ASSESSING LAND CAPABILITY, SOIL SUITABILITY AND FERTILITY STATUS FOR SUSTAINABLE BANANA PRODUCTION AT MAKULEKE FARM

BY

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DECLARATION

I, Swafo Seome Michael, hereby declare that, to the best of my knowledge, the work presented in this dissertation entitled “Assessing Land Capability, Soil Suitability and Fertility Status for Sustainable Banana Production at Makuleke Farm” is my original and that it has never been presented by anyone in any academic institution for the award of Master of Science in Agriculture in Soil Science or any other academic qualification. This dissertation does not contain other persons’ data, pictures, graphs, or other information (e.g., texts, tables, etc.) unless specifically acknowledged as being sourced from other persons. The ideas of other authors or scholars cited in this document have been profusely acknowledged.

14/02/2023

Mr. Swafo SM (Candidate) Date

I as the candidate’s supervisor have/have not approved this dissertation for submission.

Prof. Dlamini PE (Supervisor) Date

DEDICATION

This work is modestly and respectfully dedicated to the Almighty God the provider of all things. To my beloved parents (Mr. Andries Masebakela Swafo and Mrs. Julia Mahlasela Swafo (Late)), my brothers (Mr. Phineas Segogela Swafo and Mr. David Mambutla Swafo) and sisters (Miss Anna Matibe Swafo and Miss Jostina Mmatlala Swafo), and everyone contributed to the success of this work.

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ABSTRACT

In South Africa, land use planning has received limited attention in areas perceived as suitable for agricultural production. In the lack of reliable soil type and fertility status information, crop yields remain lower than the land's potential, with subsequent land degradation. Despite this, studies that focused on land capability and soil suitability to date have not considered the spatial variability of the soil nutrients and factors influencing their variability. However, this information is key for site-specific soil management. Therefore, it is vital to link land capability and soi suitability with the spatial variability of soil nutrients as it opens opportunities for more rational management of the soil resources since soil nutrients directly affect crop growth and consequently yield.

To address this issue, a study was conducted on a 12 ha banana plantation portion of the Makuleke farm. The main objectives of this study were to (1) survey, classify and characterise soils in order to derive and map land capability classes of Makuleke farm, (2) quantify the physical and chemical properties of the soils in order to derive and map the soil suitability of Makuleke farm for banana production, (3) assess the spatial variability and structure of soil nutrients across the Makuleke farm and (4) Identify the factors of control of the spatial variability of the soil nutrients across the Makuleke farm.

To begin with, a field soil survey was conducted using transect walks complemented by auger observations to sub-divide the 12 ha banana plantation portion of the farm into varied soil mapping units. Thereafter, soil classification was done to group soils based on their morphological properties and pedological processes. During soil classification, a total of 12 representative profile pits (1.5 m × 1.5 m long × 2 m deep/limiting layer) were excavated, studied, described, and sampled. At each profile pit, three replicates samples were collected at 0 – 30 cm depth intervals giving rise to 36 bulk soil samples. From the gathered soil profile information, four soil units were thus delineated and identified across the 12 ha banana plantation. For soil fertility assessment, a grid sampling strategy at 50 × 50 m was adopted to collect the samples across the 12 ha banana plantation. A total of 27 composite samples were collected at the nodes of the grid, and thereafter bagged, labelled, and transported to the laboratory. In the laboratory, all collected samples were air-dried and sieved using a 2 mm sieve in preparation for soil physical and chemical properties analysis.

The land capability assessment of Makuleke farm was done using the concepts and principles of the FAO framework for Land Evaluation (FAO, 1976), but adapted to South African conditions by Smith (2006). Soil suitability assessment was done using the FAO framework for Land Evaluation (FAO, 1976) coupled with the guidelines for rainfed agriculture (FAO, 1983) and the criteria proposed by Sys *et al.* (1993) and Naidu *et al.* (2006). To assess the spatial variability and structure of the soil nutrients across the farm, classical and geostatistical techniques were employed respectively. A correlation matrix was employed to identify key factors influencing the spatial variability of soil nutrients across the farm. For interpolation, ordinary kriging was used to generate soil nutrient spatial distribution maps.

In this study, four soil forms were identified and classified as Hutton, Westleigh, Glenrosa, and Valsrivier, which are broadly distinguished as Lixisols, Plinthosols, Leptosols, and Cambisols. Land capability results revealed that 17% of the 12 ha portion of the farm has very high arable potential (I), 60% of the farm has medium arable potential (III), 6% has low arable potential (IV) and 17 % is non-arable (VI), which might explain the varied banana yields in the farm. Soil suitability analysis revealed that 12% of the 12 ha farm is highly suitable (S1), 34% is moderately suitable (S2), 38% is marginally suitable (S3) and 16% is permanently not suitable (N2) for banana production. The low arable and marginally suitable portion of the farm was under Valsrivier soils which were limited by its shallow depth, shallow rooting depth, acidic soil pH, low organic carbon (OC), and the fact that it was located on a steeper slope gradient. The non-arable and not suitable portion of the farm for banana production was under Glenrosa and it was limited by its location on a steep slope gradient and was characterised by shallow effective rooting depth, low OC, low clay content, and acidic soil pH.

Classical statistical techniques revealed that phosphorus (P), potassium (K), calcium (Ca), zinc (Zn), manganese (Mn), and copper (Cu) content varied highly across the banana plantation, while magnesium (Mg) and total nitrogen (TN) varied moderately. In addition, the geostatistical analysis revealed that spatial dependency was weak (Ca, Cu, and TN), moderate (Mg and Zn), and strong (P, K, and Mn) for the different soil nutrients across the 12 ha banana plantation. Soil nutrients with strong spatial dependency have a good spatial structure and are easily manageable (in terms of fertilisation, liming, and irrigation) across the farm compared to the ones with weak spatial dependency which have a poor structure. This study also found that land attributes, which are soil type and topographic position were the main factors driving the spatial variability of the soil nutrients across the farm. In terms of soil type, soils such as Valsrivier and Glenrosa with 2:1 clay-type smectite were the ones that had nutrient content compared to soils with 1:1 clay-type kaolinite (e.g., Westleigh and Hutton). Higher nutrient contents were also observed in the footslope position compared to the middleslope of the farmland. Correlation analysis revealed that Mn was the key polyvalent cation influencing the spatial variability of P, K, and Zn. Soil pH and effective cation exchanges capacity (ECEC) were the key soil factors driving the spatial variability of Ca, while ECEC was the key factor affecting the spatial variability of Mg. Moreover, the spatial variability of soil Mn and Cu was driven by soil Cu and clay content, respectively. The kriged maps showed that P, Mg, Zn, and Mn were high in the northeast part and low in the northwest part of the farm. Similarly, K and Ca were low in the northwest part, but they were high in the south to the southwest part of the study area. Total nitrogen was high in the west part and low in the east-northeast part, while Cu was evenly distributed across the plantation.

This study highlights the importance of prior land use planning (i.e., land capability and soil suitability) and fertility assessment for agricultural production. The research results obtained provide the actual reference state of the capability of the land for arable farming and soil suitability for banana production at Makuleke farm. Moreover, the research results provide the spatial variability and structure of the soil nutrients which have a greater impact on the growth and yield of bananas. The results obtained in this study will be useful for site-specific management of soil nutrients and other soil management practices (e.g., irrigation, fertilisation, liming, etc.), developing appropriate land use plans, and quantifying anthropogenic impacts on the soil system and thus improving land productivity.

Keywords: Land use planning, Land evaluation, Land capability classification, Soil suitability assessment, Soil spatial variability, Soil nutrients, Classical statistics, Geostatistics, Factors of control, Ordinary kriging, GIS

CHAPTER 1: GENERAL INTRODUCTION

1.1. Background

South Africa (SA) is currently in its rebuilding phase from the economic shocks of Covid-19 (Sihlobo, 2021). Agriculture is the one sector of the economy that maintained positive growth momentum in 2020 into 2021, which policymakers identified as part of the sectors to drive economic recovery and job creation (Sihlobo, 2021). The agricultural sector is central to fostering economic growth, reducing poverty, and improving food security in the country (Greyling, 2012). However, the sector is faced with numerous challenges, which include but are not limited to low soil fertility, limited land resource base, and inappropriate agricultural practices that consequently lead to soil degradation (Sikuka, 2019). Despite that most soils in SA are extremely prone to degradation and have low recovery potential, it is estimated that 12% of the soil is fertile and about 3% is regarded to have potential for agricultural production (Goldblatt and von Bormann, 2010). Degraded and less productive soils progressively hinder the ability of SA to feed its growing population and sustain livelihoods (Hoffman and Ashwell, 2001).

One of the major challenges is to sustainably use the land to feed and sustain the burgeoning population (Barnard *et al.*, 2000). Accordingly, there is a need to maintain and increase agricultural productivity in order to meet the increasing population pressure on arable land that fosters soil degradation, which threatens food production, especially in smallholder farming systems (Nziguheba *et al.*, 2021). In recent times, there has been growing interest in better managing soils to underpin food security (Scholes and Biggs, 2004). As such, the need for reliable soil information to support agricultural decision making has never been greater (Manderson and Palmer, 2006). Improved management of soil resources and identification of the agricultural potential of soils is needed to prevent land degradation and stimulate crop production (Abd-Elmabod *et al.*, 2019).

The ability of the land to produce is limited by climate, soil and landform conditions, and the use and management applied (FAO, 1983). It is therefore vital to conduct systematic assessments of our soil resources with respect to their extent, distribution, characteristics, behavior and use potential. This is critical for establishing an effective land use system for enhancing agricultural production on a sustained basis (Getahun, and Selassie, 2017).

Knowledge of soils, their properties and spatial distribution, is indispensable for the agricultural development as it opens opportunities for a more rational management of land resources (Verdoodt and Van Ranst, 2006).

In this context, both land capability and soil suitability can be useful tools to ensure delineation of management zones aimed to improve agricultural productivity (De Feudis *et al.*, 2021). Land capability assessment is based on the inherited permanent physical properties of the land, while soil suitability is based on soil properties which have greater impact on the growth of a specific crop (Naidu *et al.*, 2006). The classification of soils on the basis of their capability and suitability is necessary to ensure sustainable food production and protection of natural resources (Deshmukh, 2016). Furthermore, the knowledge of land capability and soil suitability allows farmers and landholders to plan land uses and to develop land management practices that are able to improve crop productivity (De Feudis *et al.*, 2021).

1.2. Problem statement

Agricultural researchers, extension services, and governmental institutions continually strive to increase agricultural production, but the crop yields remain lower than the land's potential, especially in smallholder farms (Mutero *et al.*, 2016). Persistent crop cultivation with no information of location-specific inherent capabilities and limitations of soils leads to land degradation (Naidu *et al.*, 2006). Continuous degradation of the land results in nutrients loss and an overall decrease in soil fertility, which consequently contributes to a substantial decline in agricultural productivity (Goldblatt and von Bormann, 2010). Another major hindrance to agricultural production is that farmers lack a basic understanding of the spatial variation of soil properties in their fields and how they are related to soil mapping units (Abdurasak *et al.*, 2019). The variability of soils across a field is a serious source of uncertainty in agricultural production (Diacono *et al.*, 2013). This is because farmers tend to uniformly apply agricultural inputs throughout the field as if the land is homogeneous (Najafian *et al.*, 2012), ultimately resulting in certain portions of the field being undertreated or overtreated with fertiliser inputs. The inefficient application of fertilisers results in crops not getting adequate nutrients to meet their potential growth (Lark and Wheeler, 2000). Excessive application of fertilisers may also cause soil acidification and accumulation of salts, which over time lead to the degradation of the fertility status of the soil and a decline in crop yields (Goldblatt and von Bormann, 2010).

In the case of the Makuleke farm, which is currently used for banana production, the farmers have been uniformly applying cultural practices such as irrigation and fertilisation without consideration of the spatial variability of the soils across the farm. Despite investments in these field practices, yield gaps in banana production have persisted in the farm. According to H Maluleke, the land custodian (personal communication, 12 May 2021) since 2018, a banana yield of 65 tons/ha has been targeted, with only an average of 56 tons/ha obtained to date. One of the possible reasons for the below-par yields is that banana production is highly constrained by poor soil fertility (Weidmann and Kilcher, 2011). It is also probable that inconsideration of soil variability and degradation of nutrients are potentially contributing to lower and uneven distribution of banana yields at the Makuleke farm.

1.3. Rationale

A better understanding of the factors limiting crop yields may provide a solution to reducing the existing yield gaps in smallholder farms (Munialo *et al.*, 2020). The nexus between the quality of the soil and potential productivity is paramount in agriculture in pursuit of maximizing production and sustainability (Olivaries *et al.*, 2021). The assessment of the status of the soil and the capability of the land requires the proper establishment of a reference state-specific to each soil unit (Dobarco *et al.*, 2021). The intrinsic characteristics of agricultural land are chiefly related to soils, topography, and climate (Kerchof, 2016). These biophysical factors interact through land potential, which represents the ability of the land to sustainably generate ecosystem services over the long term (Kerchof, 2016).

During soil suitability assessment, more attention is given to soil characteristics because they have greater controlling capability on crops (Dharumarajan and Singh, 2014). This then gives room for the selection of suitable crops to be grown in specific locations to enhance crop productivity and reduce the negative effects brought by unsuitable crop practices (Mandal *et al.*, 2020). Furthermore, it also provides the actual limitations and potential of a specific portion of land (AbdelRahman *et al.*, 2016). This crucial information is a basic requirement for land improvement as it guides decisions on the optimal utilization of soil resources (AbdelRahman *et al.*, 2016). Matching land use with land potential is thus a prerequisite for soil suitability assessment, and as such, there is a need to assess the suitability of the soils in the Makuleke farm for the sustainable production of bananas. Proper land evaluation and subsequent generation of land capability and soil suitability maps of the farm coupled with soil nutrients maps will enable the identification of limiting factors for banana production, help farmers decide where to locate particular field activities, and thus will foster the development of judicious management practices that will enhance banana productivity (AbdelRahman *et al.*, 2016; Mazahreh *et al.*, 2019).

1.4. Purpose of the study

1.4.1. Aim

The aim of this study was to evaluate the land capability, soil suitability and fertility status of the soils of Makuleke farm for the sustainable banana production.

1.4.2. Objectives

The specific objectives of the study were to:

a) Survey, classify and characterise soils in order to derive and map land capability classes of Makuleke farm.
b) Quantify the physical and chemical properties of the soils in order to derive and map the soil suitability of Makuleke farm for banana production.
c) Assess the spatial variability and structure of soil nutrients across the Makuleke farm.
d) Identify the factors controlling the spatial variability of the soil nutrients across the Makuleke farm.

1.4.3. Research questions

The study seeks to address the following questions:

a) What is the actual capability of the land for agricultural production at Makuleke farm?
b) How suitable are the soils for banana production?
c) How spatially variable and structured are the soil nutrients?

d) What are the factors of control of the soil nutrients across the farm?

1.5. Dissertation structure

This mini-dissertation is organised into five chapters. Chapter one provides background on the status of South African soils and their management, and how land capability, soil suitability and fertility assessment can contribute to sustainable use of the soil resource for sustained crop productivity. Chapter two provides a detailed literature review on land use planning and evaluation and provides synopsis of each activity involved in the land evaluation process. Chapter three addresses the first two research questions, which entail information on the characteristics of the soils and their capability for arable agriculture and their limitations, and the suitability of each soil for growing banana and the limitations associated with each particular soil. Chapter four addresses the last two research questions (three and four), by describing the spatially variability and structure, and the influential factors of the soil nutrients across the farm. Chapter five gives a summary, conclusion and recommendations of the findings of this study.

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CHAPTER 2: LITERATURE REVIEW

2.1. Sustainable management and use of soils

Soil provides essential services for agricultural production, plant growth, animal habitation, biodiversity, carbon sequestration, and environmental protection, which are crucial for achieving the United Nations' Sustainable Development Goals (SDGs) (Fig. 2.1) (Hou *et al.*, 2020). The soil is a finite resource, and many countries are at risk of losing this resource, due to inappropriate practices and resulting from lack of knowledge (Pozza and Field, 2020). South Africa among many other countries fails to adopt sustainable soil management practices (SSM), compromising crucial soil ecosystem services (IPCC, 2019; Thorsøe *et al.*, 2019). In SA, sustainable soil management practices have received little attention at the national level (Thorsøe *et al.*, 2019).

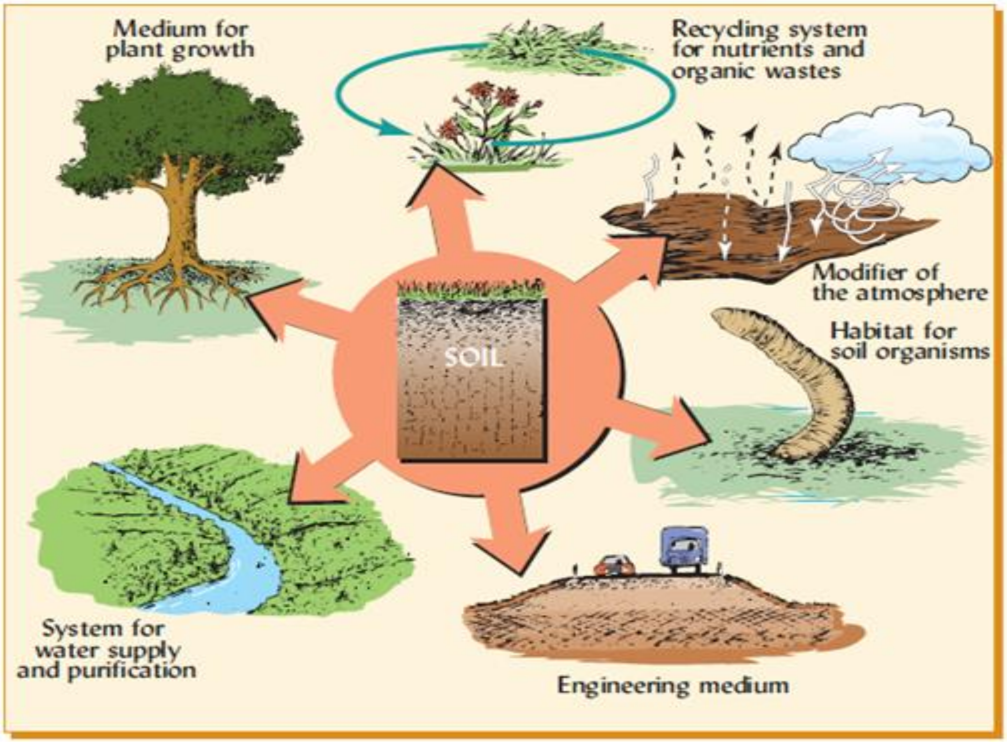

Fig. 2.1. Six important ecological roles of the numerous functions and ecosystem services performed by the soil (Source: Brady and Weil, 2013).

To achieve the SDGs that are linked to the soil resource (Fig. 2.2) by the target date of 2030, soils may need to be utilised and managed more sustainably (Hou *et al.*, 2020). In agricultural landscapes, soil management should deploy production practices that are compatible with soil-mediated ecosystem functions if they are to deliver a broad range of ecosystem services (Lal and Stewart, 2013). The term "sustainable use of soil" refers to a management system that preserves the natural fertility of the soil and allows for the long-term production of food, fiber supplies, and renewable natural resources (De Wrachien, 2001). This ensures that mineral elements do not become deficient or toxic to plants and that appropriate mineral elements enter the food chain (White *et al.*, 2012). By this concept, the natural environment is treated and managed so as to consider, preserve, or restore the cycles and energy fluxes that exist among soil, water, and atmosphere (De Wrachien, 2001). Therefore, to effectively use agricultural land sustainably, innovative management systems that provide multiple ecosystem services must be implemented on lands that differ in their inherent characteristics (Liebig *et al.*, 2017). Understanding the soil resource is pivotal to our ability to use, manage and modify soils effectively and responsibly (Manderson and Palmer, 2006).

2.2. Soil survey in land use planning

Agricultural sustainability requires proper land management, for which soil survey and land use planning play an indispensable role (Landon 2014; Ballabio *et al.*, 2018). Soil survey is a process of describing the characteristics of the soils, classifying them, mapping them, and making predictions about their behaviour (USDA, 1993; Landon, 2014). It involves grouping soils with regard to their spatial location, profile characteristics, relationships to one another, suitability for various purposes, and needs for particular types of management (Brewer, 2011). Soil surveys provide a source of information and an inventory of soil parameters of an area of interest assisting land users to make accurate predictions for the response of a specific land to a certain use (Yu *et al.*, 2014).

Soil surveys take into consideration the current use of the soils and their responses to different management practices (Landon, 2014). Therefore, a soil survey can help to assess various aspects of soil characteristics (Yu *et al.*, 2014). The data requirement during field surveys is linked to the specific objectives of the study and the types of land use under inspection (Shepande, 2002). The type of soil survey adopted may differ depending on the purpose of the survey, the type, and the intensity of field examination (Fig. 2.3) (Young, 1973). The objectives of most soil survey investigations are to provide data for rational planning and adjustment of land use (Hubrechts *et al.*, 2004).

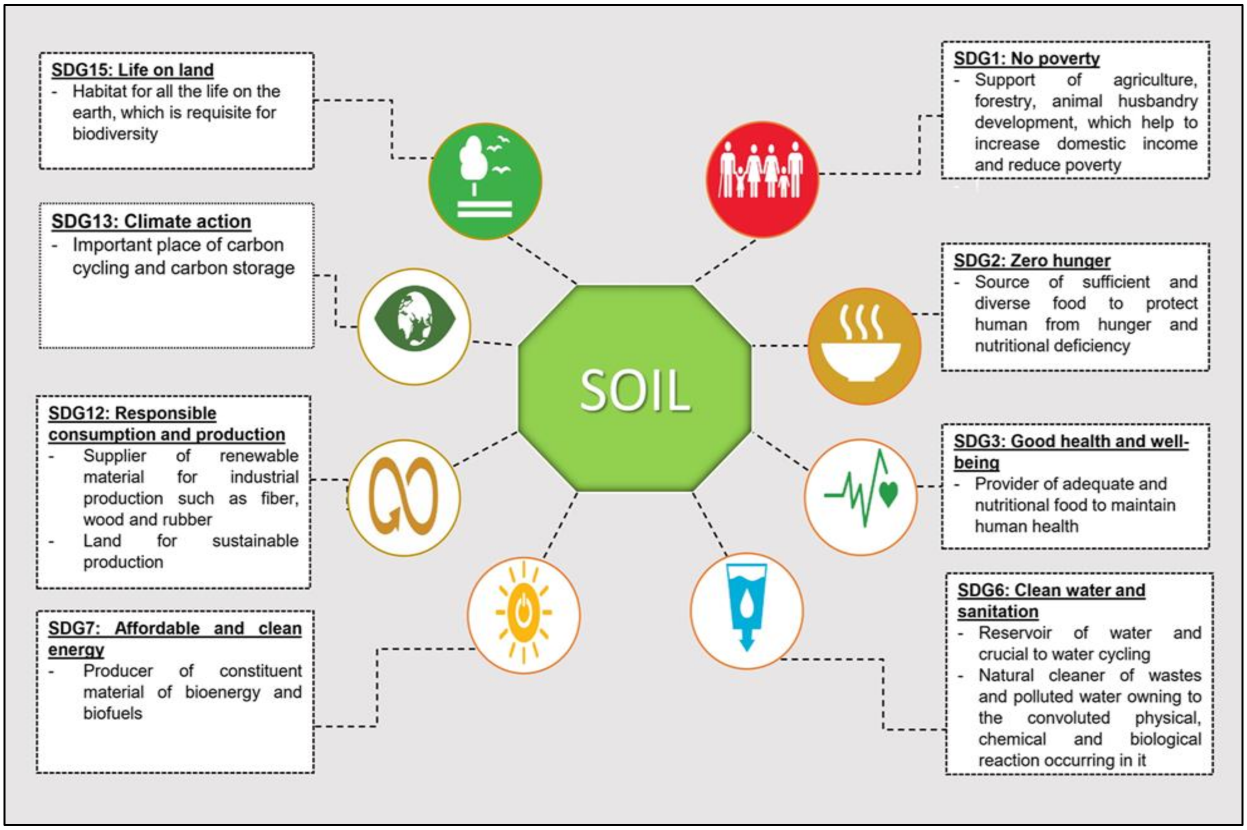

Fig. 2.2. The applicability of soil to the United Nations' Sustainable Development Goals (SDGs).

Soil surveys strive for simplifying the complex distribution of soil by providing a framework within which inter-relationships can be instituted (Nortcliff, 1988). These interrelationships between soils and soil properties are used to make interpretations of the uses to which the land may be put, either directly or by establishing further sets of relationships between the soil properties and other use-related properties (Nortcliff, 1988). Therefore, soil surveys provide the information needed for land use management and land use planning (Deckers *et al.*, 2002). The information obtained from soil surveys helps in the development of land use plans and evaluates and predicts the effects of land use on the environment (Shepande, 2002). Non-utilization of soil survey data has resulted in soil-related problems like nutrient depletion, compaction, flooding, and poor yield (Layzell and Mandel, 2019). Soil surveys provide the only currently available, economically reasonable way of gathering information about the soil component of land (Nortcliff, 1988). Therefore, it is a significant component in the overall process of land evaluation (Nortcliff, 1988).

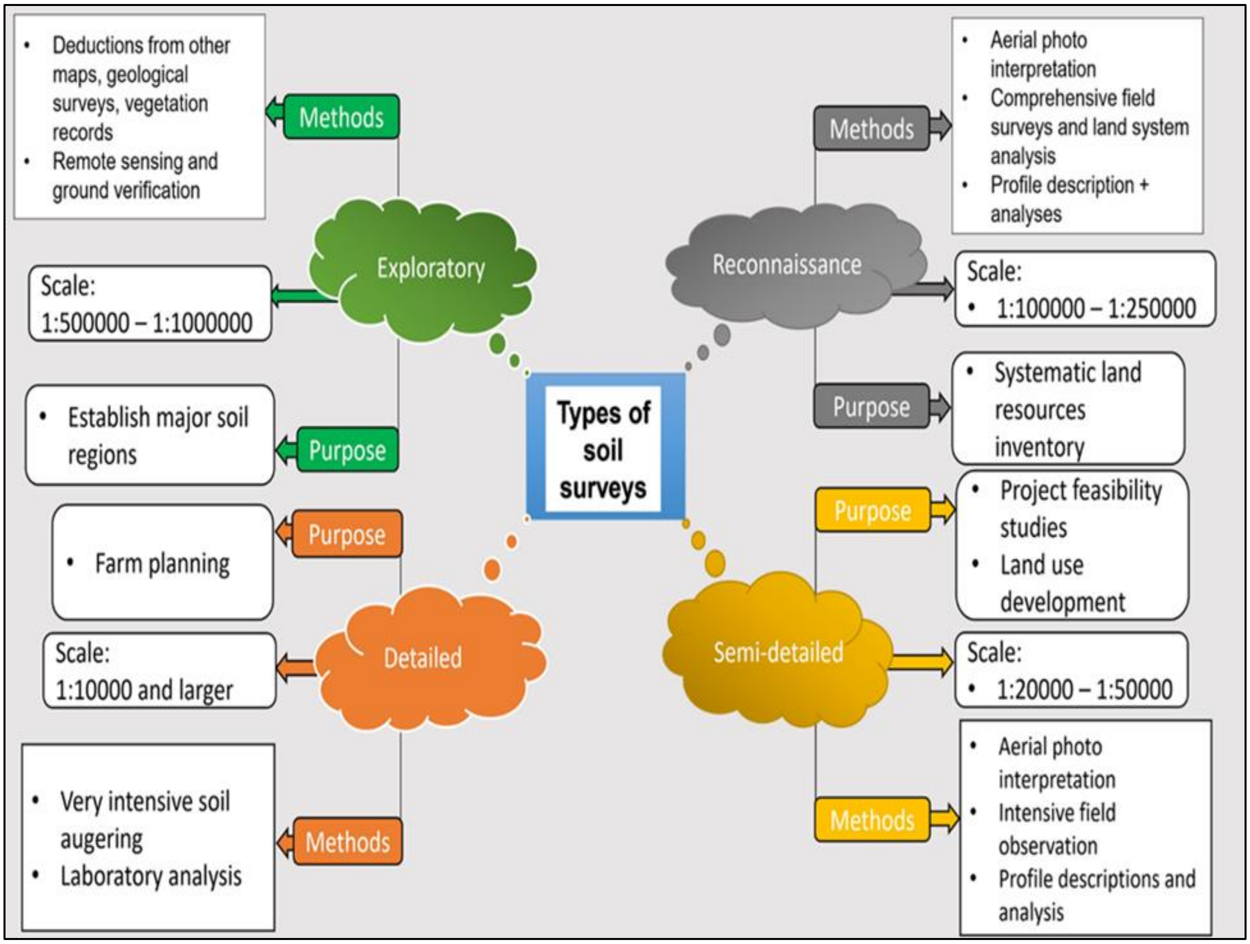

Fig. 2.3. Soil survey types, purpose and methods involved in each soil survey type. Adapted from Dent and Young, (1981).

2.2.1. Soil characterisation and classification

The need for more information about the soil as a means for sustainable use and proper conservation has continuously demanded soil characterisation and classification (Osujieke *et al.*, 2018). Soil characterisation is defined as the systematic arrangement of soils into groups or categories based on their characteristics (Osujieke *et al.*, 2018). It provides the basic information vital to make classification schemes and evaluating soil fertility to solve some unique soil problems (i.e., soil compaction, erosion, water logging, soil acidification, and nutrient loss) in an ecosystem (Lekwa *et al.*, 2004). Consequently, improve our understanding of the physical, chemical, mineralogical and microbiological properties of the soils (Ogunkunle, 2005). Soil characterisation data serve as a basis for a more detailed evaluation of the soil (Ogunkunle, 2005). This helps to gather nutrient information, and physical or other limitations needed to produce a capability class. Thus, soil characterisation is fundamental for decision-making regarding crop productivity and the determination of the intrinsic potential of the soils to resist degradation by raindrops and runoff (Schoenholtza *et al.*, 2000).

Soil classification is the grouping of soils based on their properties, soil-forming processes, and factors (Nortcliff, 1988). The benefit of a good classification scheme is that it permits relationships to be identified among discrete soils and among classes of soils, which is of value in the organisation of soil information (Nortcliff, 1988). This helps to facilitate the transfer of experience and technology from place to place and helps to compare soil properties (Sharu *et al.*, 2013). As such, soil classification is expressly significant when predicting the behaviour of soils, identifying the most suitable use, forecasting their productivity, and extrapolating the knowledge and experience gained at one location to other relatively little-known locations (Nortcliff, 1988). In essence, the characterisation and classification of soils at a specific location aid in generating soil and soil-related information which is functional in the sustained use of the soil resource (Sharu *et al.*, 2013). The linking of soil characterisation, classification, and mapping contributes a powerful resource for the benefit of mankind particularly for food security and environmental sustainability (Sharu *et al.*, 2013).

2.3. Land use planning

The best use options of land require comprehensive and accurate characterisations of soil, climate, and other environmental factors influencing the sustainability of agricultural enterprises (Budak, 2018). Land use planning is the systematic assessment of land potential and alternatives for optimal land uses (FAO, 1993). The driving force in planning is the need for change, as well as the need for improved management, or the need for a quite different pattern of land use dictated by changing circumstances (Bunning and De Pauw, 2017). Land use planning can be viewed as an iterative and continuous process whose aim is to make the best use of land resources by assessing present and future needs and evaluating the land's availability to meet them (Dent, 1991). This helps decision-makers and land users in selecting and putting into practice land use that will best meet the needs of people while at the same time protecting natural resources and ecosystem services for current and future generations (FAO, 1993). The tools and methods for land use planning used at appropriate scales should encourage and assist the diverse and frequently competing users of land resources in selecting land use and management options that increase their productivity, support sustainable agriculture and food systems, promote governance over land and water resources and meet the needs of society (FAO, 1976). Rational land use planning is required to find a balance among different land-use demands and to ensure agricultural production while conserving the natural environment (De Wrachien, 2003). The most important part of land use planning entails a systematic land evaluation process (FAO, 1976).

2.4. Land evaluation

Land evaluation is a systematic process of identifying and measuring land qualities and assessing them for alternative use with quality of land, thereby assessing the value of each type of land present for each land use (Dent and Young, 1981). It involves the execution and interpretation of basic surveys of climate, soils, vegetation, and other aspects of land in terms of the requirements of alternative forms of land use (FAO, 1983). The range of land uses considered must be limited to those which are relevant within the physical, social, and economic context of the area considered (FAO, 1993). Land evaluation generates data on the potential and constraints of land for a defined land-use type in terms of crop performance as affected by the physical environment (Ramamurthy, 2020). This allows for the management of the identified limiting factors to suit crop requirements and improve productivity (AbdelRahaman *et al.*, 2016). Thus, land evaluation enables management guidelines to advance more sustainable use of the soil and environmental resources (Maniyunda *et al.*, 2007). Notably, the land evaluation does not determine the usage of the land but provides data through which land-use decisions and alternatives can be taken (Ofem, 2016). Two components guide land evaluation which is the land capability and soil suitability assessment.

2.4.1. Land capability assessment

Land capability is the intensive safe use of an area and its management requirements and permanent hazards (FAO, 1976). It refers to the potential of land to support several predefined land use in a built-descending arrangement of suitability (i.e., arable crops, pasture, woodland, and recreation/wildlife) (Fig. 2.4) (Beek *et al.*, 1997). The land becomes suited for fewer major land uses if the capability of land decreases from capability class I (No or few limitations, very high arable potential, and very low erosion hazard) to VIII (Extremely severe limitations, not suitable for grazing or afforestation) (Fig. 2.4). Land capability systems can identify the capacity of the area for different uses and the optimal use from a biophysical, as opposed to a social and economic perspective (Brown *et al.*, 2018). The land capability of an area is the combination of intrinsic soil properties and climatic conditions (Brown *et al.*, 2018). It also includes other landscape features such as drainage patterns and slopes, which hinder agricultural land use (FAO, 1993). Land capability is assessed by comparing the characteristics of a land mapping unit with critical limits set for each capability class (Beek *et al.*, 1997).

There are eight land capability classes. Capability classes I – IV are for agriculture or planting crops (FAO, 1976). These first four classes are distinguished from each other based on the extent of a slope, erosion, depth, structure, soil reaction, and drainage (AbdelRahman *et al.*, 2016). They are grouped based on their potential and limitations for sustained production of the prevalently grown crops (Verdoodt and Van Ranst, 2003). Classes V-VII are more suited to growing grasses, forestry, and supporting wildlife (Smith, 2006), while class VIII is for conservation. These last four classes are differentiated based on problems like streamflow, flooding, ponding, rocky nature, short growing season, and snow cover (AbdelRahman *et al.*, 2016). This classification system based on land capability aids in estimating soil resources available for multiple purposes and appropriate use of soils without deterioration (AbdelRahman *et al.*, 2016). Land capability classification enhances land use planning in the sense that it helps balance the need for agricultural land against urban development or forest against agriculture or pasture (Beek *et al.*, 1997). Therefore, the capability classes can give a reasonable basis for land use planning and land resource utilization (FAO, 1993). Land capability classification gives a general idea about the capability of the soils but does not explain specific crop performance (Mandikan *et al.*, 2013).

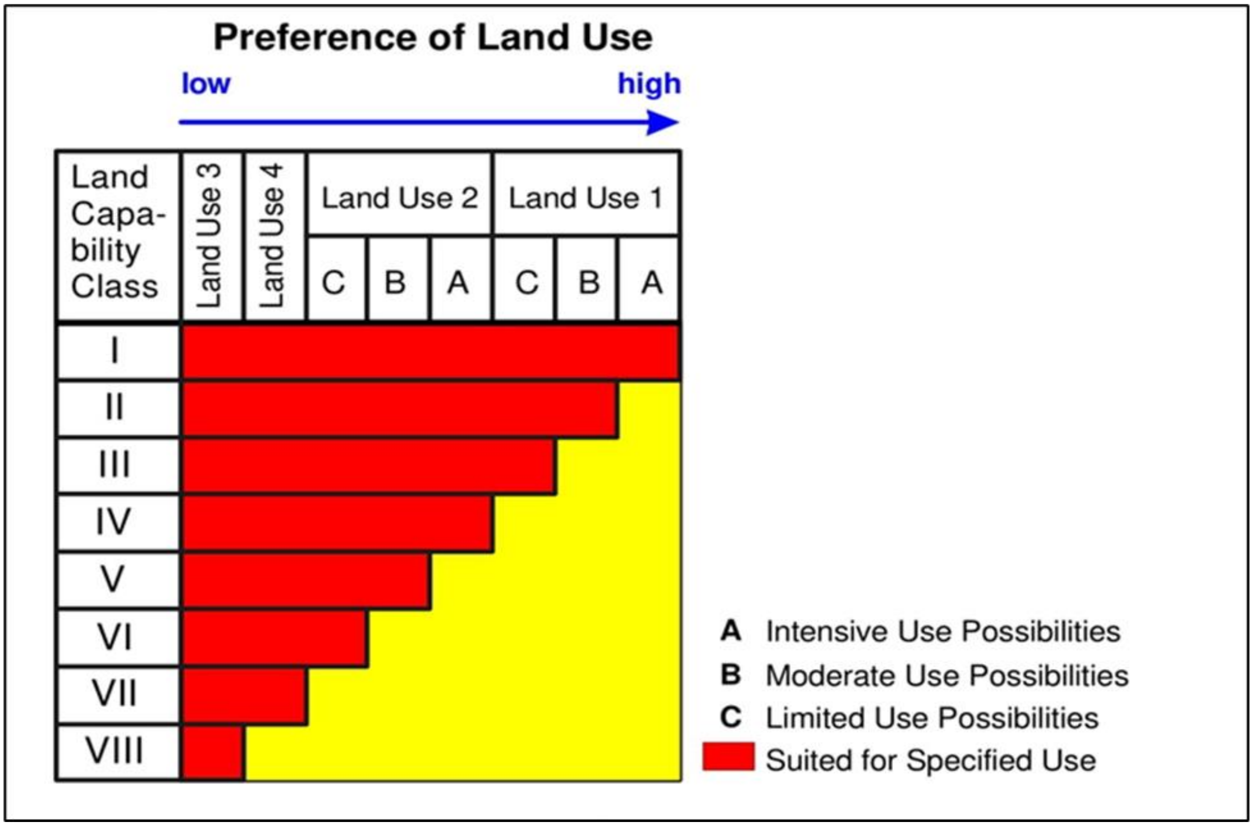

Fig. 2.4. Broad framework of a land capability classification system (Source: Beek *et al.*, 1997).

2.4.2. Land and soil suitability assessment

Land suitability classification is the appraisal and grouping of specific regions of land in terms of their suitability for defined uses (FAO, 1983). Its evaluation gives information on the constraints and alternatives for the use of the land (Mazahreh *et al.*, 2019). Therefore, it provides guideline decisions on the optimal utilisation of resources, whose knowledge is an essential prerequisite for land use planning and development (AbdelRahman *et al.*, 2016). In the agricultural context, land suitability evaluation enables the identification of the major limiting factors for agricultural production and allows decision-makers, land users, land-use planners, and agricultural support services to develop crop management able to overcome such constraints (AbdelRahman *et al.*, 2016; Ofem, 2016). However, each crop species requires specific soil and climatic conditions for its optimum growth (Sekhar *et al.*, 2018). Soil suitability classification describes how well soil conditions match crop requirements under a defined input and management regime (FAO, 1976). In soil suitability assessment, more prominence is placed on several crucial soil properties (e.g., nutrient availability and soil texture, organic carbon (OC), pH, and electrical conductivity (EC)) owing to their greater impact on cropping systems (Naidu *et al.*, 2006). Information about the suitability of soil types for various crops is vital to agricultural scientists so that they encourage farmers to choose the most suitable type of crop for a particular soil.

2.5. Soil spatial variability

Soil properties vary at different spatial scales primarily due to heterogeneity of intrinsic factors (e.g., soil texture and mineralogy) and extrinsic factors such as soil management (Mulla and McBratney *et al.*, 2002). Spatial variability and distribution of soil properties within agricultural fields can be classified as static due to soil formation processes or dynamic caused by various land management practices (Mulla, 2016). A range of static and dynamic soil properties which vary across agricultural fields contribute to varying crop yields (Jabro *et al.*, 2010). The variability of soil properties in space presents a challenge for site assessment and the detection of changes within or among sites (Boone *et al.*, 1999). Therefore, studies focusing on the spatial variability of the physicochemical properties of soil are essential. They are of great importance for improving the accuracy of soil surveys, mapping, and enhancing the efficiency of soil nutrient management (Boone *et al.*, 1999). Information on soil variable properties is important for the evaluation of agricultural land, as well as the selection of fertiliser rates, frequency, and methods of application and for soil management (Mulla, 2016). An understanding of the spatial distribution of soil properties and their mapping is critical for site-specific soil management through variable-rate nutrient application for sustainable crop production (Bogunovic *et al.*, 2017). Therefore, to determine the best soil management practices and amendments to increase crop quantity and quality while being environmentally sustainable, it is necessary to assess the spatial variability of the physical and chemical properties of soils and crop yields across a field (Gajda *et al.*, 2016).

The variability of soil properties within fields is often described by traditional statistical methods, which assume that variation is randomly distributed within mapping units (Khan *et al.*, 2019). It is assessed using classical descriptive statistics such as mean, range, standard deviation, and coefficient of variation. However, detailed soil variability is often not accounted for in traditional statistical methods (Jabro *et al.*, 2010). Geostatistical methods, based on the theory of regionalised variables, are more useful tools for describing and understanding the spatial variability of measured variables compared to traditional statistical methods (Oliver and Webster, 2014). In geostatistics, the variability of soil properties is assessed using semivariograms, autocorrelation, cross semivariogram, kriged, and co-kriged maps (Jabro *et al.*, 2010).

2.6. Soil fertility

Soil fertility can be defined as a measure of the soil's ability to sustain satisfactory crop growth, both in the short and longer-term, and is determined by a set of interactions between the soil's physical environment, chemical environment, and biological activity (Brady and Weil, 2008). Various plants have different needs for essential nutrients and different tolerances to toxic elements (Singh and Singh, 2016). As such, soil fertility is plant specific. The lack of essential nutrients in the soil causes deficiencies in plants, and their excess leads to toxicities, which have negative impacts on crop yields (Chimonyo, 2020). Depleted soil nutrients and soil degradation have been implicated as contributing factors to the decrease in crop yields and per capita food production (Henao and Baananke, 2006). Thus, assessing soil fertility is thus crucial in achieving optimum conditions for plant growth.

2.7. Soil traditional and digital mapping

Soil mapping is the process of demarcating natural soil bodies, classifying and grouping the separated soils into map units, and recording soil characteristic information for interpretation and representation of soil spatial distribution on the map (Soil survey staff, 2016). There are two approaches to mapping the soils: traditional soil mapping and digital soil mapping (DSM). Traditional soil mapping is based on the soil mapping unit. A soil map unit is a collection of areas defined and named the same in terms of their soil components (e.g., soil form, slope, texture) (Brewer, 2011). This unit is considered a separate spatial object that separates areas of the earth's surface with similar physical and chemical properties (Dobos *et al.*, 2006). Soils are grouped into mapping units because soils cannot be mapped at the scale at which they occur. Soil map units aid in the construction of boundaries when developing a soil map.

Digital soil mapping (DSM) is the computer-assisted creation of digital maps of soil types and characteristics using mathematical and statistical models that combine information from soil observations with correlated environment variables and information from remote sensing images (Dobos *et al.*, 2016). This approach is becoming essential due to the reduction of time-consuming and costly field surveys that are no longer affordable for soil surveys (Behrens and Scholten, 2006). The growing demand for spatial information has encouraged the application of DSM strategies to obtain reliable soil maps (Chabrillat *et al.*, 2019). Digital soil maps are used to analyse spatial soil structures, and to simulate the spatial variation of soil properties (Burrough, 1991). The quantitative estimation of the spatial variability of soil is important for an improved understanding of the complex relationships between soil properties and environmental factors (Mammadov *et al.*, 2021). This complexity includes intrinsic and extrinsic factors (Heuvelink and Webster, 2001) varying depending on topography, climate, vegetation, and anthropogenic activity all of which significantly affect the spatial variability of soil properties (Shi *et al.*, 2009). Information about the distribution of the natural resources of a country is vital for a wide range of purposes, including local and regional planning, economic forecasting, food security, and environmental protection (Paterson *et al.*, 2015).

2.8. Role of geostatistics and geographic information system in land use planning

Geostatistics is a branch of applied statistics that quantifies the spatial dependence and spatial structure of a measured property (Mulla and McBratney *et al.*, 2002). It uses the spatial structure to predict values of the measured at unsampled locations (Oliver and Webster, 2014). It is achieved through spatial modeling and spatial interpolation. There are various Interpolation methods which include but are not limited to inverse distance weighting, bilinear interpolation, and nearest-neighbor interpolation (Oliver and Webster, 2014). A geographic information system (GIS) is a system designed to capture, store, analyse, and manage data and associated attributes, which are spatially linked to the earth (Grimshaw, 1994). It enables users to develop interactive queries, analyse spatial information, edit data, and maps, and present the output of all these operations (Rosa and Diepen, 2002).

Using geostatistical techniques and GIS in land evaluation leads to the rapid development of thematic maps, and area estimates and allows various analytical operations to be carried out (Faturoti *et al.*, 2015). Recently, advancement in GIS coupled with a wide range of geostatistical tools is providing newer dimensions to address challenges associated with site suitability analysis (Bhagat *et al.*, 2009; Choudhury *et al.*, 2013; Kumar *et al.*, 2013; Moruma *et al.*, 2016; Bal *et al.*, 2018). Agricultural planners use GIS data to decide on the best locations for location-specific crop planning (FAO, 1993). This is achieved by integrating data on soils, topography, and rainfall to determine the size and location of suitable areas. Therefore, GIS is well suited as a tool to aid land resources appraisal by identifying parcels of land that have a given set of properties (FAO, 1993). In this regard, GIS combines data from a variety of sources including physical and socioeconomic land attributes of a given georeferenced land unit to arrive at a better decision in the evaluation (FAO, 1993). GIS techniques make it viable to collect, store, manipulate, and visualise georeferenced spatial information using thematic maps (Kumar *et al.*, 2013).

2.9. Banana production in South Africa

Banana (*Musa spp*.) is the fourth most important crop in the world after rice (*Oryza sativa L.),* maize (*Zea mays L.),* and wheat (*Triticum aestivum L.)* (Picq, 2000). Globally, around 85 million tons of bananas are produced annually (Vilijoen *et al.*, 2004). Bananas that are grown commercially are crosses between *Musea acuminata* and *Musea balbisiana* (Schulze and Maharaj, 2007). In South Africa, bananas are among the most important commercial subtropical fruits grown and are planted for sale in local markets or self-consumption and are also sold in world markets (DAFF, 2020). Bananas contributed 55% (R2.3 billion) to the total gross value of subtropical fruits (R4.2 billion) produced in South Africa during the 2018/19 marketing season (DAFF, 2020). This makes them the most important subtropical fruits grown in South Africa. However, there has been little growth in banana production over the past ten years (Fig. 2.5). This decline in banana production is principally due to the limited production areas available in South Africa where the production volume of bananas has been minimal (DAFF, 2020). Banana production in South Africa is also severely hindered by climate (DAFF, 2017). Approximately 11 360 ha of land in the country is under banana cultivation (DAFF, 2017). Mpumalanga province constitute 58 % (6600 ha), Kwa Zulu Natal 22% (2500 ha) and 20% (2260 ha) in Limpopo (DAFF, 2017).

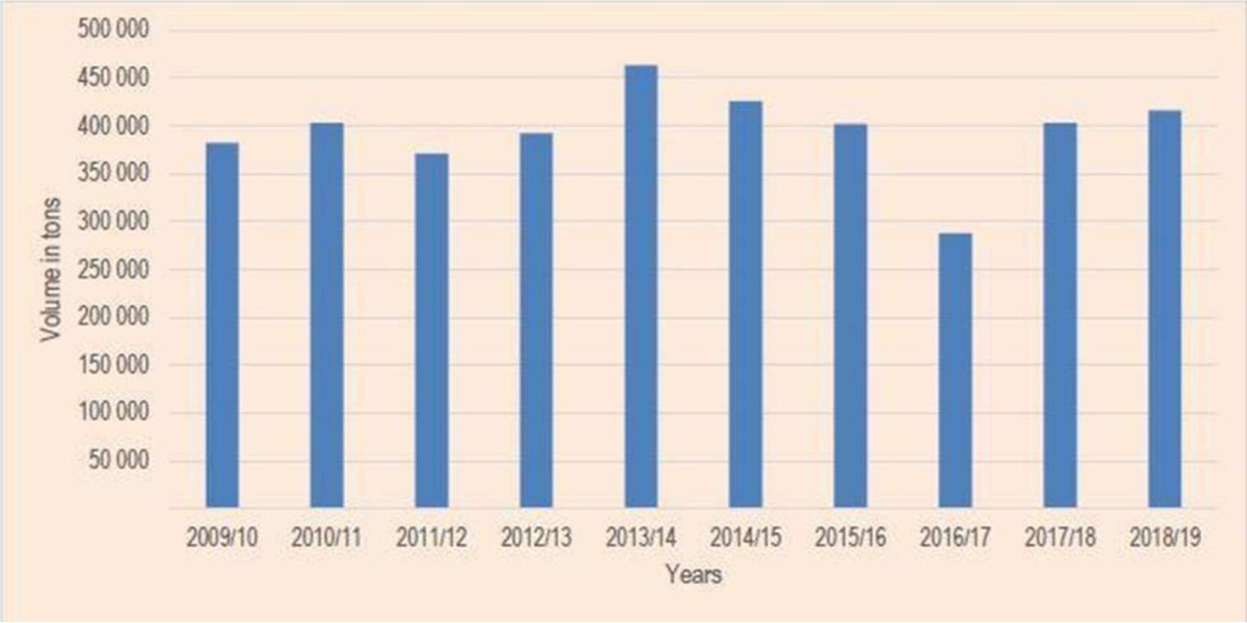

Fig. 2.5. Banana total production 2009/10 – 2018/19 (Source: DAFF, 2020).

2.10.Morphology of a banana plant

Banana is a tall plant perennial monocotyledon growing up to 9 m (Rieger, 2006). Thus, the plant is classed as an arborescent herb (Rieger, 2006). According to INIBAP (2000), the wild species of banana (*Musa ingens*) may grow up to 15 m with a circumference of 2.5 m. The above-ground part of the plant is called pseudostem (Fig. 2.6) (Schulze and Maharaj, 2007). The pseudostem has concentric layers of leaf sheaths rolled in a shape like a cylinder with a diameter ranging from 20 to 50 cm (Schulze and Maharaj, 2007). The true stem (sometimes referred to as butt) is a large underground corn (Pillay and Tripathi, 2007). The leaves of the plant originate from the meristem of the apical bud before it elongates. The meristem of the apical bud emerges through the pseudostem 10 to 15 months after planting as a large terminal inflorescence (INIBAP, 2000). The leaves of the plant emerge from the centre of the pseudostem tightly rolled in a counterclockwise spiral pattern (Rieger, 2006). The plant consists of 8 to 12 leaves, they can be up to 2.7 m in length and 0.6 m breadth at maturity (INIBAP, 2000). The plant has an adventitious root system like all monocotyledons (INIBAP, 2000). The root system of bananas can spread horizontally up to 5.5 m and in loose soils, and it can spread up to 9 m laterally (Rieger, 2006).

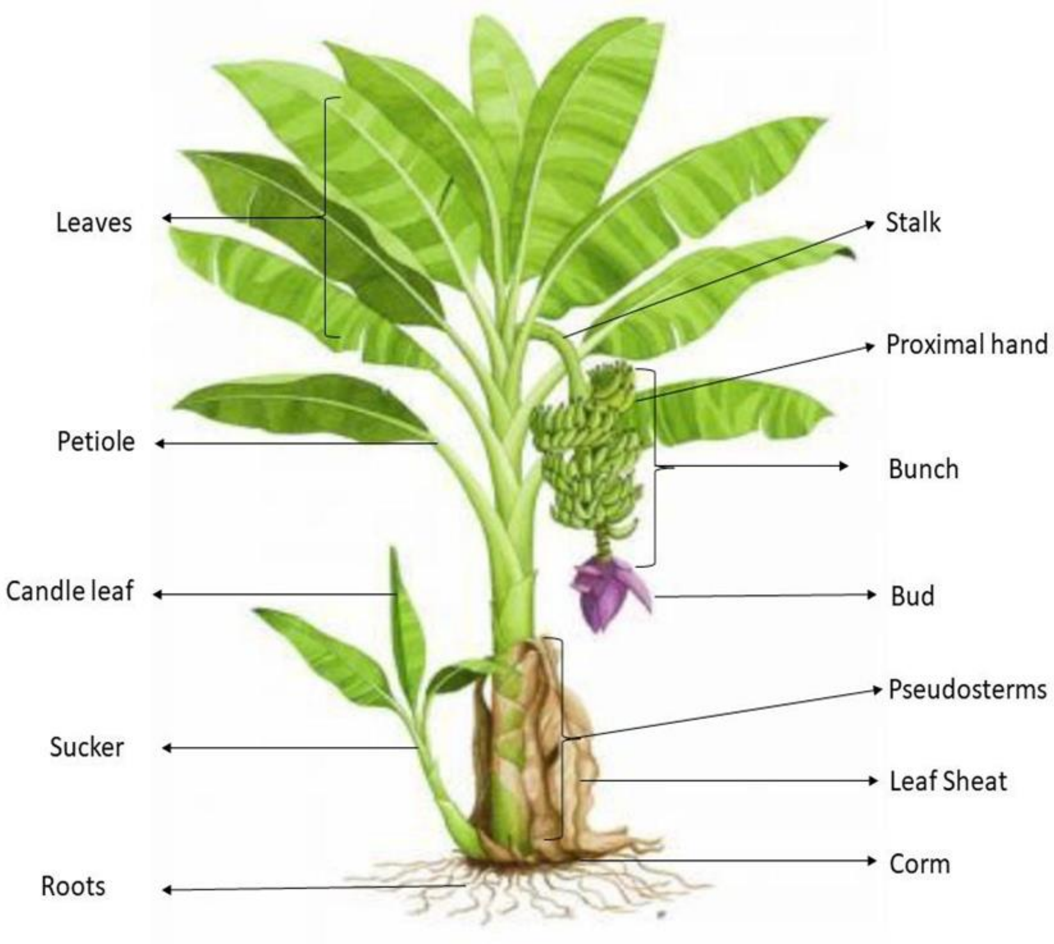

Fig. 2.6. Morphology of the banana fruit. Adapted from Repon *et al.* (2016).

2.11.Climatic requirements of banana production

Bananas grow best in humid tropical conditions but can also be produced under humid or semi-arid subtropical conditions (Reay, 2019). They grow well in areas that receive 2500 mm or more of well-distributed rainfall annually (FAO, 2018). Ideally, bananas require 125 mm of water per month, which is equivalent to 1500 mm per annum (Smith, 2006). During the banana-growing season, there should not be a period exceeding 3 months of the dry season (Reay, 2019). Bananas are prone to wind damage, and as such, they require areas that are protected from the wind (FAO, 2018). A strong wind can damage pseudostems, resulting in crop losses (Smith, 2006). Bananas require temperatures ranging from 25ºC to 35ºC for growth and yield but can be produced at a temperature range of 10 – 40ºC (Reay, 2019). Temperatures below 12ºC impede growth, and moderate growth is achieved at temperatures between 15 and 20ºC (Smith, 2006). Growth is retarded if the mean temperature of any month drops below 21ºC (Smith, 2006). The shoots and bunch development of bananas are negatively affected at a temperature that is not more than 10ºC (Reay, 2019). All growth processes stop immediately when the temperature falls below 11ºC (Reay, 2019). The suitable temperature for ripening bananas is 20 – 21ºC, with the relative humidity at 90% (Reay, 2019).

2.12.Soil requirements for banana production

Bananas can be grown in any type of soil provided that the soil is highly fertile (FAO, 2018). A well-fertilized soil plays an important role during banana cultivation because banana is a heavy nutrient feeder (DAFF, 2008). Typically, bananas grow better in high-nutrient soils (Sys, 1993). The adequate levels of N, P, and K are 1200 mg/kg, 50 – 100 mg/kg, and 300 – 350 mg/kg respectively, and the critical levels for both P and K are 20 mg/kg and 150 mg/kg, respectively (Sys, 1993). The suitable pH of the soils should be in the range of 5.5 – 7 (FAO, 2018). The best soils for bananas are those that have a clay content of 30 - 50%, contain good water retention, and are well-drained (Reay, 2019). In waterlogged soils, diseases such as Panama can occur (FAO, 2018). The soil depth optimum for bananas should be at least 0.51m in depth (Reay, 2019). The rooting depth should mostly not be above 0.75m (FAO, 2018).

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CHAPTER 3: UNLOCKING THE LAND CAPABILITY AND SOIL SUITABILITY OF MAKULEKE FARM FOR SUSTAINABLE BANANA PRODUCTION

ABSTRACT

Sub-Saharan Africa (SSA) is experiencing an increase in food insecurity, which is fueled by both high population growth and low agricultural productivity. Smallholder farmers (i.e., farmers who produce crops on a limited scale) are seriously affected by low soil fertility, land degradation, and poor agronomic management practices, which reduce crop productivity. As such, there is a huge need for reliable soil information to support agricultural decision-making in smallholder farms to ensure sustainable agricultural production. The main objectives of this study were (1) to survey, classify and characterise soils at Makuleke farm in order to derive and map the land capability classes and (2) to quantify the physical and chemical properties of the soils in order to derive and map the suitability classes. A field survey and classification of soils led by transect walks complemented by auger holes revealed existent spatial variation of soils across the 12 ha banana plantation. The dominating soil forms in the plantation were Hutton, Westleigh, Glenrosa, and Valsrivier. Land capability analysis revealed that 17% of the 12 ha portion of the farm had very high arable potential, while 60% had medium arable potential, 6% of the farm had low arable potential and 17% was considered non-arable. Subsequent soil suitability analysis revealed that 12% of the farm is highly suitable, 34% is moderately suitable, 38% is marginally suitable and 16% is permanently not suitable for banana production. The variable capability of the land and suitability of soils for banana production led to notable yield gaps. The in-depth description and quantification of the productive capacity of the land are pivotal to the farmers at Makuleke to effectively manage the soil and utilise the land resources for sustainable banana production.

Keywords: Land evaluation, Land capability, Soil suitability, Smallholder farmers, Soil spatial variability, Banana

3.1. Introduction

Food insecurity in Sub-Saharan Africa (SSA) is worsening, and it is underpinned by low crop output and high population expansion (Giller, 2020). In South Africa, smallholder agriculture has been recognised as the vehicle through which the goals of poverty and rural development can be attained (Pienaar and Traub, 2015). However, this type of farming is faced with numeral challenges, chief among which is soil degradation caused by unsustainable farming practices (Adekunle, 2014). Soil degradation is often caused by the mismatch between land use and land potential, specifically using marginal lands for agriculture (Quandt *et al.*, 2020). Moreover, the ever-increasing African population, which is directly proportional to an increase in the demand for food, makes the situation grimmer. This has consequently resulted in the active search for alternative approaches to agricultural production that not only ensure that there is enough food on the table but do so sustainably (Nciizah *et al.*, 2022).

The solution to agricultural land use problems lies in land evaluation in support of rational land use planning and appropriate and sustainable use of natural resources (Quandt *et al*., 2020). The potential of land for agricultural use is determined by an evaluation of the factors affecting land capability and suitability, such as soil characteristics and climate. The principal purpose of conducting land capability and soil suitability assessment on agricultural land is to predict the potential and limitation of land for crop production (Pan and Pan, 2012). A comprehensive soil suitability assessment incorporates informative strategic planning, in-depth spatial planning, and optimal allocation of crops (Ndwambi *et al.*, 2020). An assessment of the factors influencing the capability and suitability of the land, such as the soil quality and climate, yields essential information on the potential of the land for agricultural use (AbdelRahman *et al.*, 2016). A majority of land capability and soil suitability studies do not consider the spatial variability of the soils and their inherent properties, yet this information is crucial for resolving site or location-specific land management issues (Amara *et al.*, 2021). A thorough analysis of the soil spatial variability results in the precise derivation of land capability and soil suitability classes (De Feudis *et al.*, 2021). In light of this, gathering precise site-specific information on land and soil resources can aid in identifying the limitations and potentials of these limited resources. The objectives of this study were (1) to survey, classify and characterise soils at Makuleke farm in order to derive and map the land capability classes and (2) to quantify the physical and chemical properties of the soils in order to derive and map the soil suitability classes.

3.2. Methodology

3.2.1. Site description

The Makuleke farm (30º56’16.3” E and 22º51’31.9” S) is situated in the Collins Chabane Local Municipality, Vhembe District, Limpopo Province in South Africa (Fig. 3.1). The study was conducted in a 12 ha banana plantation portion of the farm. The farm has a humid subtropical climate with long summers and short winters characterised by rain and cool weather respectively (Hilton-Baber and Berger, 2007). The average annual temperature of the site is 21.7ºC, while the mean annual rainfall is 731 mm (Kock, 2017).

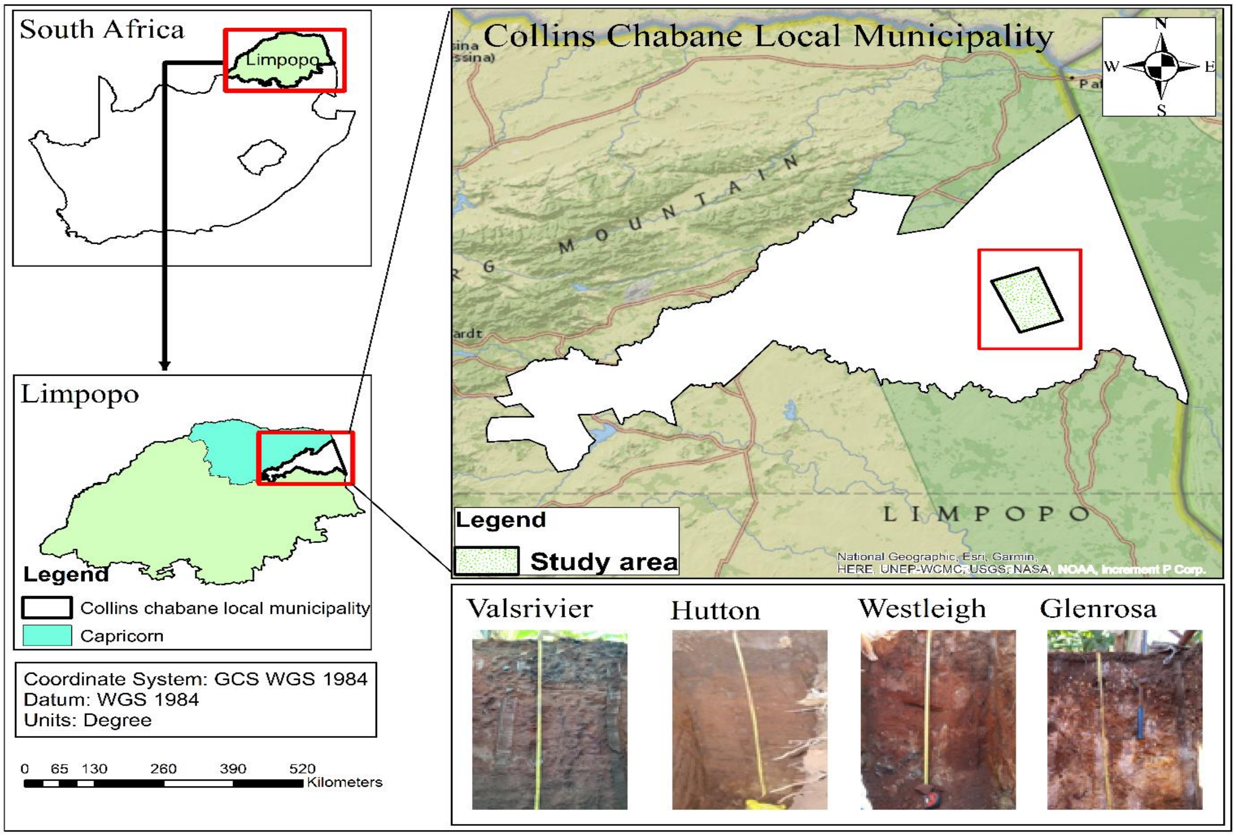

Fig. 3.1. Location of Makuleke farm in the Collins Chabane Local Municipality, Vhembe District, Limpopo province, and photographs showing the dominant soil forms in the farm.

3.2.2. Site history

The Makuleke Farm (formerly known as Makuleke Irrigation Scheme) was established in 1985. The sole purpose of the scheme was to produce food (by planting crops) and to create jobs for Makuleke community members. This led to the establishment of the Makuleke Farmers' Cooperative. The cooperative was first registered in 1991, comprising 52 farmers. The farmers were producing maize, tomatoes, and cabbage until the cooperative collapsed in 1998. It was only after the year 2000 that the farmers mobilised again to start cultivating crops. In 2007, Makuleke farm was producing maize, dry beans, and potatoes until December 2018, when they switched to banana fruit production. They switched to banana fruit because the crops (i.e., maize, dry beans, and potatoes) were not doing well and were characterised by low yield throughout the seasons. In terms of bananas, the farm can produce up to 56 tons per hectare, which is below the average target yield of tons of bananas and which is 65 tons/ha. This then led to an active search for possible reasons behind the decrement in yield and hence land evaluation was conducted at the farm. Below (Fig. 3.2.) are the various activities (in steps) involved in land evaluation and the activities are elaborated in the subtopics following one another.

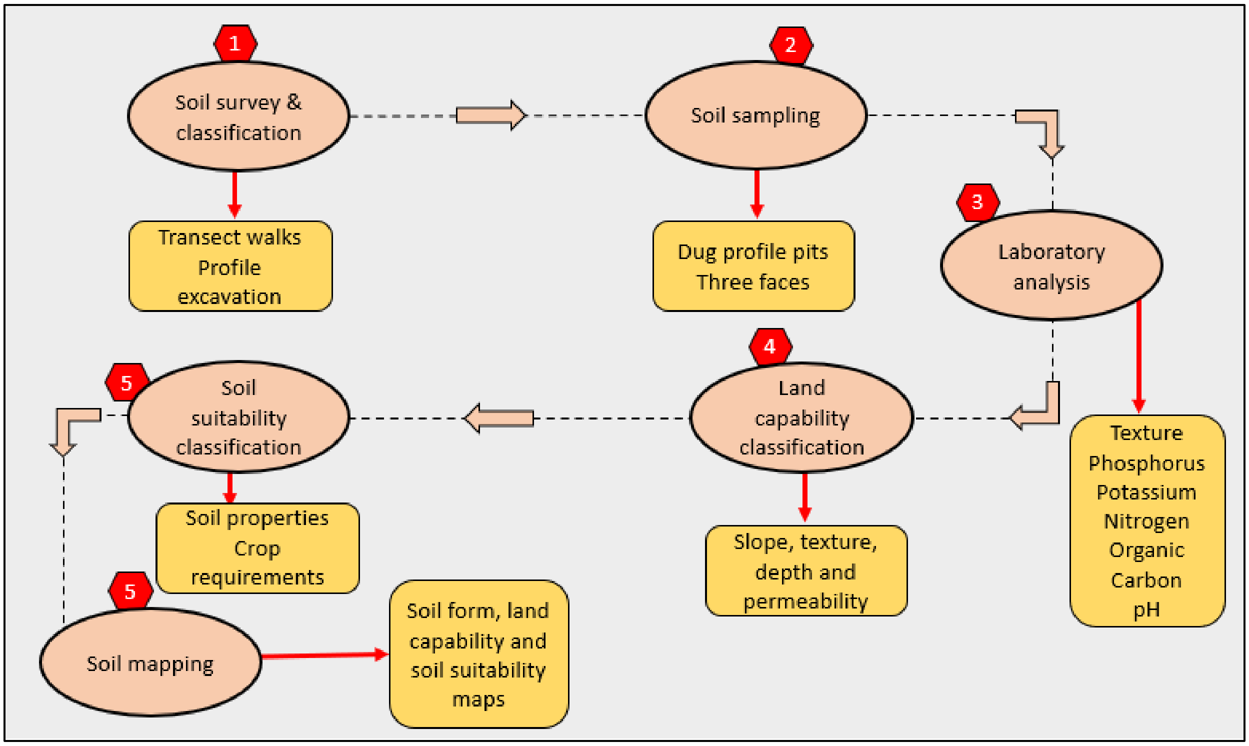

Fig. 3.2. Flowchart of the activities involved in the land evaluation process.

3.2.3. Field soil survey and classification

A field soil survey was conducted using transect walks complemented by auger holes to sub-divide the 12 ha portion of the farm into varied soil units. This was done by grouping soils both to their properties and where they are located across the farm. At each defined soil unit, morphological features including soil colour, texture, and topographic attributes (i.e., slope gradient and elevation) were determined in the field. The focus on soil morphological properties, described in the field including soil texture, consistency, and structure is because they yield a significant benefit on the potential productivity of the soil (Olivaries *et al.*, 2021).

Soil classification, which is linked to soil survey was done to determine the morphological and pedological characteristics of the soil. To aid soil classification, pits were dug up to the limiting layer using an excavator. The dimensions of the dug soil profiles were 1.5 m wide × 1.5 m long, and the depth was defined to the limiting layer. Twelve soil profile pits were sited, excavated, studied, described, and sampled. Each soil profile was georeferenced using a portable handheld global positioning system (GPS) (Model Garmin 12 L). Soil profile pits were then classified into soil form following the procedure outlined by the Soil Classification Working Group (2018). Soil profiles were described, and horizons were delineated to determine the form, structure, and organization of soil material. The thickness of each horizon and the effective rooting depth of the soil profiles were determined using a measuring tape. Specifically, the effective rooting depth was determined based on the number of roots found within the depth of each opened soil pit. Soil colour for each diagnostic horizon was determined by matching a freshly broken soil fragment to the Munsell colour chart both in a dry and moist state. Soil permeability and slope percentage were determined following the methodology by Smith (2006).

3.2.4. Collection of samples in the field

The soil samples were collected from the 12 dug soil profile pits. At each pit soil samples were collected at the 30 cm depth interval on three faces. The three faces served as replicates. This means that from each pit three soil samples were collected at the 30 cm depth interval. As such a total of 36 samples were collected using a spade, representing the 12 dug profiles. The collected samples were bagged and labeled according to the pit and replicate number. The soil samples were then taken to the laboratory for analysis.

3.2.5. Preparation and laboratory analysis of soil physicochemical properties

In the laboratory, soil samples were air-dried, crushed, and then passed through a 2 mm sieve in the laboratory before soil physical and chemical analyses. Particle size distribution of sand, silt, and clay content were determined using the hydrometer method (Bouyoucos, 1962). Soil organic carbon (SOC) was determined using the Walkley-Black Method (Walkley and Black, 1934). The electrical conductivity (EC) of the soil was determined using an EC meter (Manson *et al.*, 2020). Soil pH (H_2O and KCl) was determined using a 1:2.5 water ratio and 1:2.5 1 mol dm^3 KCl ratio suspensions on mass-based methods respectively and read with a glass electrode pH meter (Manson *et al.*, 2020).

3.2.6. Derivation of land capability classes

The land capability classes were derived using the concepts and principles of the FAO Framework for Land Evaluation (FAO, 1976), but adapted to South African conditions by Smith (2006). The physical land attributes and morphological characteristics of the soil that were used to derive the capability classes include slope percentage, soil texture, soil permeability, and effective rooting depth (Smith, 2006). Once all the physical characteristics of the land and morphological features of the soil were gathered, a land evaluation criterion was followed to assess the capability of the land for arable agriculture. Land capability classes of the studied farm were derived using the agricultural assessment framework developed by Smith (2006). The guideline for capability classification determination is shown in appendix 5.2.

3.2.7. Derivation of soil suitability classes

The FAO framework for land evaluation (FAO, 1976) coupled with the guidelines for rainfed agriculture (FAO, 1983) was used to determine the suitability of the soil at Makuleke farm. The criteria proposed by Sys *et al.* (1993) and Naidu *et al.* (2006) for crop suitability with degrees of limitations were adopted and logically categorized based on soil site characteristics for highly suitable (S1), moderately suitable (S2), marginally suitable (S3), currently not suitable (N1), and permanently not suitable (N2) classes (appendix 5.3). Soil suitability classification was done by matching the growth requirements of bananas with agro-climatic, soil properties (soil texture, pH, and SOC), and land physical characteristics (Table 3.1) (FAO, 1982; Sys *et al.*, 1991; Naidu *et al.*, 2006).

Table 3.1. Soil site suitability criteria for banana fruit

Land characteristics	**Class, degree of limitation, and rating scale**					
		S1	**S2**	**S3**	**N1**	**N2**
Topography (t)						
Slope (%)	0-2	2-4	4-8	8-16	-	>16
Wetness (w)						
Drainage	Good	Well	Moderately	Poorly	Very poorly	
Physical soil characteristics (s)						
Texture	l, cl, scl, sil		sicl, sc, c	c (>45%),	ls, s	
Soil depth (M)	>1,25		1,25-0,75	0,5-7,5	<0,5	
Soil fertility characteristics (f)						
Base saturation (%)	>50	50-35	35-20	<20	-	-
Sum of basic cations (cmol (+)/kg soil)	>6,5	6,5-4	4-2,8	-	-	-
pH	7,0-5,5	5,5-5,0	5,2-5,4,8	5,8-4,1	<4,1	-
Organic carbon (%)	>2,4	2,4-1,5	1,5-0,8	<0,8	-	-

*L, loam; cl, clay; scl, sandy clay loam; sil, silt loam; sc, sandy clay; c, clay; ls, loamy sand; s, sand.

3.2.8. Generation of soil, land capability, and soil suitability maps

The soil form (also called soil type), land capability, and soil suitability maps were generated using Google Earth pro (Google earth, 2022, Keyhole, Inc. CA, USA) and ArcGIS 10.8.1 software (ESRI, Redlands, CA, USA). Firstly, the coordinates of the 12 profile pits were used to demarcate the location of each profile pit using the “add placemark” tool in Google Earth. Each placemark was labelled according to the name of the soil form found at that particular profile pit. Once all the 12 placemarks were inserted and labelled, the “add path” tab was used to join placemarks of the same soil name. The soil characteristics determined from the profile pits were used to establish the mapping units. The “add polygon” tool was used to create a polygon using the joined placemark of Westleigh, Valsrivier, Hutton, and Glenrosa soil forms. Then the polygon was digitised to create the shape of each soil form. The polygon was named according to soil form and then saved as a KML layer. Secondly, in ArcMap, a conversion tool “From KML” was used to convert the KML layers of the polygons from google earth to layer and thereafter saved as a shapefile. Once all the shapefile of the four soil forms were produced, a spatial distribution map was produced by “checking” all the shapefiles on the same data frame. The “add data” tool was used to insert the base map of the Makuleke farm. Thereafter shapefiles of South Africa, Limpopo, district, and local municipalities were used to extract the Limpopo province, Vhembe district, and Collins Chabane local municipality using the “select tool”. In the case of land capability and soil suitability maps, each profile pit was renamed according to a derived land capability and soil suitability class. Then they were mapped following the procedure of the soil forms map.

3.3. Results

3.3.1. Pedological and morphological characteristics of the soils

Morphology is the field perceptible characteristics of the soil within the numerous soil horizons and the description of the kind and arrangement of the horizons (Balasubramanian, 2017). In the study area (Makuleke farm), four soils were identified and classified as Valsrivier (4.5 ha), Westleigh (1.4 ha), Hutton (4.05 ha), and Glenrosa (2.05 ha) (Fig. 3.3.) (Soil Classification Working Group, 2018). The classified soils at the farm, namely Valsrivier, Westleigh, Hutton, and Glenrosa are well known as Lixisols, Plinthosols, Cambisols, and Leptosols, respectively from the World Reference base for soil resources (IUSS Working Group WRB, 2022).

The Valsrivier soil (Lixisol) covered 38% (equivalent to 4.5 ha) of the 12 ha banana plantation. The soil form was mainly found at the footslope and middleslope positions (Table 3.2). At the footslope, the soil was characterised by a dark reddish colour (10R 2.5/1), 0.30 m thick orthic A horizon underlain by dusky red colour (2.5YR 3/2), 1.2 m thick pedocutanic B horizon. The permeability of the soil ranged from 1-3 s, with a clay content of 19 and a slope class of 0-3%. The effective rooting depth was 0.3 m and total depth 1.5 m. At the middleslope, the Valsrivier soil form was characterised by a dark reddish brown (5YR 3/3) colour, 0.31 m thick orthic A horizon underlain by a dusky red (10R 3/3), 0.597 m thick pedocutanic B horizon. The permeability of this soil ranged from 1-3 s, with 29% clay and a slope class of 3-8%. The effective rooting depth of the soil was

0.3 m and total depth 0.907 m. These types of soils fall under the duplex soil group (Fey, 2010). They are enriched with clay in the subsoil, which results in a strong blocky, prismatic, or columnar structure and cutanic character (Fey, 2010).

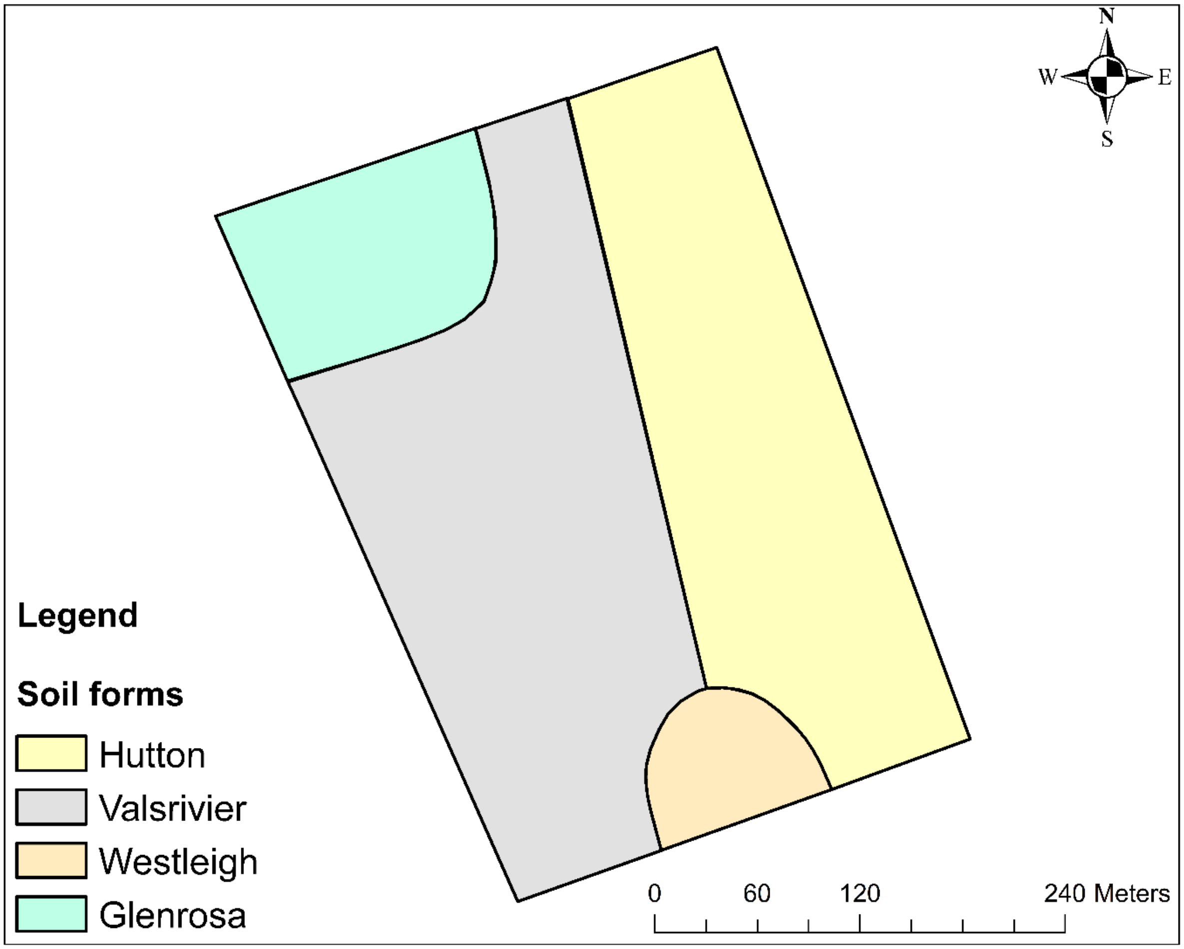

Fig. 3.3. Spatial distribution of soil forms across the 12 ha banana plantation.

The Westleigh soil form (Plinthosol) covered 12% (1.4 ha) of the studied farm at the footslope position (Table 3.2). The soil was characterised by a dark reddish (5YR 3/4), 0.34 m thick orthic A horizon underlain by a red (2.5YR 4/6), 0.68 m thick soft plinthic B horizon. The permeability of the soil ranged from 1-3 s, with a clay content of 29% and a slope class of 0-3%. The effective rooting depth was 0.2 m and total soil depth of 1.02 m. The Westleigh soil form falls under the plinthic soil group (Fey, 2010). The plinthic horizon has 25% by volume or more of an iron-rich, humus-poor mixture of kaolinitic clay with quartz, which changes irreversibly to a hard mass or to irregular aggregates on exposure to repeated wetting and drying with free access to oxygen (Fey, 2010).

The Hutton soil (Cambisol) covered 34% (4.05 ha) of the farm. It was found at the footslope and middleslope positions (Table 3.2). This soil at the footslope was characterised by a dark reddish brown (5YR 3/4), 0.34 m thick orthic A horizon underlain by a dark reddish brown (5YR 3/4), 1 m thick red apedal B horizon. The permeability of the soil ranged from 1-3 s, with a slope class of 0-3%. The effective rooting depth of the soil was 0.3 m and total depth of 1.35 m, with a clay percentage of 36.2. At the middleslope position, the Hutton soil was characterised by a dark reddish brown (5YR 3/4), 0.35 m thick orthic A horizon underlain by a dark reddish brown (2.5YR 3/4), 0.77 m thick red apedal B horizon. The permeability of the soil ranged from 1-3 s, with a slope class of 3-8%. The effective rooting depth and total depth of the soil was 0.3 m and 1.12 m respectively. The Hutton soil falls under the Oxidic soils group (Fey, 2010). An overriding feature of Oxidic soils is uniformity of the B horizon colour. Oxidic soils have a B horizon that is uniformly coloured with red and/or yellow oxides of iron (Fey, 2010).

The Glenrosa (Leptosols) soil form covered 16% (2.05 ha) of the farm at the middleslope position. The soil was characterised by a dark reddish brown (5YR 3/3) colour, 0.05 m thick Orthic A surface horizon underlain by a reddish brown (2.5YR 4/4), 1.15 m thick Lithocutanic B horizon. The permeability of the soil ranged from 1-3 s, with a slope class of 3-8 %. The total depth of the horizon was 1.2 m and the effective rooting depth 0.2 m. This soil type falls under the lithic soil group. The prevailing characteristic of lithic soils is their resemblance with the underlying parent rock (Fey, 2010)

Table 3.2. Pedological and morphological characteristics of soils of Makuleke farm at the footslope and middleslope

Transect no.	Pit no.	Topsoil Name	Colour (Topsoil)	Subsoil Name	Colour (Subsoil)	TSD (m)	ERD (mm)	Soil Form	Permeability (s)	Slope (%)	Terrain unit	Particle size distribution			
												Clay (%)	Silt (%)	Sand (%)	Texture class
1	1	Orthic A	10R 2.5/1 Reddish black	Pedocutanic B	2.5YR 3/2 Dusky Red	1.5	200-300	Valsrivier	1-3	0-3	Footslope	19.2	26	54.8	Sandy loam
	2	Orthic A	5YR 3/4 Dark Reddish Brown	Soft Plinthic B	2.5YR 4/6 Red	1.02	0-200	Westleigh	1-3	0-3	Footslope	29.2	25	45.8	Sandy clay loam
	3	Orthic A	5YR 3/4 Dark Reddish Brown	Red Apedal B	5YR 3/4 Dark Reddish Brown	1.35	200-300	Hutton	1-3	0-3	Footslope	41.2	33	25.8	Clay
2	1	Orthic A	7.5YR 3/4 Dark Brown	Pedocutanic B	7.5YR 3/3 Dark Brown	1.32	300-500	Valsrivier	4-8	0-3	Footslope	25.2	27	47.8	Sandy clay loam
	2	Orthic A	7.5YR 3/4 Dark Brown	Pedocutanic B	2.5YR 4/4 Reddish Brown	3.01	200-300	Valsrivier	4-8	0-3	Footslope	41.2	33	25.8	Clay
	3	Orthic A	10R 3/3 Dusky Red	Red Apedal B	5YR 4/6 Yellowish Red	1.16	200-300	Hutton	4-8	0-3	Footslope	39.2	32	28.8	Clay loam
3	1	Orthic A	5YR 3/3 Dark Reddish Brown	Pedocutanic B	10R 3/3 Dusky Red	0.907	200-500	Valsrivier	1-3	4-8	Middleslope	29.2	27	43.8	Clay loam
	2	Orthic A	5YR 3/3 Dark Reddish Brown	Pedocutanic B	2.5YR 3/3 Dark Reddish Brown	1.35	0-200	Valsrivier	1-3	4-8	Middleslope	33.2	33	33.8	Clay loam
	3	Orthic A	5YR 3/4 Dark Reddish Brown	Red Apedal B	2.5YR 3/4 Dark Reddish Brown	1.12	200-300	Hutton	1-3	4-8	Middleslope	33.2	31	35.8	Clay loam
4	1	Orthic A	5YR 3/3 Dark Reddish Brown	Lithocutanic B	2.5YR 4/4 Reddish Brown	1.2	0-200	Glenrosa	1-3	4-8	Middleslope	21.2	17	61.8	Sandy clay loam
	2	Orthic A	5YR 3/3 Dark Reddish Brown	Pedocutanic B	5YR 3/4 Dark Reddish Brown	1.3	0-200	Valsrivier	1-3	4-8	Middleslope	25.2	33	41.8	Loam
	3	Orthic A	7.5YR 3/3 Dark Brown	Red Apedal B	5YR 3/4 Dark Reddish Brown	1.1	200-300	Hutton	1-3	4-8	Middleslope	39.2	32	28.8	Clay loam

3.3.2. Land capability classification for arable farming

The farm showed variable capability use classes, ranging from class I to VI (Fig. 3.4). The land capability class I, III, IV, and VI covered 17%, 61%, 6%, and 16% respectively of the farm. Lands in class I, III, and IV are referred to as good cultivable with class I having none or few limitations. Class III and IV lands have moderate and severe limitations respectively, that constrain their use (Appendix 5.1). Class VI lands are described as not suitable for the cultivation of crops, their limitations hinder the growth of crops. Class I falls under Hutton (occupied 17%). Class III falls under Westleigh, Hutton (occupied 17%), and Valsrivier (occupied 32%) while Class IV falls also under Valsrivier (occupied 6%). Class VI lands fall under Glenrosa soil. Classes (I to IV) fall under arable and class IV under low arable potential while class VI falls under non-arable potential (Appendix 5.1).

Fig. 3.4. Spatial distribution of land capability classes across the 12 ha banana plantation.

3.3.3. Soil site suitability for banana production

The soil suitability classes of Makuleke farm are depicted in fig. 3.5. Soil site suitability assessment for banana revealed that 12%, 34%, 37%, and 17% is highly suitable (S1), moderately suitable (S2), marginally suitable (S3), and permanently not suitable (N2) respectively for banana cultivation. The moderately suitable portion of the farm has slight to moderate limitations caused by slope, texture, pH, and OC % for banana cultivation. The S3 portion of the studied area has severe limitations posed by slope, texture, pH, and depth. The N2 portion of the area is permanently not suitable because of severe limitations posed by slope, depth, texture, and erosion.

Fig. 3.5. Spatial distribution of soil suitability classes across the 12 ha banana plantation. The main liming factors, indicated by the suitability subclasses alongside the suitability classes on the map: t, topography; e, erosion; m, moisture; s, soil physical characteristics (i.e., clay and effective rooting depth); f, soil fertility limitation (i.e., organic carbon and pH).

3.4. Discussion

In this study, we found that a greater proportion of the farm was arable (78%). This arable portion of the farmland was characterised by Westleigh, Hutton, and Valsrivier soil types. These soils were found to be highly (Westleigh), moderately (Hutton), and marginally suitable (Valsrivier-footslope) for banana production. Even though Westleigh soil was arable and highly suitable for bananas, the presence of the soft plinthites (an iron-rich, humus-poor mixture of kaolinitic clay with quartz) below the topsoil horizon may impose limitations (Baxter, 2007). Soils characterised by a clay fraction dominated by kaolinite have a low cation exchange capacity (CEC). The implications of soils with low CEC are that they are likely to develop deficiencies in potassium (K), magnesium (Mg), sulphur (S), and other cations (Brady and Weil, 2017). Another limitation associated with plinthic horizons is that even when soft they do not appear to be well colonised by roots. This is because the plinthites are cemented by iron to the extent that the dry fragments do not slake in water, and cannot be penetrated by roots (Fey, 2010). The consequence of such cementations is that during a period of heavy rainfall and irrigation, the soil gives rise to waterlogging conditions. Intermittent wetness in the soil directly affects plant growth through oxygen deficiency and indirectly by reducing the availability of nitrogen (N) and sometimes causing manganese (Mn) toxicity (Baxter, 2007). In sandy soils, excessive water can leach nitrate nitrogen beyond the rooting zone of the developing plant. In heavier soils (soils with very high clay content), nitrate nitrogen can be lost through denitrification (the microbial process of reducing nitrate and nitrite to gaseous forms of nitrogen, principally nitrous oxide (N_2O) and nitrogen (N_2) (Baxter, 2007). In as much as the Hutton soil was arable and moderately suitable, it was found to be limited by its location in the field as evident in slope ranging from 4-8%, low levels of OC (1.1%), and an acidic pH (5.1). Moreover, the Hutton soil had a high clay content (42%) and falls under the Oxisols, which are mostly rich in oxides (Fey, 2010). In oxides or oxide layer silicate-coated systems, phosphorus (P) fixation increases with an increase in clay content (Kome *et al.*, 2019). Therefore, the nutrient P in Hutton may be fixed in the soil and not be available for plant uptake.

The land capability assessment further revealed that some portions of the farmland had low arable potential (6%) and 16% of the land was considered non-arable. The low arable potential and the non-arable portion of the farmland was characterised by Valsrivier (middleslope) and Glenrosa soil forms respectively. Notably, Valsrivier was found to be marginally suitable while Glenrosa was permanently not suitable for banana production. Limiting factors for the Valsrivier soil included its shallow rooting depth (0.5 m), acidic pH (5.0), low OC (1.54%), and the fact that it was located on a steeper slope gradient (4-8%). Similarly, Glenrosa was limited by its location on a steep slope gradient (4-8%), shallow effective rooting depth (0.05 m), low OC (1.1%), low clay content (21%), and acidic pH (4.6). To grow bananas optimally, the slope percentage must be in the range of 0–3%, clay content ranging from 30% to 50%, pH varying between 5.5 and 7, OC and depth of at least 1.5% and 0.51 m, respectively (Sys *et al.*, 1993; Naidu *et al.*, 2006; FAO, 2018). At high altitudes, banana plants may break since they are prone to wind damage because of their height (FAO, 2018). Additionally, water tends to travel from less-level areas to flat ones during periods of high rainfall or irrigation. This leads to the removal of smaller topsoil particles, which causes soil erosion and subsequent loss of nutrients (they are carried away with finer topsoil). Bananas in less flat lands would thus receive less water and nutrients. Moreover, low clay-content soils typically have a poor capacity to hold water and nutrients. This is explained by the combination of high surface area and density of clay, which causes moisture and nutrients to be retained (Brady and Weil, 2017). The particles that makeup clay soil are negatively charged, which means they attract and hold positively charged particles, such as calcium (Ca), potassium (K), and magnesium (Mg) (White, 2005). For these reasons, bananas grown on low clay soils will suffer from water and nutrient stress which would lead to poor crop growth and subsequent yield reduction. Plant growth and most soil processes, including nutrient availability and microbial activity, are favoured by a soil pH range of 5.5 – 8 (Havlin *et al.*, 2016). When soil pH drops, aluminium (Al) becomes soluble. A small drop in pH can result in a large increase in soluble Al (Neina, 2019). In this form, Al retards root growth, thus restricting access to water and nutrients. Accordingly, poor banana growth and yield reduction would occur as a result of inaccessible water and nutrients (Neina, 2019). In very acid soils, all the major plant nutrients (e.g., N, P, K, S, Ca, Mn, and also the trace element molybdenum (Mo)) may be unavailable, or only available in insufficient quantities (Neina, 2019). This is because most microbial processes, including the breakdown of organic matter and cycling of nutrients, are reduced in acidic soil because the growth and reproduction of the soil microbes, primarily bacteria, and fungi, are reduced (White, 2005). This would explain why there is low OC in such soils even though the farmer practices organic mulching using banana leaf litter. Consequently, this would imply that the soil might not have enough nutrients and water for bananas since OC is responsible for nutrients and water retention.

The defining characteristic of Valsrivier soils is clay enrichment in the subsoil (Fey, 2010) which causes the development of strong structure in the B horizon (Pedocutanic B). The overriding feature of Glenrosa soils is their clear resemblance with the underlying parent rock (Lithocutanic B) (Fey, 2010). The B horizons (of Valsrivier and Glenrosa) are often sufficiently hard and dense, and as such impede both root growth and water movement (Fey, 2010). As a result, the roots of the bananas planted on these soils will remain confined to a small volume of soil that cannot provide adequate anchorage, water, and nutrients (Fullen and Catt, 2014). Shallow Lithocutanic and Pedocutanic B horizons reduce the usable soil depth and enhance the tendency of soil to waterlog in heavy rains, and fall below the permanent wilting percentage under drought conditions (Jackson, 2008). Consequently, bananas grown on these soils will suffer from stunted root growth and waterlogging. Stagnant water in banana farmlands might cause diseases such as Panama disease (a wilting disease caused by the fungus *Fusarium oxysporuf*. sp. *Cubense*) (Ploetz, 2000; FAO, 2018). This disease can kill the banana plant. The Panama disease is caused by an upsurge (favoured by reducing soil environment caused by stagnant water) in the solubility and bioavailability of redox-sensitive micronutrients (Orr and Nelson, 2018). Increased micronutrient bioavailability from reduced pockets within the crop root zone has been linked to increased *F. oxysporum* pathogenicity (Dominguez *et al.*, 2001). Furthermore, a reducing environment inhibits nitrification, increasing the concentration of soil ammonium, which is favourable to Fusarium wilt development (Orr and Nelson, 2018).

The excess water in the root zone is accompanied by anaerobic conditions (refer to when the soil has little to no available oxygen) (Moreno-Roblero *et al.*, 2020). In the case of plants, oxygen (O_2) is a necessary component in many processes including respiration and nutrient movement from the soil into the roots (White, 2005). In the absence of O_2, root respiration, and nutrient movement are hampered. This is because root respiration in aerobic conditions requires a continuous supply of O_2 to the rhizosphere (Moreno-Roblero *et al.*, 2020). As a result, the banana plant will show reduced water consumption and stomatal conductance, slow growth, wilting, and decreased yield (Bhattarai *et al.*, 2008; Maestre and Martínez, 2010).

The principal soil-forming process of Glenrosa soils is the dissolution and subsequent removal of carbonates (IUSS Working Group WRB, 2015). This intensive removal of soil carbonates leads to further ecological consequences, mostly related to a decline of soil functions such as decreased net primary production and lower soil organic matter (OM) stability (Rowley *et al.*, 2020). Soil OM has both a direct (It serves as a source of N, P, S through its mineralization by soil microorganisms) and indirect (is required as an energy source for N-fixing bacteria hence influences the supply of nutrients from other sources) effect on the availability of nutrients for plant growth (Senesi and Loffredo, 2018). Moreover, OM leads to the synthesis of complex organic compounds (e.g., humic and fluvic acids) that bind soil particles into structural units called aggregates (Stott *et al*., 2018). Therefore, the less stable soil OM will contribute to decreased nutrients and a poorly structured soil which would limit water infiltration because of compaction subsequently leading to less water in the root zone (Stott *et al*., 2018). Consequently, bananas grown on these soils will suffer from inadequate water and nutrient supply.

3.5. Conclusion

In conclusion, four soil forms were identified and classified in the study area, namely Hutton, Westleigh, Valsrivier, and Glenrosa. The land capability assessment revealed that the Makuleke farm is categorised by four land capability classes with class I, III, IV and VI occupying 17%, 61%, 6%, and 16% sequentially. In essence, 78% of the farm was arable, 6% has low arability and 16% was non-arable. Furthermore, soil site suitability assessment revealed that the suitability of the soils at Makuleke farm for banana production is highly variable. The farm was grouped into four suitability classes for banana production; S1 (highly suitable), S2 (moderately suitable), S3 (marginally suitable), and N2 (not suitable), which covered 12%, 34%, 38%, and 16% respectively. Owing to that the farmers at Makuleke were utilising the land and soil resource without prior land evaluation, which contributed to below-par banana yield and soil degradation in some portions of the farm.

The findings of this study will be useful to decision-making and planning at the farm going forward. The land capability and soil suitability assessment of this farm would help to define the best agricultural practices to adopt in order to preserve soil functions (soil and water retention). It will help farmers to tailor their soil management practices to specific areas on the farm in order to improve the productivity of the land. By doing so, the farmers will be able to improve banana yield which was affected by a lack of soil information on their plantation.

This study provides a baseline for agricultural land assessment. It will help farmers and decision-makers in other agroecological zones on how best to conduct a land evaluation in order to improve their agricultural productivity and avoid inappropriate agricultural practices which might lead to land degradation.

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CHAPTER 4: SPATIAL ANALYSIS OF SOIL NUTRIENTS AND CONTROLLING FACTORS ACROSS THE 12HA BANANA PLANTATION

ABSTRACT

Soil variability results in variable responses of crops to fertiliser applications at the farm level. Therefore, developing and improving site-specific land management strategies necessitates a deeper comprehension of the variation of soil, inherent nutrients, and their controlling factors. The objectives of this study were to (i) assess the spatial variability and structure of soil nutrients across a smallholder banana plantation farm in Makuleke, Limpopo province, South Africa, and (ii) identify the factors controlling the spatial variability of soil nutrients across the farm. Within a 12 ha banana plantation, 27 composite samples were collected from 0-30 cm depth at the intersections of a 50 m × 50 m and analysed for soil physicochemical properties. Soil nutrient variability was assessed by descriptive statistics, while the structure of soil nutrients was determined by generating semivariogram model parameters, and driving factors were explored using univariate correlation analysis. The spatial variability of soil nutrients across the farm was then mapped using ordinary kriging (OK) spatial interpolator. The results indicated that phosphorus (P), potassium (K), calcium (Ca), zinc (Zn), manganese (Mn), and copper (Cu) content varied highly, while magnesium (Mg) and total nitrogen (TN) varied moderately across the banana plantation. Geostatistical analysis revealed that P, K, and Mn contents were strongly spatially dependent, while Mg and Zn were moderately spatially dependent across the banana plantation. Soil Ca, Cu, and TN contents were found to be weakly spatially dependent across the farm. In this study, we found that soil type and topographic position were the principal factors affecting the spatial variability of soil nutrients across the farm. High nutrient contents were mostly found in Glenrosa and Valsrivier soils located in the footslope position of the farm. The spatial variability maps showed that P, Mg, Zn, and Mn were highly distributed in the northeast part and low in the northwest part of the banana plantation farm. Similarly, K and Ca were low in the northwest part, but they were high in the south to the southwest portion of the farm. Total N was high in the west part and low in the east-northeast part while Cu was evenly distributed across the plantation. The present study provides a better insight into the spatial variability of soil nutrients within the 12 ha banana plantation at Makuleke farm.

The results of this study will be useful for site specific management of soil nutrients in the farm in order to improve banana productivity.

Keywords: Soil spatial variability, Soil nutrients, Classical statistics, Geostatistics, Factors of control, Ordinary kriging, GIS

4.1. Introduction

Soil nutrients represent one of the main factors regulating plant growth, and ecological functions and play an important role in the sustainable use of soils (Wang *et al*., 2009; Fu *et al*., 2010). Essential nutrients in the soil influence plant productivity and without them plants cannot complete their life cycle (i.e., vegetative, flowering, and fruit production) (Gwanyong *et al.,* 2017; Abad *et al.,* 2014). Soil nutrient depletion is one of the major causes of high yield gaps in South Africa (SA) (Msangi, 2007; Uwiragiye *et al.*, 2022). Depletion of soil nutrients is caused by low soil nutrient supply, crop nutrient uptake, and high soil nutrient loss through leaching and soil erosion (Mulualem *et al.*, 2021). Agricultural practices inevitably affect soil properties, plant nutrient concentrations, and subsequently, the potential to optimise crop production (Peukert *et al.,* 2016). The altered soil properties, consequently, affect ecosystem services and functions including nutrient sources and their mineralisation and mobilisation, and delivery to surface water (Peukert *et al.*, 2016).

Soil spatial variability is present over short distances not only in natural ecosystems but also in agricultural systems with presumed uniform management and vegetation cover (Goovaerts *et al.*, 1998; Haygarth *et al.*, 2006). Such variability has been linked to the combined action of physical, chemical, and biological properties as well as anthropogenic activities, which differ in space across the landscape (Goovaerts *et al.*, 1998; Tittonell *et al.*, 2008; Niang *et al.*, 2017). Assessing spatial variability and mapping soil nutrients constitute important prerequisites for soil and crop management in agricultural areas (Song *et al.*, 2020). Knowledge of soil spatial variability and understanding the relationships among soil properties are important for evaluating agricultural land management practices (Huang *et al.*, 2001). Proper understanding of the spatial distribution of soil properties and mapping their spatial variability is key to site-specific soil management for sustainable crop production as it allows for the variable-rate application of nutrients (Behera and Shukla, 2015).

In recent years, classical statistics coupled with geostatistics have been used to analyse soil nutrients distributions, and these tools are considered good for use in better understanding nutrient dynamics in the field (Park and Vlek 2002; *Liu et al.,* 2006; Zhang *et al.,* 2007; Niang *et al.,* 2017; Song *et al.,* 2020). Classical statistics help to understand the overall variability for the exploratory analysis of data (Kumar *et al.,* 2022). Geostatistical methods are used to quantify the spatial distribution and variability based on the spatial scale of the study area, the distance between sampling points, and spatial patterns of modelled semivariograms (Shit *et al.*, 2016). They have been widely applied to evaluate spatial correlation in soils and to analyze the spatial variability of soil properties, such as soil physical, chemical, and biological properties (Fromm *et al.* 1993; Wigginton *et al.* 2000; Vieira *et al.* 2007; Zheng *et al.* 2009; Liu *et al.* 2014; Niang *et al.*, 2017; Uwiragiye *et al.*, 2022). In spite of the sophisticated analytical techniques available and the recognition of the importance of understanding nutrient variability, the degree of nutrient variability is still poorly understood (Gallardo, 2003; Silveira *et al.,* 2009). Moreover, most studies to date have focused solely on the distribution on the spatial distribution of soil nutrients rather than determining the factors influencing the spatial distribution of soil nutrients (Wang *et al*., 2009; Naing *et al*., 2017). Studies that focus on fruit cultivation, for example banana, are still scarce, especially in areas with the potential for agricultural expansion (Song *et al.,* 2019). In spite of that, the quantitative information on the spatial heterogeneity of soil nutrients is a precondition for present-day soil management decisions targeted for sustainable use of soil resources (e.g., site-specific management of plant nutrients), land use planning and environment modelling (McBratney *et al.*, 2014; Mishra and Riley, 2015). The objectives of this study were to (i) assess the spatial variability and structure of soil nutrients across the Makuleke farm, and (ii) identify the factors control of the spatial variability of the soil nutrients across the farm.

4.2. Methodology

4.2.1. Site description

The study was conducted on a 12 ha banana plantation (30º56’16.3” E; 22º51’31.9” S) in Makuleke farm, which is situated in Malamulele in the Collins Chabane Local Municipality, Vhembe District. In the study area, there are relatively flat terrains, with elevations ranging from 392 to 405 meters above sea level. The average temperature and rainfall in the area is 21.7°C and 731 mm, respectively (Kock, 2017). The study area is dominated by Hutton, Westleigh, Valsrivier, and Glenrosa soil forms (Soil Classification Working Group, 2018), which are broadly defined by the World Reference Base for soil resources (IUSS Working Group WRB, 2022) into Lixisols, Plinthosols, Cambisols, and Leptosols respectively. Valsrivier (1.32 m) and Hutton (1.35 m) are deep, dark brown, and dark reddish brown clayey soils respectively. Westleigh is a moderately deep (1.02 m) dark reddish brown sandy clay loam soil, while Glenrosa is a shallow (0.2 m) dark reddish brown sandy clay loam. The main land use is intensive agriculture with banana fruit as the main crop.

As shown in Table 4.1, on average, Westleigh soil had a lower exchangeable acidity (0.01 cmol/kg) than Valsrivier (0.06 cmol/kg), Glenrosa (0.07 cmol/kg) and Hutton (0.08 cmol/kg) soil. Similarly, the average effective cation exchange capacity (ECEC) content of Westleigh was lower (11 cmol/kg) compared to Hutton (14.5 cmol/kg), Valsrivier (17.6 cmol/kg), and Glenrosa (18.43 cmol/kg). There was little variation in soil carbon to nitrogen (C:N) ratios of the soils. Soil pH was lower in Westleigh (5.3) compared to Hutton (5.5), Valsrivier (5.6), and Glenrosa (5.7) soil as the highest. The mean clay content of Hutton (38%) and Valsrivier (38%) was slightly below that of Glenrosa (39%) and Westleigh (42%).

Table 4.1. Soil physicochemical characteristics for the different soils found across the 12 ha banana plantation

Soil	Elev (m)	Exch. Acidity (cmol/kg)	ECEC (cmol/kg)	pH (KCl)	C:N	Clay (%)	TC (g/kg)
Hutton	401	0.08±0.01	14.5±2.0	5.5±0.24	19±3.57	38±3.0	10.2±2.0
Valsrivier	399	0.06±0.0	17.6±1.4	5.6±0.2	20±2.6	38±2.7	12.1±1.8
Glenrosa	401	0.07±0.0	18.4±2.8	5.7±0.3	19.5±2.7	39±2.7	10.5±2.1
Westleigh	400	0.1±0.0	11±1.0	5.3±0.05	20.5±3.4	42±2.5	13.5±3.2

*Hu, Hutton; Va, Valsrivier; Gs, Glenrosa; We, Westleigh; Elev, Elevation; Exch. Acidity, Exchangeable acidity; ECEC, effective cation exchange capacity; C:N, carbon to nitrogen ratio; TC, total carbon.

4.2.2. Land management practices in the banana plantation

The banana plants receive 31 mm of water for irrigation twice per week for four hours using micro jet sprinklers. The pH of the soils is corrected using lime and gypsum at the commercially recommended rates. Organic (banana litter) and inorganic fertilisers (NPK 2:3:2 [24]) are applied to increase the nutrients level of the soils. The farmer applies herbicides to kill weeds, mulching to prevent weed growth, and keeps the canopy of the banana trees closed to prevent sunlight from reaching the weeds on the ground which inhibits the weeds from growing.

4.2.3. Soil sampling strategy and collection of soil nutrients samples in the field

To assess the spatial variability of soil nutrients, a systematic grid sampling strategy was adopted to locate the sampling points across the banana plantation. The sampling points were located using a grid method at 50 × 50 m intervals (Baxter, 2007). At the intersection of the grid, soil samples were collected in a radial pattern (one sample was collected in the centre and then three samples were collected in a circular pattern surrounding the grid intersection point) in the topsoil layer (0-30 cm) using a bucket auger. The samples were combined to make a composite sample yielding 27 samples at the intersection of the grid. At each sampling location, the GPS latitude (south) and longitude (east) coordinates were recorded using a Garmin Etrex (South American 69) to georeference the points in preparation for digital soil mapping. The collected samples were bagged, labeled, and taken to the laboratory for soil physicochemical analysis.

4.2.4. Soil sample preparation and analysis of soil physicochemical properties in the laboratory

Prior to soil analysis, soil samples were air-dried, crushed, and then passed through a 2 mm sieve in the laboratory. Particle size distribution of sand, silt, and clay content were determined by the hydrometer method (Bouyoucos, 1962). Phosphorus was determined on a 2-mL aliquot of filtrate using a modification of the Murphy and Riley (1962) molybdenum blue procedure (Hunter, 1974). Soil Ca, Mg Ca, and K were determined by atomic absorption (using an air-acetylene flame) on a 5 ml aliquot of the filtrate after dilution with 20 ml de-ionized water. Soil Zn, Cu, and Mn were determined by atomic absorption on the remaining undiluted filtrate. Total nitrogen (TN) and carbon (TC) were analyzed by an automated Dumas dry combustion method using a LECO TruSpec CN (LECO Corporation, Michigan, USA; Matejovic, 1996). The electrical conductivity (EC) of the soil was determined using an EC meter. Soil pH (H_2O and KCl) was determined using a 1: 2.5 water ratio and 1: 25 1 mol dm^3 KCl ratio suspensions on mass-based methods, respectively, and read with a glass electrode pH meter.

4.2.5. Classical and geostatistical analysis

The data was organised in Microsoft Excel (Microsoft software 365, NASDAQ, MSFT, One Microsoft Way, Redmond, Washington, USA) into soil mapping units, slope gradient and soil depth. Descriptive statistics was used to summarise the soil physicochemical properties data to the mean, median, maximum, minimum, variance, standard deviation, coefficient of variation (CV), skewness, and kurtosis. The mean (μ) is the sum of the observations divided by their number (Nageswara, 1983) and is calculated as follows:

$$\mu = \frac{1}{n}\sum_{i=1}^{n} xi \qquad (2)$$

The median of a data set is the middle value when the values are ranked in ascending or descending order (Boslaugh, 2012). The median is a better measure of central tendency than the mean for data that is asymmetrical or contains outliers. The minimum, maximum, mean, and median were used as the primary estimates of central tendency. The most common measures of dispersion for continuous data are the variance (s^2) (Eq**.** 2) and standard deviation (s) (Eq**.** 3). Both describe how much the individual values in a data set vary from the mean or average value (Boslaugh, 2012). The variance and standard deviation were used as estimates of spatial variability (Cambardella *et al.*, 1994) using the following equations:

$$s^2 = \frac{1}{n-1}\sum_{i=1}^{n}(xi - \mu)^2 \tag{3}$$

$$S = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(xi - \mu)^2} \tag{4}$$

Where xi is the value i from the data set and µ is the mean of the data set.

The CV, which gives a normalised measure of spreading around the mean was calculated to characterize the variability of the studied properties. The criterion by Wilding (1985) was used to classify the soil properties into low (CV <15%), medium (CV 15-35%) and high (CV > 35%). The CV is expressed as:

$$CV = \frac{s}{\mu} \times 100\% \tag{5}$$

Where s is the standard deviation of the data set and µ is the mean of the data set.

A correlation matrix was generated to determine the univariate relationships between land physical characteristics (slope gradient), soil physical properties (clay content), and soil nutrients (P, TC, TN, C:N ratio, K, Ca, Mg, Exch.Acidity, ECEC, pH, Zn, Mn, and Cu) (Verma *et al.*, 2016) at $p < 0.05$ using STATISTICA software (StatSoft, Inc, Tulsa, OK). The strength of correlations among the parameters was determined using the standard by Ratnasari (2016), where perfect negative ($r = -1$), strongly negative ($r = -0.8$), moderately negative ($r = -0.5$), weakly negative ($r = - 0.2$), no association ($r = 0$), weakly positive ($r = 0.2$), moderately positive ($r = 0.5$), strongly positive ($r = 0.8$) and perfectly positive ($r = 1$). A one-way analysis of variance (ANOVA) was used to assess the effect of soil types (i.e., Hutton, Glenrosa, Westleigh, and Valsrivier) and slope gradient (i.e., footslope and middleslope) on the soil nutrients using Genstat 20.0 software (VSN International, (VSNI) Software Inc., England and Wales, UK). 10.0. Differences between means of the significant factor were assessed with Duncan multiple range test ($p \leq 0.05$). Box plots, which characterise the sample using the minimum, lower quartile, median, upper quartile, and maximum were computed to visually assess the variability of selected soil fertility properties in different soils and topographic positions using the Sigma Plot 14.0 (Systat Software Inc., Richmond, California, USA).

Geostatistical analysis was conducted using GS+ v. 7.0® software (Gamma Design Software 2004, LLC, Plainwell, MI) to encapsulate the variation of the soil nutrients across the banana plantation (Oliver and Webster, 2014). The spatial analysis was conducted using the following procedures. Firstly, a semivariogram of each soil nutrient was drawn in the active lag distance of 275.25 m with a uniform interval of 31.45 m. Secondly, a suitable model was fitted depending on the smallest residual sum of squares (RSS). Lastly, the semivariogram parameters were calculated (nugget (Co), sill (Co + C), range (Ao), and an index of spatial dependence (Co/Co + C ratio).

The semivariogram is a graph of semi-variance (semi-variance represents the variance between all pairs of measured samples at a given separation distance) values on the y-axis versus all separation distances on the x-axis (Mulla, 2016). The semivariogram is derived from the values of semi-variance (the values for semi-variance are based directly on calculations with measured data) using a regression model (Mulla, 2016). The semivariogram based on the regionalized variable theory and intrinsic hypothesis (Nielsen and Wendroth, 2003) is expressed as:

$$y(h) = \frac{1}{2N(h)} \sum_{i=1}^{N(h)} Z[(xi) - Z(xi + h)]^2 \tag{6}$$

Where $y\ (h)$ is the semi-variance, h is the lag distance, Z is the parameter of the soil property, $N\ (h)$ is the number of pairs of locations separated by a lag distance $h,\ Z\ (xi)$, and $Z\ (xi\ +\ h)$ are values of Z at positions Xi and $Xi\ +\ h$ (Wang and Shao, 2013). The semivariograms models (spherical, exponential, linear, and gaussian) and parameters (range, nugget, sill, and nugget/sill ratio) were computed, fitted, and plotted using the GS+ software. The spherical model is one of the most used models in variogram modeling. It is a modified quadratic equation where spatial dependence flattens out as the sill and the range (Gamma Design Software, 2004). The model is expressed as:

$$y(h) = Co + C[1.5h\left(\frac{h}{Ao}\right) - 0.5\left(\frac{h}{Ao}\right)^3] \tag{7}$$

Where (y) is the severance for interval distance, class h, h is the lag distance interval, Co nugget variance, C structural variance, and Ao range parameter. In the case of the spherical, the effective range $A = Ao$.

The exponential model approaches the sill gradually like the spherical but is different from the spherical in the rate at which the sill is approached and the model and the sill never actually converge (Roberson, 2008). The exponential model is expressed as:

$$y(h) = Co + C[1 - exp(-\frac{h}{Ao})] \tag{8}$$

Where (y) is the semivariance for interval distance class h, h is the lag distance interval, Co nugget variance, C structural variance, and Ao range parameter. In the case of the exponential model, the effective range $A = 3Ao$, which is the distance at which the $sill\ (C + Co)$ is within 5% of the asymptote (Robertson, 2008). The Gaussian model is akin to the exponential model, though it assumes a gradual rise for the y-intercept and uses a normal probability curve (Robertson, 2008). This type of model is useful where phenomena are similar at short distances because of its gradual rise on the y-axis (GISGeography, 2022). The model is expressed as:

$$y\ (\mathrm{h}) = \mathrm{Co} + \mathrm{C}[1 - \exp(-\frac{\mathrm{h}^2}{\mathrm{Ao}^2})] \tag{9}$$

Where (y) is the semivariance for interval distance class h, h is the lag distance interval, Co nugget variance, C structural variance and Ao range parameter. In the case of the Gaussian model, the effective range $\mathrm{A}= 3^{0.5}\mathrm{Ao}$, which is the distance at which the sill (C + Co) is within 5% of the asymptote. The sill never meets the asymptote in the gaussian model (Robertson, 2008). The linear model describes a straight-line variogram. It is the simplest type of model without a plateau, meaning that the user must arbitrarily select the sill and range. The linear model is expressed as:

$$\mathrm{y}\ (\mathrm{h}) = \mathrm{Co} + \mathrm{C}[\mathrm{h}(\frac{\mathrm{C}}{\mathrm{Ao}})] \tag{10}$$

Where (y) is the semivariance for interval distance class h, h is the lag distance interval, Co nugget variance, C structural variance, and Ao range parameter. In the case of the linear model, there is no effective range A. Spatial autocorrelation occurs across the entire range sampled (Robertson, 2008).

The three basic parameters of a semi-variance are the nugget (Co), sill (Co + C), and range (Ao) (Mondal *et al.*, 2020). The nugget is the value at which the semi-variogram intercepts the y-value (Cameron and Hunter, 2002). It indicates the total variance associated with the sampling or measurement (Mulla and McBratney, 2002). If the nugget parameter is about equal to the sample variance, it is an indication that the sampled property has very little spatial structure or varies randomly (Mulla and McBratney, 2002). The sill value is the value at which the model first flattens out (Cameron and Hunter, 2002). It refers to the local variance that occurs due to sampling errors or measurement errors (Mulla and McBratney, 2002). The range is the distance at which the model first flattens out (Oliver and Webster, 2002). It is the separation distance of spatial dependence. Spatial dependence refers to the degree of spatial autocorrelation between independently measured values observed in geographical space that are more similar (positive autocorrelation) or less similar (negative autocorrelation) than expected for randomly associated pairs of observations (Miller *et al.*, 2007, Crawford, 2009). The spatial dependence of selected soil parameters was estimated through the Co to Co + C ratio. A Co/Co + C ratio of < 25%,25 – 75%, > 75%, and = 100% reflects a strong, moderate, weak, and non-spatial dependence (pure nugget) respectively (Cambardella *et al.*, 1994). The strong spatial dependence is controlled by intrinsic factors (i.e., topography, parent material, soil types, organisms, climate), while moderate and weak spatial dependences are more related to extrinsic factors (i.e., soil management practices), which can homogenise some soil attributes (Cambardella *et al.*, 1994).

4.2.6. Generation of soil nutrients spatial maps

To generate soil nutrient maps, a spreadsheet was created in Microsoft Excel (Microsoft software 365, NASDAQ, MSFT, One Microsoft Way, Redmond, Washington, USA) listing the geographic coordinates in columns, easting (x-coordinate or longitude), and northing (y-coordinate or latitude). The coordinates were expressed in a suitable coordinate system (GCS WGS 1984) that was used to carry the map projection and datum (WGS 1984). The soil properties (z value) were then interpolated (a process of obtaining a soil property value at an unsampled location within a field of sampled locations) using ordinary kriging (OK) (Wollenhaupt *et al.*, 1997). Ordinary kriging is calculated by the following equation (Webster and Oliver, 2014):

$$Z^*(x_0) = \sum_{i=1}^{n} \lambda_i z(x_i) \qquad (1)$$

Where $Z^*(x_0)$ is the predicted value at the position x_0, $z(x_i)$ the known value at the sampling site x_i, λ_i the weighting coefficient of the measured site and n is the number of sites within the neighborhood searched for the interpolation. Ordinary kriging is the most widely used technique to estimate the value of a soil property at an unsampled location using the structural property of a semivariogram (Mondal *et al.*, 2020). The estimates are the best of their kind in the sense that they are unbiased and the variance, which is also estimated, is the minimum (Oliver and Webster, 2014). OK relies on the spatial autocorrelation of measured points to interpolate the values in the spatial field with distance as a function defined by the variogram modeling (Oliver and Webster, 2014). Ordinary kriging provides less bias in prediction than any other interpolation method (Burges and Webster, 1980). This is because when interpolating at a location where a measurement exists, kriging will always generate a value equal to the measured value (Mulla and McBratney, 2002). Therefore, kriging is the best interpolation technique that aided in defining the major limitations in banana production.

4.3. Results

4.3.1. Descriptive statistics of soil nutrients

The descriptive statistics for the selected soil macro and micro-nutrients across the 12 ha banana plantation are presented in Table 4.2. Soil P varied widely across the plantation, ranging from 1 to 44 mg/kg with a mean of 22 mg/kg and a high coefficient variation (CV) of 50%. Likewise, K ranged from 82 to 516 mg/kg, with a mean of 212 mg/kg and a high CV of 50%. Soil Ca ranged from 715 to 4364 mg/kg with a mean of 2338 mg/kg and a high CV of 40%. In contrast, TN varied slightly across the plantation, ranging from 0.3 to 1.1 g/kg with a mean of 0.58 g/kg and a medium CV of 28%. Similarly, Mg ranged from 238 to 751 mg/kg with a mean of 453 mg/kg and a medium CV of 26%.

Additionally, soil micronutrients varied widely across the banana plantation. Specifically, Zn ranged from 0.2 to 16 mg/kg, with a mean of 7 mg/kg and a high CV of 60%. Similarly, soil Mn ranged from 5 to 78 mg/kg with a mean of 27 mg/kg and a high CV of 58%. Once again, soil Cu ranged from 3.5 to 23 mg/kg with a mean of 12 mg/kg and a high CV of 39%.

Table 4.2. Descriptive statistics of the soil nutrients (n = 27)

Property	Min	Max	Mean	Median	SD	Skewness	Kurtosis	CV (%)
P (mg/kg)	1	44	22	22	11	0.02	-0.17	51
K (mg/kg)	82	516	212	195	105	1.21	1.49	49
Ca (mg/kg)	715	4364	2338	1987	941	0.43	-0.65	40
Mg (mg/kg)	238	751	453	429	117	0.31	0.1	26
Zn (mg/kg)	0.2	16	7	8	5	-0.11	-0.8	60
Mn (mg/kg)	5	78	27	24	16	1.24	2.67	58
Cu (mg/kg)	3.5	23	12	12	6	0.43	0.23	39
TN (g/kg)	0.3	1.1	0.58	0.5	0.16	1.47	2.79	28

*SD, Standard deviation; CV, Coefficient of variation; SE, Standard error, P, phosphorus; Ca, calcium; Mg, magnesium; Zn, zinc; Mn, manganese; Cu, copper; TC, total carbon; TN, total nitrogen.

4.3.2. Spatial structure of the soil nutrients

The semivariograms were extensively adopted to determine the spatial structure of the soil nutrients. The parameters of the semivariograms are given in Table 4.3 and the semivariograms of the nutrients are shown in Figs. 4.1 to 4.3. Analysis of the isotropic variograms indicated that P and K were well described by the spherical model (Fig. 4.1a-c), while TN was described by the linear model (Fig. 4.1b) (Table 4.3). The nugget and sill of P were 6 and 126 respectively, while the range was 51 with a determination coefficient of 0.43. Both the nugget and sill of TN were 0.03 with a range of 234 and a determination coefficient of 0.34. The nugget and sill of K were 10 and 12020 respectively with a range of 130 and a determination coefficient of 0.70. The best-fitted models for Ca (Fig. 4.2.a) and Mg (Fig. 4.2b) was the linear and exponential model respectively (Table 4.3). The nugget and sill of Ca were 818206 with a range of 234 and a determination coefficient of 0.74. The nugget of Mg was 9300 with a sill of 28060, while the range and determination coefficient were 1833 and 0.15 respectively.

Table 4.3. The optimal parameters of fitted semivariogram models for soil nutrients across the banana plantation

Variable	N	Model	Nugget variance (Co)	Sill (Co + C)	Range (Ao)	N:S (%)	(R^2)
P (mg/kg)	27	Spherical	6	126	51	5	0.43
K (mg/kg)	27	Spherical	10	12020	130	0.08	0.70
Ca (mg/kg)	27	Linear	818206	818206	234	100	0.74
Mg (mg/kg)	27	Exponential	9300	28060	1833	33	0.15
Zn (mg/kg)	27	Exponential	11	26	721	42	0.26
Mn (mg/kg)	27	Spherical	0.1	279	110	0.04	0.68
Cu (mg/kg)	27	Linear	23	23	234	100	0.01
TN (mg/kg)	27	Linear	0.03	0.03	234	100	0.34

*P, phosphorus; K, potassium; Ca, calcium; Mg, magnesium; Zn, zinc; Mn, manganese; Cu, copper; TN, total nitrogen; N:S, nugget to sill ratio; R^2, determination coefficient.

The best-fitted models for Zn (Fig. 4.3a), Mn (Fig 4.3b), and Cu (Fig. 4.3c) was the exponential, spherical, and linear model respectively. The nugget of Zn was 11 with a sill of 26 while the range and determination coefficient were 721 and 0.26 respectively. Soil Mn had a nugget of 0.1 and sill of 26, while the range and determination coefficient were 110.1 and 0.68 respectively. The nugget and sill of Cu were both 23.49, while the range was 234 and the determination coefficient was 0.01.

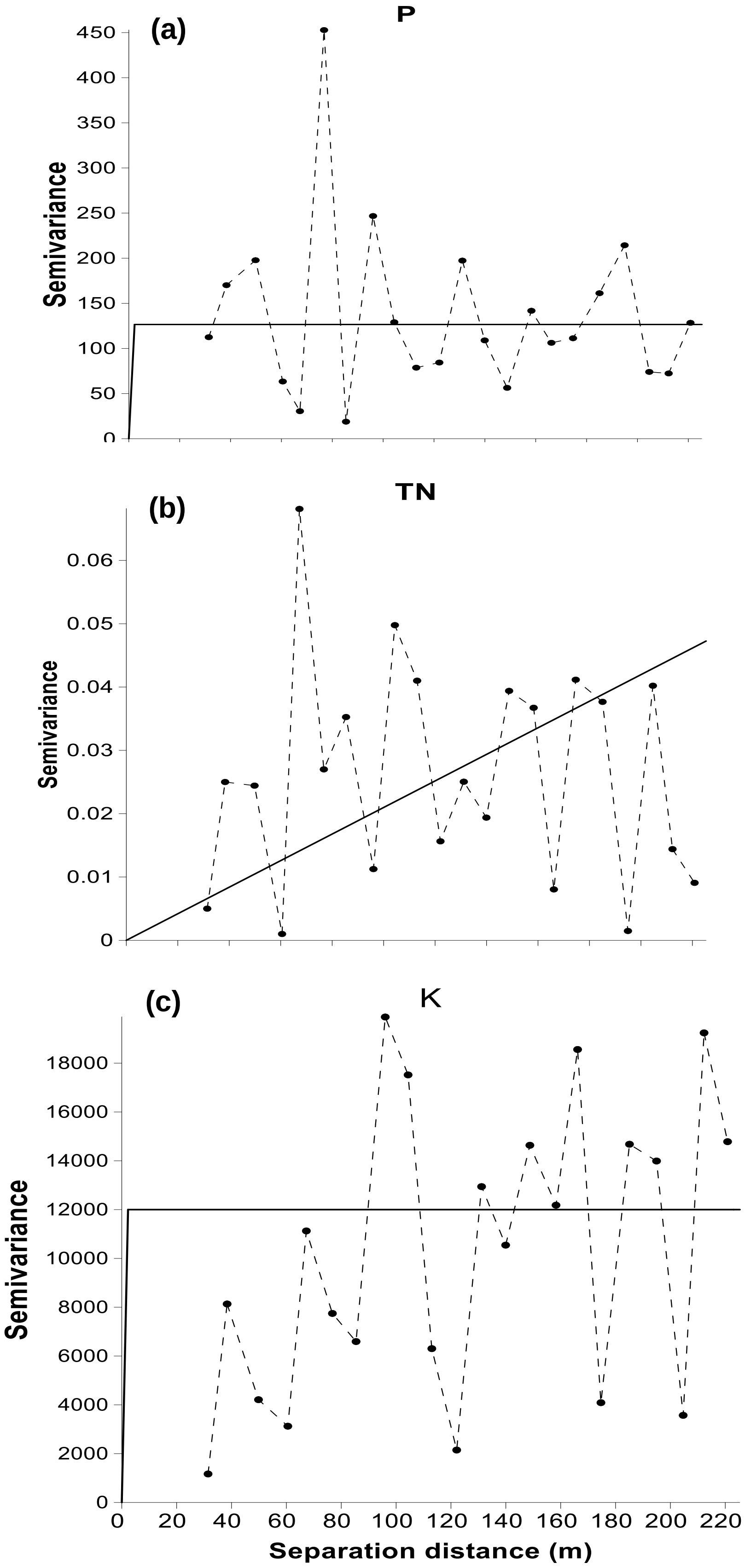

Fig. 4.1. Semivariograms of soil (a) phosphorus (P), (b) total nitrogen (TN) and (c) potassium (K) across the 12 ha banana plantation.

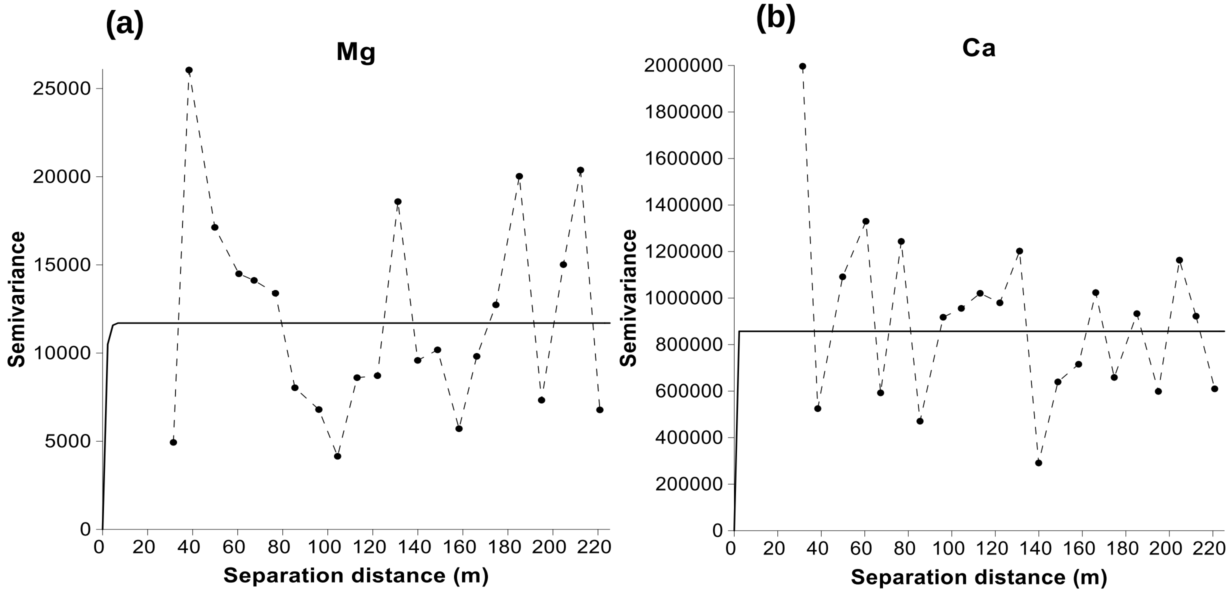

Fig. 4.2. Semivariograms of soil (a) calcium (Ca) and (b) magnesium (Mg) across the 12 ha banana plantation.

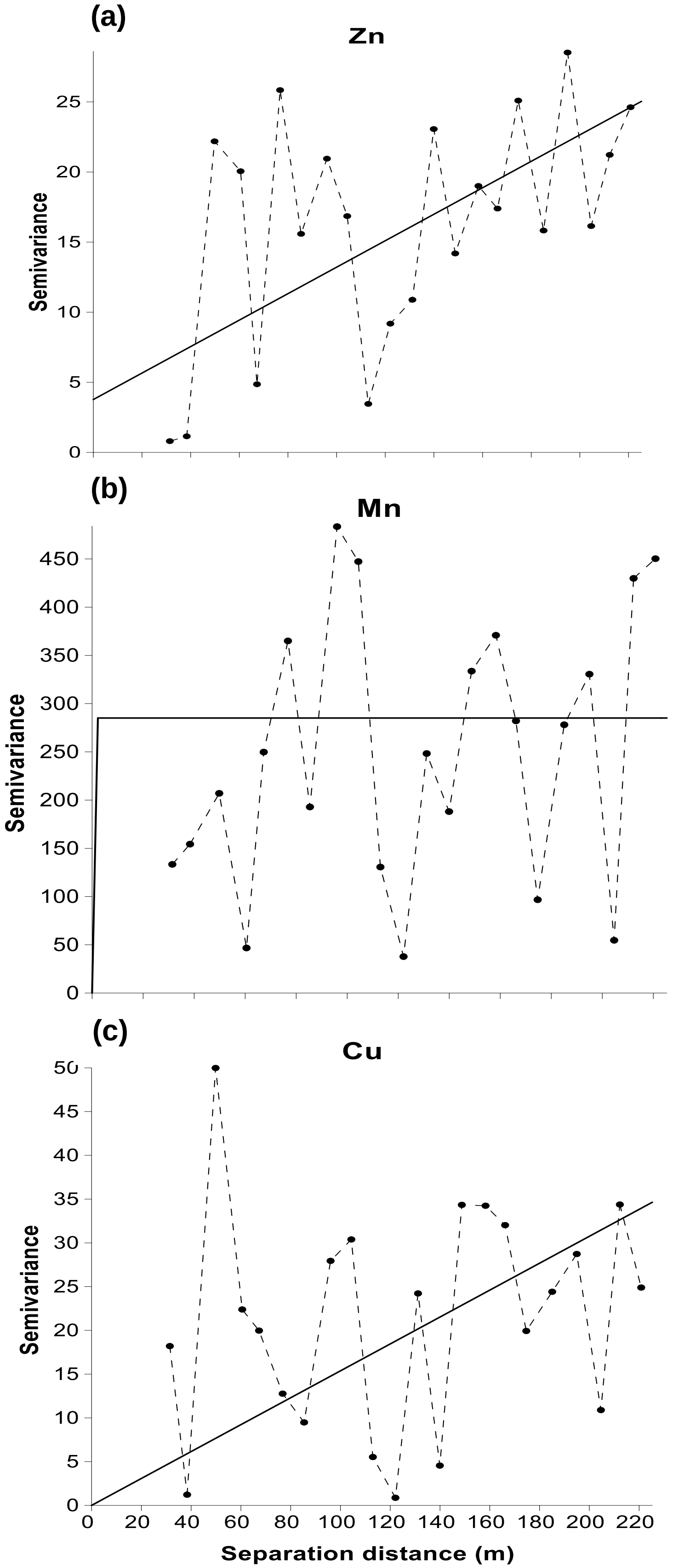

Fig. 4.3. Semivariograms of soil (a) zinc (Zn), (b) manganese (Mn) and copper across the 12 ha banana plantation.

4.3.3. Spatial distribution of soil nutrients across the 12 ha banana plantation

The surface predicted maps of P, K, and TN are illustrated in Fig. 4.4. The map of P shows that there's a slight variation in the distribution of P across the banana plantation farm. The slightly low P content was poorly distributed in the northwest part of the farm while the slightly high P content was distributed in the northeast part (Fig. 4.4a). Soil TN changed markedly from the east to the west part of the farm (Fig. 4.4b). The low TN content was poorly distributed in the east-northeast part of the study area surrounded by coarse bands which shows an increase in the TN content with the highest in the west part of the study area. The K content changed markedly from the northwest to the southeast part of the study area as shown by Fig. 4.4c. The low K content was less variable in the northwest part of the study area with the high K content highly variable in the south to the southeast part of the plantation.

The spatial maps of Mg, and Ca are depicted in Fig. 4.5. As shown by Fig. 4.5a, the low Mg content was highly variable at the center of the study area surrounded by bands that show a continuous increase in Mg content outwards with the high Mg content less variable in the northwest part of the farm. The Ca content changed markedly from the southeast to the northwest part of the farm as shown by Fig. 4.5b. The low Ca content was highly variable in the southeast part of the farm with the high Ca content highly variable in the west to the northwest part of the plantation (Fig. 4.5.b).

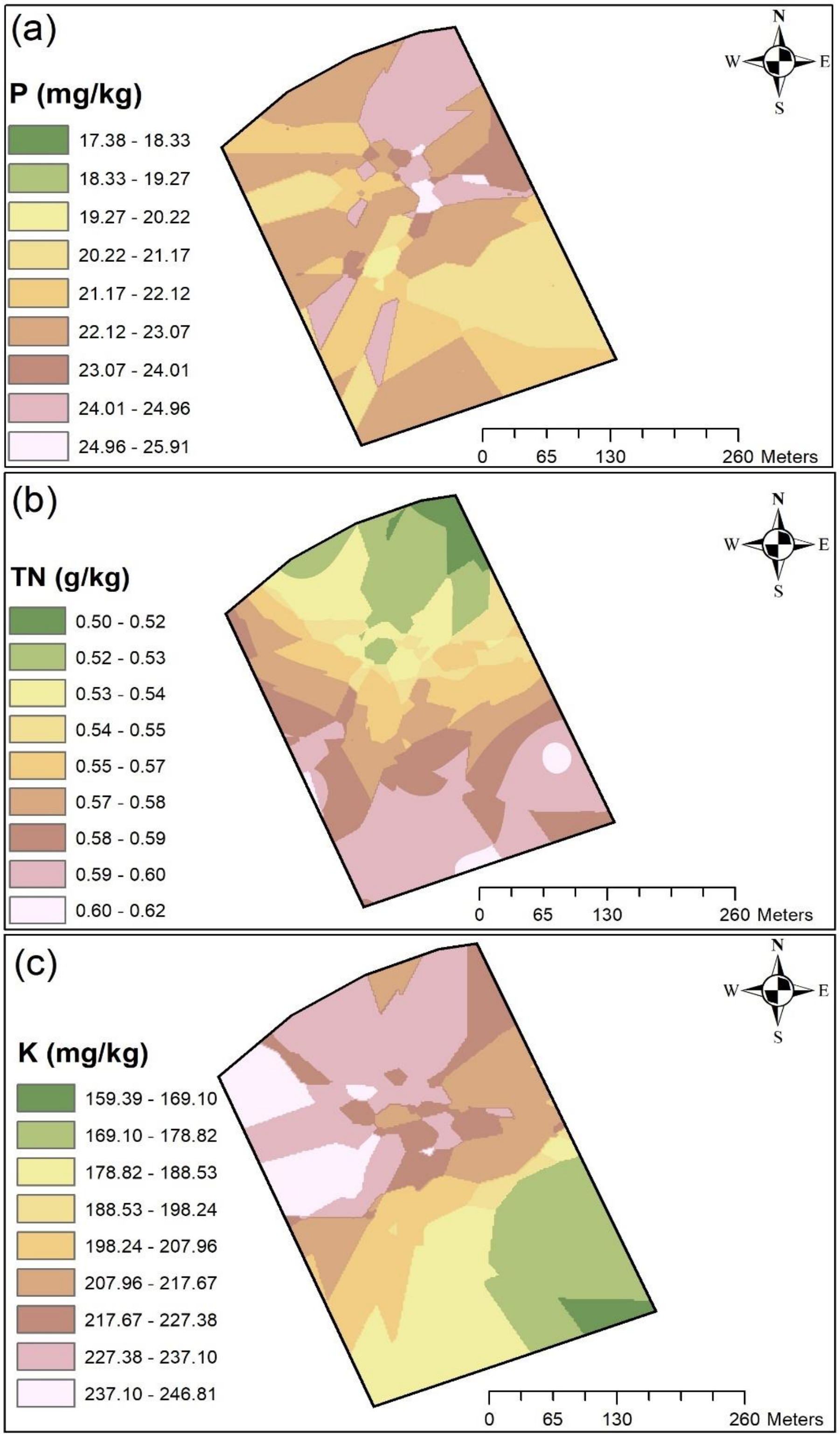

Fig. 4.4. Spatial distribution of soil (a) phosphorus (P), (b) total nitrogen (TN) and (c) potassium across the 12 ha banana plantation.

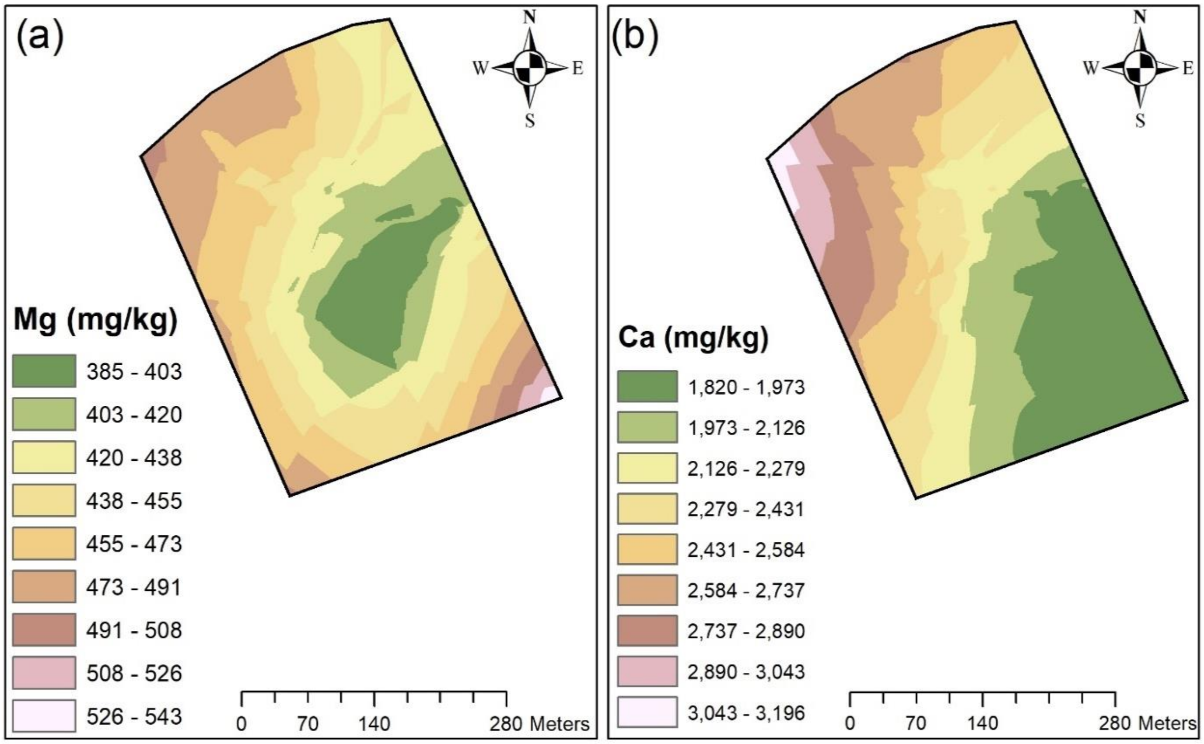

Fig. 4.5. Spatial distribution of (a) magnesium (Mg) and (b) Calcium (Ca) across the 12 ha banana plantation.

The spatial maps of the selected micronutrients are depicted in Fig. 4.6. As shown by Fig. 4.6a, low content Zn was poorly distributed in the northwest part. The map further reveals a marked increase (bands) change of the Zn content towards the centre of the farm with patches of the high Zn content in the middle. The Mn content followed a similar trend to Zn content (Fig. 4.6b). However, Mn patches of high Mn content were found in the southwest part of the farm. There was a low variation of soil Cu as shown by the Cu map, slightly low soil Cu content was evenly distributed across the farm (Fig. 4.6c).

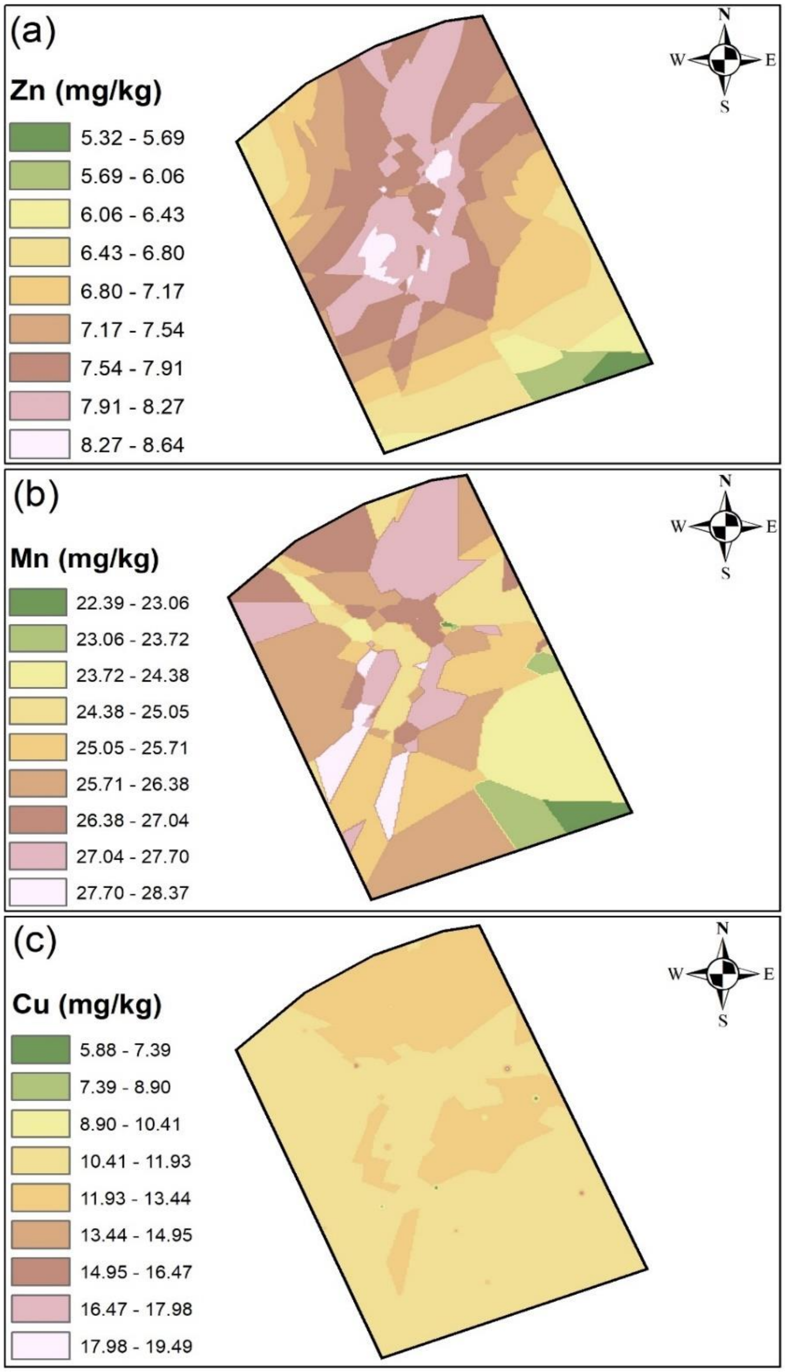

Fig. 4.6. Spatial distribution of (a) zinc (Zn), (b) manganese (Mn) and (c) copper (Cu) across the 12 ha banana plantation.

4.3.4. Correlation of soil nutrients and edaphic factors

The univariate correlation analysis (shown in Table 4.4) showed that the macronutrient P was positively correlated with K (r = 0.55), Zn (r = 0.55), Mn (r = 0.59), Cu (r = 0.52), and C:N (r = 0.47). Potassium was mainly positively correlated with Mn (r = 0.85), Cu (r = 0.64), and Zn (r = 0.6) and negatively related to Exch. acidity (r = -0.47). Total nitrogen was positively correlated with TC (r = 0.66) and clay content (r = 0.56). Calcium was positively correlated with Mg (r = 0.42), pH (r = 0.72), and ECEC (r = 0.98). Magnesium was positively correlated with ECEC (r = 0.58), Cu (r = 0.44), and C:N (r = 0.48), but negatively correlated with elevation (r = -0.39).

Zinc was positively correlated with Mn (r = 0.64) and Cu (r = 0.61) but negatively correlated with Exch. acidity (r = -0.72). Manganese was positively correlated with Cu (r = 0.76), TC (r = 0.40), C:N (r = 0.43) and clay content (r = 0.39) but negatively correlated with Exch.acidity (r = -0.63). Copper was positively correlated with clay content (r = 0.54; $p < 0.05$), but negatively affected by Exch. acidity (r = -0.4) across the 12 ha banana plantation.

Table 4.4. Pearson correlation coefficients of soil nutrients and edaphic factors across the 12 ha banana plantation.

	Elevation	P	K	Ca	Mg	Exch. Acidity	ECEC	pH	Zn	Mn	Cu	TC	TN	C:N	Clay
Elevation	1														
P	-0.07	1													
K	-0.07	**0.55**	1												
Ca	-0.02	-0.29	-0.07	1											
Mg	**-0.39**	-0.04	0.18	**0.42**	1										
Exch. Acidity	0.1	-0.33	**-0.47**	-0.11	-0.15	1									
ECEC	-0.1	-0.25	0.02	**0.98**	**0.58**	-0.14	1								
pH	0.22	-0.17	-0.21	**0.72**	0.01	-0.21	**0.65**	1							
Zn	0.1	**0.55**	**0.6**	0.1	0	**-0.72**	0.12	0.19	1						
Mn	-0.15	**0.59**	**0.85**	-0.34	0.08	**-0.63**	-0.25	-0.37	**0.64**	1					
Cu	-0.03	**0.52**	**0.64**	-0.13	0.28	**-0.4**	-0.03	-0.22	**0.61**	**0.76**	1				
TC	**-0.43**	0.31	0.32	0.02	**0.44**	-0.27	0.12	-0.2	0.12	**0.4**	0.3	1			
TN	-0.09	-0.06	0.06	0.18	0.14	-0.22	0.2	0.03	0.22	0.1	0.06	**0.66**	1		
C:N	**-0.48**	**0.47**	0.35	-0.12	**0.48**	-0.13	0	-0.31	-0.02	**0.43**	0.38	**0.81**	0.11	1	
Clay	-0.17	0.38	0.36	0.09	0.26	-0.19	0.15	-0.07	0.25	**0.39**	**0.54**	**0.75**	**0.56**	**0.56**	1

*P, phosphorus; K, potassium; Ca, calcium; Mg, Exch. Acidity, exchangeable acidity; ECEC, effective cation exchange capacity; Zn, zinc; Mn, manganese; Cu, copper; TC, total carbon; TN, total nitrogen. Significant correlations ($p < 0.05$) are highlighted in bold.

4.3.5. Distribution of soil nutrients with varying soil types

As shown in Fig. 4.7a, the average P content was higher in Valsrivier (25 mg/kg) as compared to Glenrosa (21.1 mg/kg), Hutton (20.3 mg/kg), and Westleigh (15.4 mg/kg). Average K content (shown by Fig. 4.7b) was higher in Glenrosa (251.20 mg/kg) as compared to Valsrivier (234.1 mg/kg), Hutton (153.0 mg/kg) and Westleigh (119.7 mg/kg). The average mean TN content was slightly lower in Hutton soil (0.54 g/kg) as compared to Glenrosa (0.52 g/kg), Valsrivier (0.59 mg/kg), and Westleigh (0.65 mg/kg) being the highest (Fig. 4.7c).

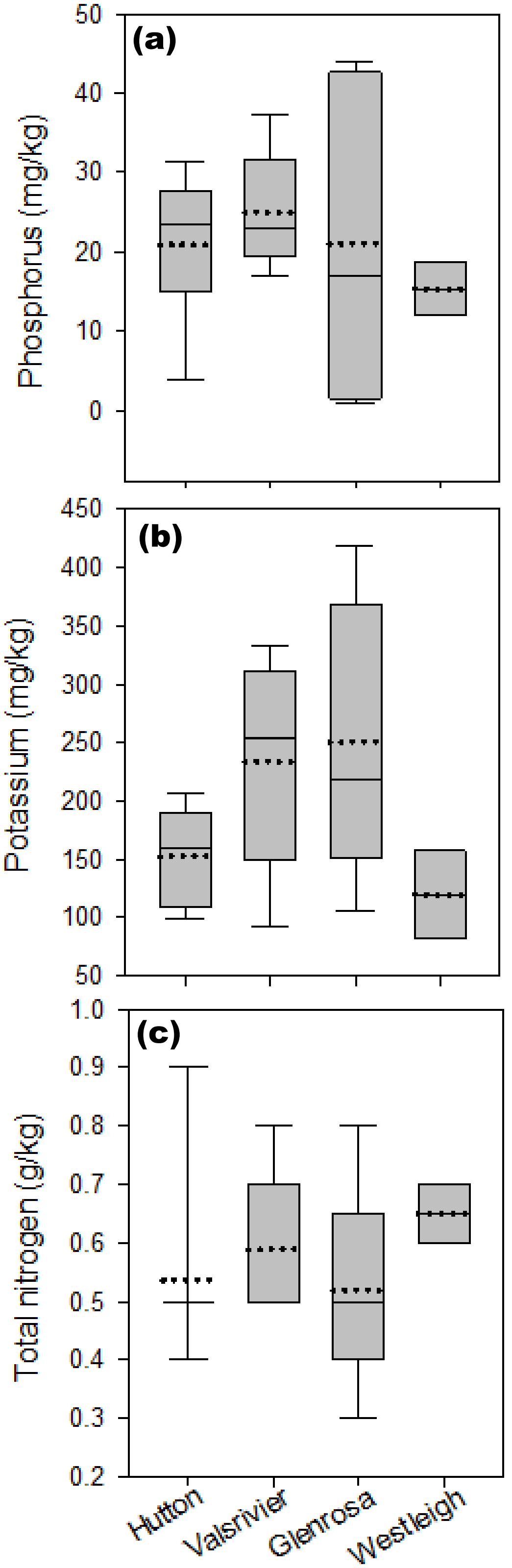

Fig. 4.7. Comparison of soil (a) phosphorus (P), (b) potassium (K), and (c) total nitrogen (TN) in Hutton, Valsrivier, Glenrosa, and Westleigh using box plots, with whiskers extending from the 25th and 75th percentile. The black horizontal line and the black dotted line across the box represent the median and mean respectively. The black dots outside the whiskers represent the outliers.

The average Mg content of Glenrosa (480.34 mg/kg) was higher as compared to Valsrivier (458.19 mg/kg), Hutton (451.95 mg/kg), and Westleigh (384.65 mg/kg) as depicted in Fig. 4.8a. The average Ca content was lower in Westleigh (1502 mg/kg) as compared to Hutton (2079.43 mg/kg), Valsrivier (2632.9 mg/kg), and Glenrosa (2757.32 mg/kg) (Fig. 4.8b).

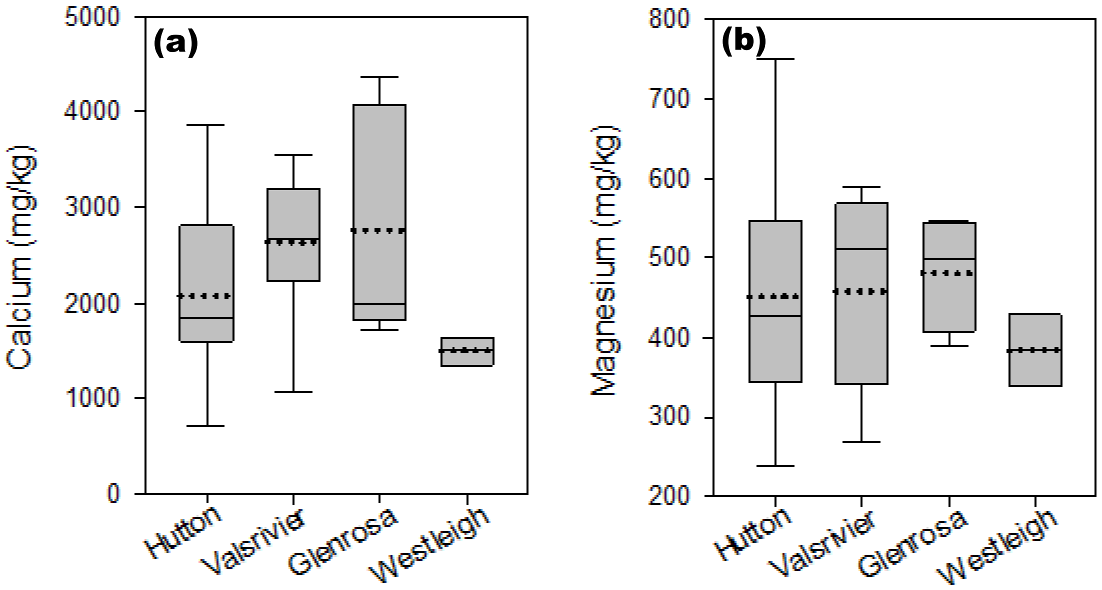

Fig. 4.8. Comparison of soil (a) calcium (Ca) and (b) magnesium (Mg) in Hutton, Valsrivier, Glenrosa, and Westleigh using box plots, with whiskers extending from the 25th and 75th percentile. The black horizontal line across the box represents the median and the black dotted line indicates the mean. The black dots outside the whiskers represent the outliers.

Fig. 4.9a shows that the average Zn content was higher in Valsrivier (8.73 mg/kg) as compared to Hutton (6.4 mg/kg), Glenrosa (5.24 mg/kg), and Westleigh (5.10 mg/kg). Average Mn content (shown by Fig. 4.9b). was lower in Hutton (21.25 mg/kg) as compared to Westleigh (26.15 mg/kg), Glenrosa (26.74 mg/kg), and Valsrivier (28 mg/kg). As shown by Fig. 4.9c the average Cu content was slightly lower in Valsrivier (10.77 mg/kg) as compared to Glenrosa (11.9 mg/kg), Hutton (12.1 mg/kg) and Westleigh (12.9 mg/kg).

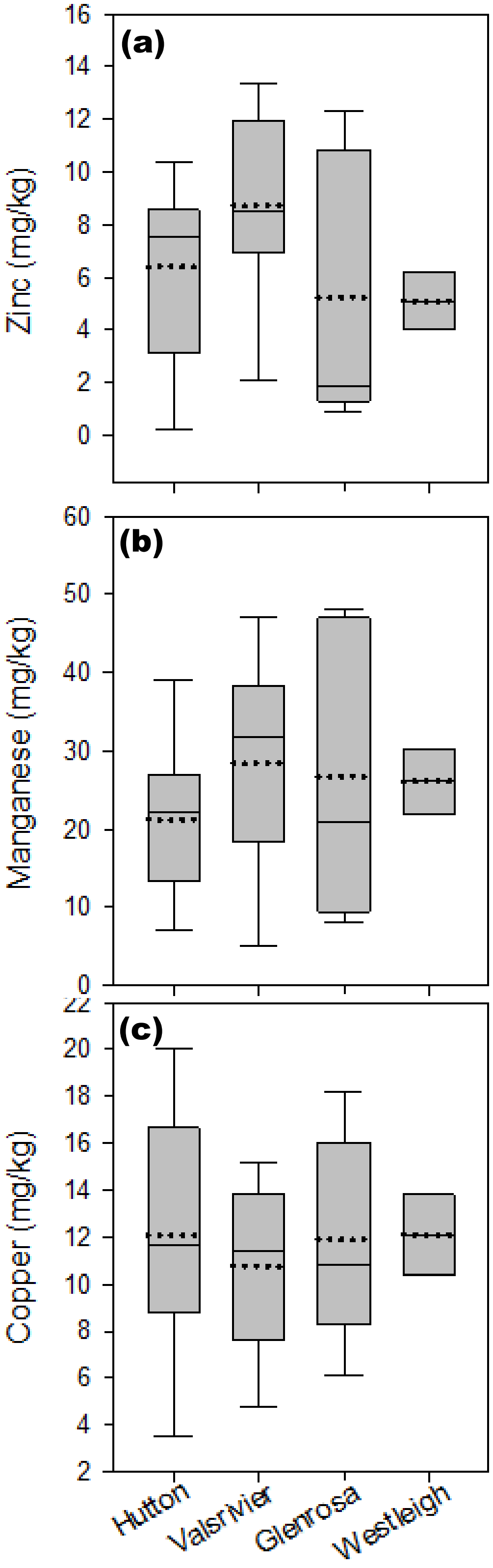

Fig. 4.9. Comparison soil of (a) zinc (Zn), (b) manganese (Mn), and (c) copper (Cu) Hutton, Valsrivier, Glenrosa, and Westleigh using box plots, with whiskers extending from the 25th and 75th percentile. The black horizontal line across the box represents the median and the black dotted line indicates the mean. The black dots outside the whiskers represent the outliers.

4.3.6. Distribution of soil nutrients with varying topographic positions

Soil P was slightly higher in the footslope position (23.25 mg/kg) and lower in the middleslope (21.35 mg/kg) (Fig. 10a). Similarly, TN was slightly higher in the footslope (0.63 g/kg) compared to the middleslope position (0.53 g/kg) (Fig.10b). Soil Mg was higher in footslope (503.08 mg/kg) when compared to the middleslope, where we recorded a value of 430.36 mg/kg. Likewise, Mn was higher in the footslope (30.71 mg/kg) compared to the middleslope (22.9 mg/kg) as shown by fig. 12b. Soil Cu was slightly higher in the footslope (12.73 mg/kg) compared to the middleslope (10.96 mg/kg). On the contrary, soil K was higher in the middleslope (205.91 mg/kg) relative to the footslope (191.5 mg/kg). Compared to the middleslope (205.91 mg/kg), K was lower in the footslope position with a recorded value of 191.5 mg/kg (Fig. 10c). Soil Ca followed the same trend as shown by Fig. 11a, with the footslope recording a value of 2091 mg/kg while the middleslope recorded a value of 2525 mg/kg. Similarly, Zn was slightly higher in middleslope (7.03 mg/kg) as compared to footslope (6.71 mg/kg) (Fig. 12a).

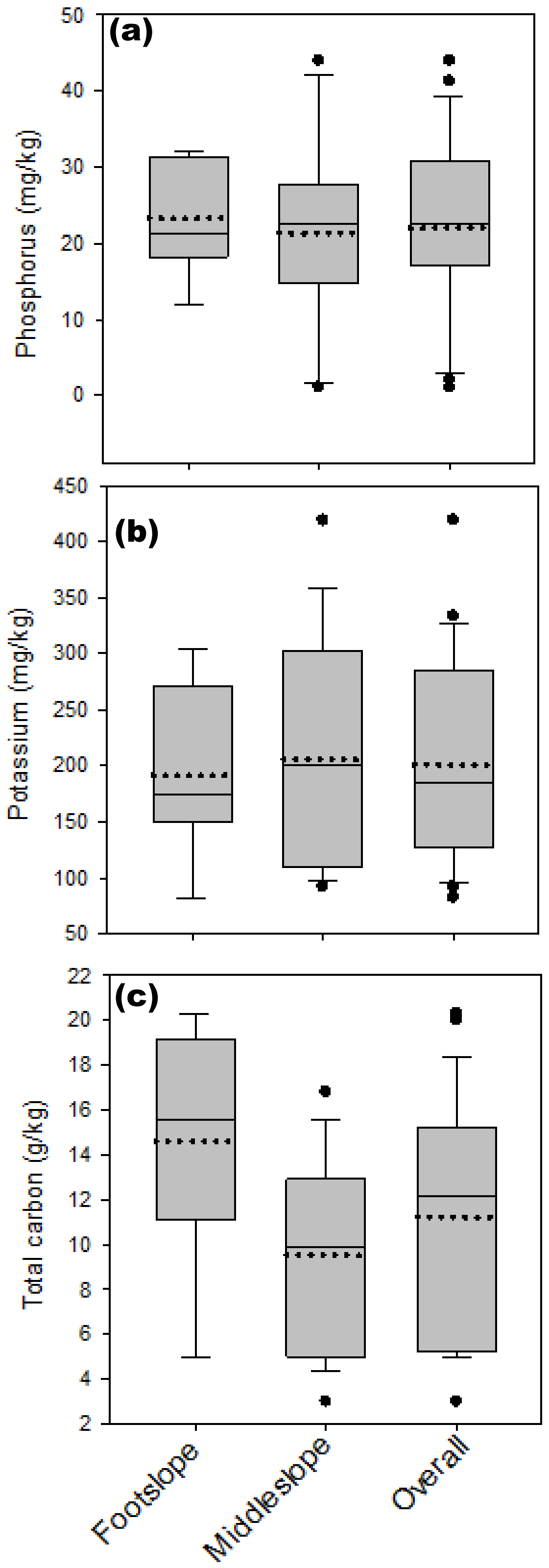

Fig. 4.10. Comparison of soil (a) phosphorus (P), (b) potassium (K) and (c) total nitrogen (TN) in footslope and middleslope using box plots, with whiskers extending from the 25th and 75th percentile. The black horizontal line and the black dotted line across the box represents the median and mean respectively. Black dots outside the whiskers represent the outliers.

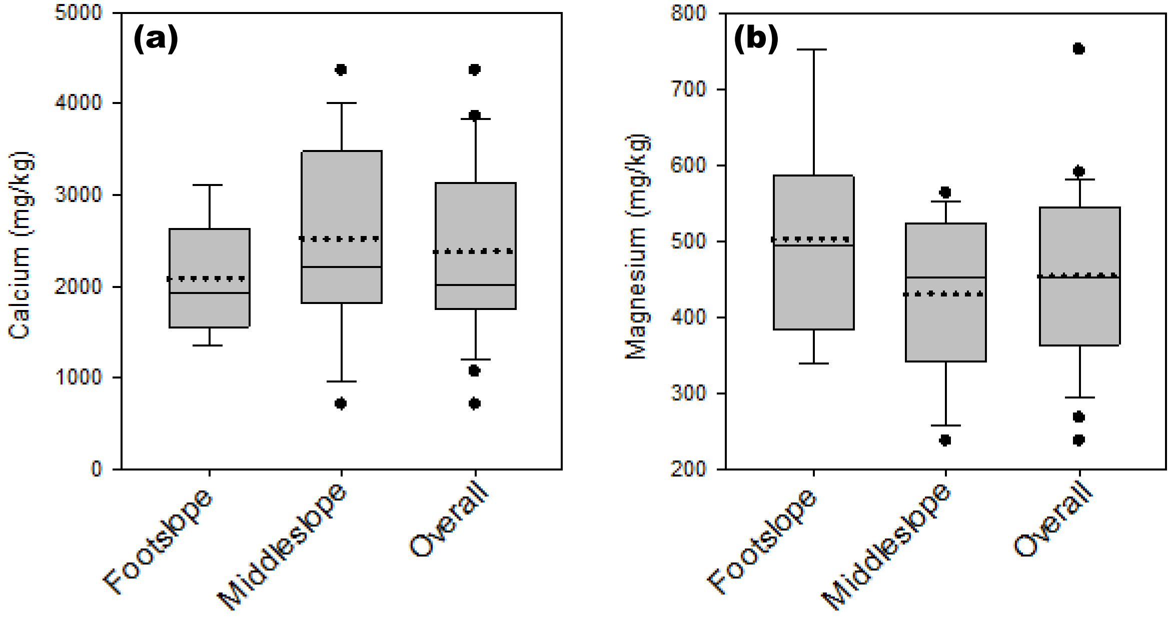

Fig. 4.11. Comparison of soil (a) calcium (Ca) and (b) magnesium (Mg) in footslope and middleslope using box plots, with whiskers extending from the 25th and 75th percentile. The black horizontal line across the box represents the median and the black dotted line indicates the mean. The black dots outside the whiskers represent the outliers.

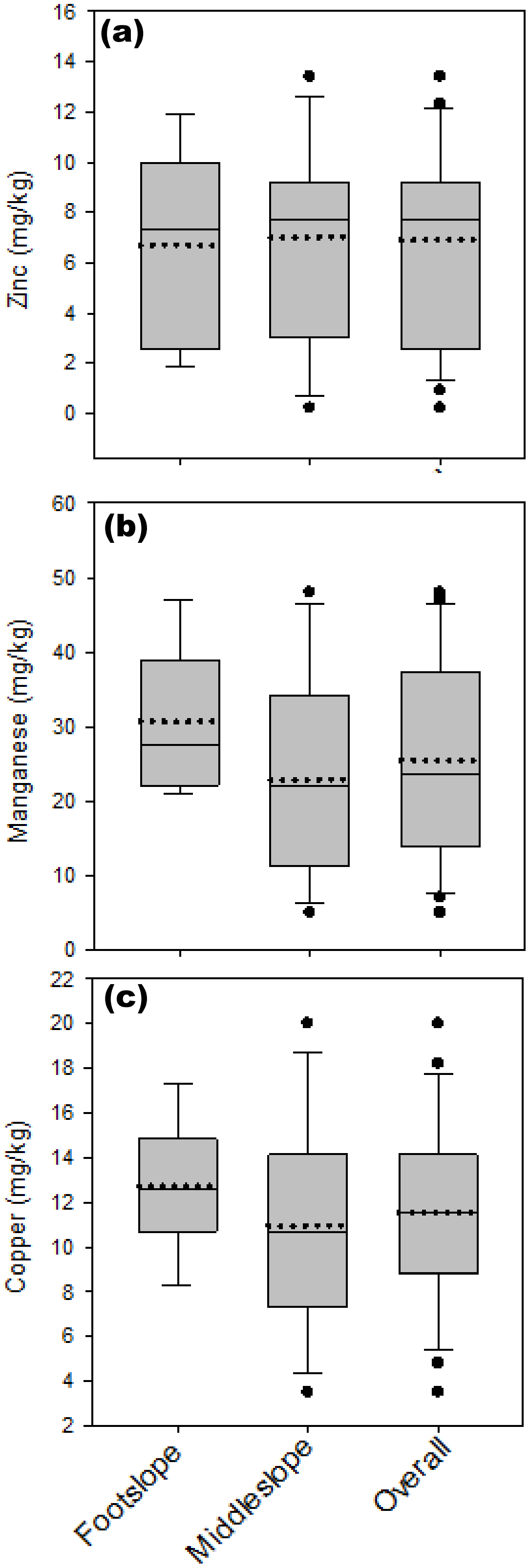

Fig. 4.12. Comparison soil of (a) zinc (Zn), (b) manganese (Mn), and (c) copper (Cu) in footslope and middleslope using box plots, with whiskers extending from the 25th and 75th percentile. The black horizontal line across the box represents the median and the black dotted line indicates the mean. The black dots outside the whiskers represent the outliers.

4.4. Discussion

4.4.1. Spatial variability and structure of soil nutrients across the 12 ha banana plantation

In this study, classical and geostatistical techniques were used to analyse the spatial variability and structure of soil nutrients across the 12 ha banana plantation. We found that P was highly variable (CV = 58%) and had a strong spatial dependency (N:S = 5%). Moreover, the nugget and range of 6 and 51, respectively revealed that P was more correlated at short distances within the farm. The high P variability and strong spatial dependence were driven by the Mn and C:N ratio, an indicator of soil mineralisation in the soil (Dotaniya *et al.,* 2016). The strong spatial dependency might also be ascribed to the potential of the banana plantation in enhancing the growth of beneficial microbial population, especially P solubilising microorganisms and their activity through the deposition of banana residues and litter taking into consideration that the farmer in this study practices mulching (Mondal *et al.,* 2020). This is also supported by the positive correlation of the P and C:N ratio (an important factor determining how easily microorganisms can decompose organic material) (Potthast *et al.,* 2010). Phosphorus originates in the soil both in inorganic and organic forms. Microorganisms decompose the organic P compounds to release P in the simple organic form (Foth and Ellis, 2018). Therefore, the higher microbial activity would promote a good spatial structure of P and increase its availability and uptake by plants (Donoghue *et al.,* 2019). The high variability (CV = 49%) coupled with the strong spatial dependency (N:S = 0.08%) of K at short was driven by the concentration of Mn in the soil (Foth and Ellis, 2018). Soil Mn was also highly variable (CV = 58%) and strongly spatial dependent (N:S = 0.04). The high variability and strong spatial dependency of Mn were driven by clay content as shown by the positive correlation between Mn and clay content. Clay particles tend to carry a negative charge, so they tend to hold onto the polyvalent Mn (Kome *et al.,* 2019). The strong spatial dependency of K and Mn might also be ascribed to the higher microbial activity which was promoted by mulching using banana residues. Higher microbial activity has been linked to a good spatial structure (shown by strong spatial dependency) of soil nutrients (Donoghue *et al*., 2019).

The micronutrient Zn was found to be highly variable (CV = 60%) and moderately spatial dependent (N:S = 42%) and was also found to be correlated to Mn. Soil Zn has been reported to have low mobility in soils (Chesworth, 1991) and tends to be adsorbed on clay-sized particles (Alloway, 2008). The higher spatial variability and moderate spatial dependency of Zn were driven by Mn and Cu in this study. The moderate spatial dependency might be due to mulching (contributing to organic carbon) as well as finer fractions of soils (clay particles) leading to an increase in the surface ion exchange and thus increasing the Zn content in some areas of the farm (Sharma *et al*., 2003). Magnesium was moderately variable (CV = 26%) and moderately spatially dependent (N:S = 33%) across the 12 ha plantation. The moderate spatial dependency of Mg may be controlled by ECEC, TC, and C:N in the banana plantation. The correlation of Mg, TC, and C:N might be because soil organic carbon (SOC) is an important part of soil organic matter (SOM) which influences soil physical, chemical, and biological properties affecting soil nutrient availability to crops (Behera *et al.,* 2018).

Soil Ca (CV = 40%), and Cu (CV = 39%) were highly spatially variable and had a pure nugget (N:S = 100%). Similarly, soil TN had a pure nugget but was moderately variable across the farm (CV = 28%). A pure nugget shows that there is no spatial dependency of these nutrients across the farm. No spatial dependency implies that the spatial structure of the soil nutrients is poor, and this is generally accredited to extrinsic factors. In our case, this means that the distribution of Ca, Cu, and TN was more sensitive to extrinsic factors such as fertilisation, irrigation, and other soil management practices (weeding), which might have led to a reduction in their spatial dependency (Bhunia *et al.,* 2018).

4.4.2. The effect of soil type on the spatial variability of soil nutrients across the banana plantation

In the current study, soil type was the key factor affecting the spatial variability of the soil nutrients across the farm. We found that soil P and Zn were higher in Valsrivier soil by 38% and 41% respectively compared to Westleigh soil. Valsrivier soils are characterised by 2:1 clay-type mineral which has a greater cation exchange capacity (CEC) (ECEC was 17.6 cmol/kg) and high surface area (IUSS Working WRB, 2015). On the other hand, Westleigh soils are characterised by 1:1 kaolinitic clay, which has low CEC (ECEC was 11 cmol/kg), low surface area, and low base saturation (Driessen *et al.,* 2000). Soil minerals with low CEC (i.e., ECEC) often have a higher affinity for anions hence the low

P, Mg, and Zn in Westleigh soils (Qafoku *et al.,* 2004). The high amounts of P and Zn in Valsrivier soils might be attributed to the presence of 2:1 smectite minerals. Smectite minerals offer exchange sites that hold a number of essential nutrients in their cationic form (Sollins *et al.,* 1988). The nutrients are retained by the outer-sphere complex formation and may be taken up by plant roots through diffusion and mass-flow transfer processes (Dotaniya *et al.,* 2016; Yadav *et al.,* 2016).

Soil K, Mg, and Ca were high in Glenrosa soil compared to Westleigh soil by 52%, 20%, and 45% respectively. Glenrosa soils are characterised by a 2:1 clay-type mineral (smectite) which has a high surface area and negative surface charge, which is responsible for the adsorption and release of nutrients such as K and Ca since bonds are held together by weak oxygen-to-oxygen bonds (Kome *et al.,* 2019). Westleigh soil (pH = 5.3) was more acidic than Glenrosa soil (pH = 5.7), and high acidic soils have poor K^+ binding capacity and thus are low in K (Pilbeam and Barker, 2007). Furthermore, incipient soil formation and proximity of readily recognised rock material close to the surface suggest a high base in the status of Glenrosa soils (Fey, 2010).

Total nitrogen was high in Westleigh soil by 17% compared to Hutton soil. Nitrogen in soil comes from the mineralisation of SOM (Berg, 2000) and Westleigh soil had a higher TC compared to Hutton soil. This is also supported by the significant positive correlation between TN and TC (r = 0.66). Manganese content was higher in Valsrivier soil by 24% compared to Hutton. This result might be because Valsrivier has higher ECEC as compared to Hutton soil (Driessen *et al*., 2000). The overriding feature of Hutton soils is uniformity of B horizon colour (referred to as the red apedal B). The apedal soils are characterised by a relatively low CEC (< 11 cmolc kg-1 clay) reflecting oxidic mineralogy in association with a predominantly kaolinitic clay mineral assemblage (Fey, 2010). Soil Cu was 17% high in Westleigh soil compared to Valsrivier soil. The results could be explained by the positive relationship between Cu and clay content. We found that Westleigh soil on average had a high clay content compared to Valsrivier soil.

4.4.3. The effect of topography on the spatial variability of soil nutrients across the banana plantation

In this study, the topographic position had minimal influence on the distribution of the soil nutrients across the sampled banana plantation. Soil Mn, TN, and Mg were high in the footslope position compared to the middleslope position by 34%, 19%, and 17%

respectively. Moreover, Cu (16%) and P (9%) were also slightly higher in the footslope respectively. The higher Mn and Cu content in the footslope could be attributed to high clay content. In general, it was found that clay content on the footslope (42%) was higher than the middleslope position (36%). The slight increase in clay content in the footslope could be driven by soil erosion. During the process of soil erosion finer particles get suspended in the accumulating water and are transported down the slope with nutrients (this is to be expected since clay particles are capable of absorbing soil cations on sites on their surfaces that carry unsatisfied negative charges), thus leaving coarser material at the top positions (Khan *et al.,* 2013). Coarse textured soils encourage the leaching (removal of nutrients from the topsoil to the subsoil beyond the reach of roots of plants) of nutrients from the soil (Bronson *et al.,* 1997). This is because coarser fractions are chemically inert and are incapable of absorbing cations (Khan *et al*., 2013). The high TN and Mg in the footslope position are because of their association with TC. Soil TN and Mg in the study were positively correlated with TC (r = 0.66). Organic matter (expressed by TC % in our study) is capable of absorbing soil cations on sites on its surfaces that carry unsatisfied negative charges (Berg, 2000)). High TC was found in the footslope (15%) compared to the middleslope position (10%). Low-lying areas hold more water either from rain or irrigation, and this results in seasonal submergence, depletion of oxygen, and proliferation of anaerobic microorganisms (Bado and Bationo, 2018). Thus, leading to a slower decomposition of organic residues in lowlands than in uplands thereby favouring the accumulation of SOC (Bronson *et al*., 1997). This is also supported by the negative relationship observed in this study between TC and elevation. The results of this further revealed that soil Ca was also higher (21%) in the middleslope position compared to the footslope position, but the difference was not significant. Similarly, soil K (8%) and Zn (5%) were slightly higher in the middleslope compared to footslope. Soil Ca was strongly influenced by pH which explains the high soil Ca content in the middleslope. Soil pH in the middleslope (5.7) was marginally higher than in the footslope position (5.2). Low soil pH results in less CEC of the soil (pH was a controlling factor of ECEC in our study). Soils that have less CEC have fewer exchangeable cations (such as soil Ca), and these nutrients are required in large quantities by the crop (McCauley *et al*., 2014).

4.4.4. Spatial distribution of soil nutrients across the 12 ha banana plantation

From the distribution maps, we found that soil nutrients P and Zn were higher in northeast part under the footslope and middleslope respectively and this part was mostly underlain by Valsrivier soil. The lower soil P and Zn contents were found in the northwest part of the farm under the middleslope and footslope respectively and underlain by Westleigh soil. Potassium, Mg, and Ca were higher in the south to southwest (underlain by Glenrosa), with both K and Ca found in the middleslope position and Mg under the footslope position. Soil K and Ca were lower in the footslope, and Mg was lower in the middleslope in the northwest part (underlain by Westleigh soil) of the farm. Total N was higher in the west part (underlain by Westleigh) in the footslope position and lower in the east-northeast part (underlain by Hutton) in the middleslope position of the farm. Soil Mn was low in the northwest part (underlain by Hutton soil) located in the footslope with the high Mn content in the centre of the farm (underlain by Valsrivier), mainly middleslope position. The variability of the soil nutrients across the 12 ha banana plantation was influenced by a combination of agricultural practices (e.g., fertilisation and tillage), soil biophysical characteristics (e.g., soil texture), and forming factors (e.g., topography).

4.5. Conclusion

The purpose of the study was to determine the spatial variability and structure and to identify the factors controlling the distribution of soil nutrients across a 12 ha banana plantation at Makuleke farm. This study has shown that great variation exists in the soil properties across the farm. The most variable soil nutrients were P, K, Ca, Zn, Mn, and Cu, whereas TN and Mg were moderately variable. The soil nutrients exhibited a varied spatial dependency, with P, K, and Mn demonstrating a strong spatial dependency while Zn and Mg had a moderate spatial dependency. In addition, soil Cu, TN, and Ca had a weak spatial dependency. In the study, we found that soil type and topography were the key factors influencing the spatial variability of the soil nutrients across the farm. Soil Mn was found to be the key nutrient driving the spatial variability of P, K, and Zn in the farm. The spatial variability of Ca was controlled by both pH and ECEC, while Mg was only influenced by ECEC. Soil micronutrients Mn and Cu spatial variability were influenced by Cu and clay content respectively. The spatial distribution maps showed that P, Mg, Zn, and Mn were high in the northeast part and low in the northwest part of the banana plantation farm. Similarly, K and Ca were low in the northwest part, but they were high in the south to the southwest part of the farm. Total N was high in the west part and low in the east-northeast part while Cu was evenly distributed across the banana plantation.

The evidence gathered from this study shows that there is a huge variation of soil nutrients across the 12 ha plantation. This can result in over- or under-fertilisation, thus decreasing the efficiency of the fertiliser use and consequently affecting banana growth. In light of the variability, there is a need to demarcate the farm into parcels of relatively homogenous units in order to achieve effective soil management. Fertiliser recommendations without prior soil testing should also be avoided. Therefore, the results of this study will help the farmers to tailor their fertilisation and other soil management practices such as irrigation to specific locations of the 12 ha banana plantation.

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CHAPTER 5: SUMMARY, CONCLUSION, AND RECOMMENDATIONS

The overall aim of this dissertation was to evaluate land capability, soil suitability, and fertility status for sustainable banana production at Makuleke farm. In chapter 3, a field intensive study was conducted to unlock the land capability and soil suitability of Makuleke farm for sustainable banana production. The land capability was determined using the principles and concepts of the FAO Framework for Land Evaluation (FAO, 1976) but adapted to South African conditions by Smith (2006). This approach was done to derive the land capability classes of the farm which were used to check which areas of the farm were arable and non-arable based on the inherent characteristics of the land. Soil suitability analysis for banana production was derived using the principles and concepts of the FAO framework for land evaluation (FAO, 1976) coupled with the guidelines for rainfed agriculture (FAO, 1983) and the criteria proposed by Sys *et al.* (1993) and Naidu *et al.* (2006) for crop requirements of banana. This analysis was determined to check which soils were suitable and not suitable for growing bananas based on the climatic conditions of the area and soil requirements for banana production. Beyond the evaluation of land capability and soil suitability, this work assessed the spatial variability and structure of soil nutrients and identified controlling factors (chapter 4). In this chapter, spatial variability and structure of the soil nutrients were assessed using classical and geostatistical techniques, with which the ordinary kriging method was used to interpolate the unobserved points. A correlation matrix was employed to identify influential factors affecting the spatial variability of soil nutrients across the farm. Spatial distribution maps were used to evaluate which areas of the farm had a low and high levels of nutrients. It is envisaged that such a determination would then be used as a guide by Makuleke farmers to assign appropriate soil management practices chief among which is a nutrient application through organic and inorganic fertilisation.

The results obtained in this dissertation showed that the Makuleke farm investigated in this study was dominated by four different soil forms (i.e., Hutton, Westleigh, Valsrivier, and Glenrosa). Indeed, the variability of the soils in the farm affected the arability of the land and soil suitability for banana production. Soil heterogeneity and topographic position affected the ability of the different portions of the farm to accumulate and lose nutrients essential for banana production. Specifically, land capability analysis revealed varying capability classes from I to VI. Land capability class I covered 17% of the 12 ha portion of the farm, which was classified as very high arable potential, while 60% had medium arable potential (Class III), 6% of the farm had low arable potential (Class IV) and 17 % was considered non-arable (Class VI). Subsequent soil suitability analysis revealed that 12% of the farm is highly suitable (S1), 34% is moderately suitable (S2), 38% is marginally suitable (S3) and 16% is permanently not suitable for banana production (N2). The spatial analysis of soil nutrients through classical and geostatistical techniques indicated that P, K, Ca, Zn, Mn, and Cu had high spatial heterogeneity while Mg and TN had moderate spatial heterogeneity across the farm. Moreover, P, K, and Mn were strongly spatially dependent implying that these nutrients were well structured, while Mg and Zn were moderately spatially dependent, and Ca, Cu, and TN was weakly spatially dependent (suggesting that these nutrients varied randomly or had poor structure). The kriged maps generated using digital soil mapping showed varied patterns of soil nutrients across the farm. As revealed by the maps, the high content of soil P, Mg, and Zn was in the northeast part and the low content was in the northwest part of the farm. Soil K and Ca were low in the northwest part and high in the southwest part of the farm. High TN content was found in the western part with the low in the east-northeast part of the farm. Soil Cu showed even distribution across the banana plantation.

The in-depth classification and description of soil and evaluation of the productive capacity of the land are pivotal to the farmers at Makuleke. Such information could provide an accurate record of the soil resources in the farm and form the basis of land use planning for the sustainable production of bananas. The research results obtained provide the actual reference state of the capability of the land at Makuleke farm as well as the suitability of the soil for banana production. The gathered land's physical characteristics and morphological properties coupled with the spatial variability of soil nutrients crucial for banana production could aid the farmers to make prudent management decisions that would enhance the production of bananas to optimal levels by encouraging site-specific soil management practices (e.g., fertilisation and irrigation). It could further enable land users at the farm to come up with better soil management decisions that could mitigate soil fertility degradation and foster sustainable banana yields.

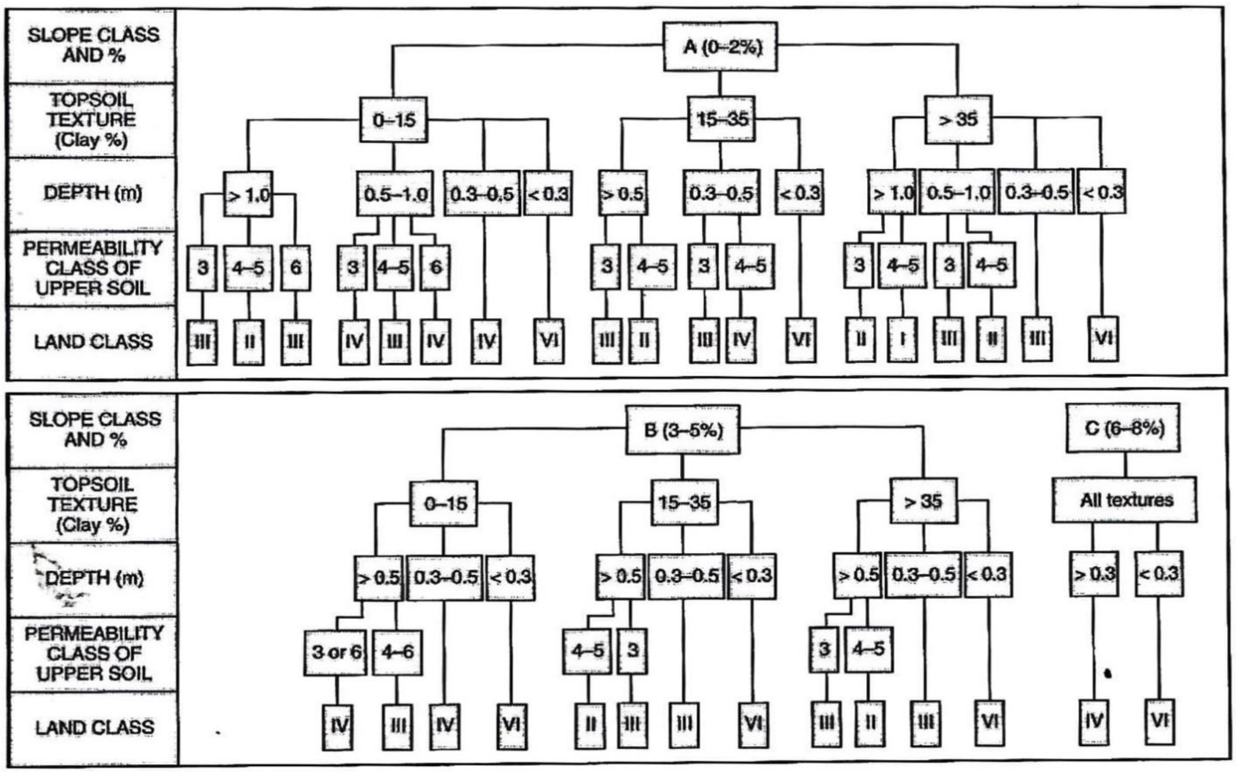
The following recommendations are suggested to achieve sustainable use of the studied soils and thus sustain the production of bananas on the Makuleke farm. A site-specific soil management system should be adopted which embraces a comprehensive approach that considers the spatial variability of the soil, which would allow the usage and management of organic and inorganic nutrient sources. Periodic soil nutrient testing is essential to properly monitor the soil nutrient status and to mitigate soil nutrient depletion. It is also recommended that the farmers should utilize both organic and inorganic fertilisers (non-acidifying types such as nitrate based) to increase banana productivity. The low TN and OC contents in the soils need to be amended through integrated nutrients management. The low TN should be amended by N fertilisation. Soil OC in the soils can be improved by increasing OC inputs and/or reducing losses. Increasing OC inputs can be achieved by adding cover crop mixtures high in C such as grasses and also legumes to stabilise that soil. Reducing losses can be achieved by reducing tillage. In Glenrosa soil, aluminium (Al) toxicity may be a serious problem because of the high acidity (pH = 4.6). Therefore, lime should be applied to raise the pH to above 5.5 to be suitable for banana production. In addition, OM application should be used also to reduce the Al toxicity by binding the Al ions into the OM complexes and also it will help in moisture conservation and nutrients since this soil (Glenrosa) has low clay content (21%). Further studies are needed in similar farms in other agroecological zones for sustainable banana production in South Africa.

APPENDICES

Appendix 5.1. Description of the land capability classes (Camp *et al.*, 1998).

Land capability classes		**Definition of class**	**Conservation need**	**Use-suitability**
ARABLE	I	No or few limitations. Very high arable potential. Very low erosion hazard.	Good agronomic practice	Annual cropping
	II	Slight limitations. High arable potential. Low erosion hazard.	Adequate run-off control	Annual cropping with special tillage or ley (25%)
	III	Moderate limitations with some erosion hazard.	Special conservation practice and tillage methods	Rotation of crops and ley (50%)
	IV	Severe limitations. Low arable potential. High erosion hazard.	Intensive conservation practice	Long term leys (75%)
NON-ARABLE	V	Water course and land with wetness limitations.	Protection and control of water table	Improved pastures, suitable for wildlife
	VI	Limitations preclude cultivation only Suitable for perennial vegetation.	Protection measures for establishment such as sod-seeding	Veld, pasture and afforestation
	VII	Very severe limitations and Suitable only for natural vegetation.	Adequate management for natural vegetation	Natural veld grazing and afforestation
	VIII	Extremely severe limitations and also not suitable for grazing or afforestation	Total protection from agriculture	Wildlife

Appendix 5.2. Guideline for land capability class determination (Smith, 2006).



Appendix 5.3. Description of the suitability classes (FAO, 1976)

Suitability class	Rating	Description
S1	Highly suitable	Land having no significant limitations to sustained application of a given use, or only minor limitations that will not significantly reduce productivity or benefits and will not raise inputs above an acceptable level.
S2	Moderately suitable	Land having limitations which in aggregate are moderately severe for sustained application of a given use; limitations will reduce productivity or benefits and increase required inputs to the extent that the overall advantage to be gained from the use, although still attractive, will be appreciably inferior to that expected on Class S1 land.
S3	Marginally suitable	Land having limitations which in aggregate are severe for sustained application of a given use and will so reduce productivity or benefits, or increase required inputs, that this expenditure will be only marginally justified.
N1	Currently not suitable	Land having limitations which may be surmountable in time, but which cannot be corrected with existing knowledge at currently acceptable cost; the limitations are so severe as to preclude successful sustained use of the land in the given manner.
N2	Permanently not suitable	Land having limitations which appear so severe as to preclude any possibilities of successful sustained use of the