22	2,65	P49	2,39	P76	1,05
Z23	0,85	Z50	0,91	P23	1,76	P50	1,98	P77	1,18
Z24	1,38	Z51	1,46	P24	2,93	P51	1,90	P78	1,59
Z25	1,19	Z52	1,70	P25	0,37	P52	2,40		
Z26	1,36	Z53	2,04	P26	1,74	P53	1,75		
Z27	1,48	Z54	1,71	P27	2,55	P54	2,11		

Appendix 6A: Results of penetrative resistance in (kg/cm^2)

Sample	PR(kg/cm2)	Sample	PR (kg/cm2)	Sample	PR (kg/cm2)	Sample	PR (kg/cm2)
Z01	27,42	Z23	25,66	Z45	26,01	Z68	28,65
Z02	27,95	Z24	28,65	Z46	28,65	Z69	29,18
Z03	29,88	Z25	29,53	Z47	29,35	Z70	28,30
Z04	21,80	Z26	30,23	Z48	28,91	Z71	29,88
Z05	28,12	Z27	30,58	Z49	28,30	Z72	29,53
Z06	29,88	Z28	30,67	Z50	27,24	Z73	29,53
Z07	29,53	Z29	28,12	Z51	28,12	Z74	29,00
Z08	28,83	Z30	29,53	Z52	27,60	Z75	28,83
Z09	30,58	Z31	27,42	Z53	27,60		
Z10	29,18	Z32	31,64	Z54	27,42		
Z11	30,76	Z33	29,70	Z55	28,65		
Z12	28,47	Z34	28,83	Z56	26,19		
Z13	29,88	Z35	29,00	Z57	28,12		
Z14	27,07	Z36	27,33	Z58	29,88		
Z15	25,66	Z37	28,47	Z59	29,53		
Z16	26,72	Z38	29,88	Z60	30,94		
Z17	27,60	Z39	29,53	Z61	28,47		
Z18	29,88	Z40	28,12	Z62	29,53		
Z19	28,65	Z41	28,47	Z63	30,23		
Z20	28,47	Z42	29,35	Z64	29,53		
Z21	26,37	Z43	29,88	Z65	30,58		
Z22	27,77	Z44	28,12	Z67	27,60		

Appendix 6B: Results of penetrative resistance in (kg/cm^2)

Sample	PR (kg/cm2)	Sample	PR (kg/cm2)	Sample	PR (kg/cm2)
P21	27,42	P43	30,58	P65	27,60
P22	28,65	P44	26,01	P66	28,65
P23	26,19	P45	28,65	P67	29,18
P24	28,12	P46	29,35	P68	28,30
P25	29,88	P47	28,91	P69	29,88
P26	29,53	P48	28,30	P70	29,53
P27	30,94	P49	27,24	P71	29,53
P28	28,47	P50	28,12	P72	29,00
P29	29,53	P51	27,60	P73	28,83
P30	30,23	P52	27,60	P74	27,60
P31	27,95	P53	27,42	P75	29,88
P32	29,88	P54	28,65	P76	28,65
P33	30,94	P55	26,19	P77	28,47
P34	28,47	P56	28,12	P78	29,88
P35	27,42	P57	29,88		
P36	27,95	P58	29,53		
P37	29,88	P59	30,94		
P38	21,80	P60	28,47		
P39	28,12	P61	29,53		
P40	29,88	P62	30,23		
P41	29,53	P63	29,53		
P42	28,83	P64	30,58		