Farm typology and spatial variability of selected soil fertility parameters on selected small-holder farms in KwaZulu-Natal Province, South Africa

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DECLARATION

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Prof P. Muchaonyerwa

ABSTRACT

Diversity of resource endowment, soil and climatic conditions may affect the level of management and productivity and soil fertility in small-holder farms. The objectives of this study were to (i) develop farm typologies, (ii) assess fertility gradients, and (iii) map spatial variability of soil fertility in small-holder farms of uMbumbulu and Msinga regions in KwaZulu-Natal province, South Africa. To obtain data for the identification of farm typologies, a detailed open-ended questionnaire was used with topics including socio-economic attributes, local crops grown, soil amendments, management practices, labour, crop residue management, farmers perceptions and production constraints. The questionnaire was administered to fifty farmers per region. The data which had Kaiser-Meyer-Olkin (KMO) measure values of 0.67 and 0.51 for uMbumbulu and Msinga respectively, qualified for Principal component analysis (PCA). Three PCs which had significant eigenvalues of >1, provided key factors that determine the farm typologies, namely land size, livestock ownership, income from farming and external income. Multiple correspondence analysis (MCA) and cluster analysis were used to analyse quantitative and qualitative data, and variables and aggregate farms into clusters according to production, socioeconomics, and demographics. Three farm topologies were identified, namely (i) resource-endowed farms which have large land and profit from farming (type I), (ii) the middle-resourced group (type II), which is neither poor nor rich, and (iii) Poor resource groups (type III) with limited to no resources at all and have small land holdings and minimum profits from farming. For fertility gradients and mapping, soils were sampled from 0 – 20 cm depth, using a sampling interval of 5×5m and analysed for fertility parameters. There were no fertility gradients observed between homefields and outfields for both sites. Mapping was done only in uMbumbulu site with descriptive statistics (mean, standard deviation, covariance, skewness, and kurtosis) tested for normality to be used for kriging, and only the spherical model was tested in this study using R-Studio. For geo-statistics (Lag size, sill, and nugget) for semiviriograms produced was done using ArcMap-GIS as well as the maps. For type I farms the spatial dependency was strong (< 25%) for most variables tested (pH, total carbon, calcium, magnesium, potassium, and Clay %), while type III had a variety of spatial dependency from pH and clay % were weak (<75%), Ca and total carbon moderate (25-75%) to phosphorus, magnesium, potassium, and acid saturation strong (<25%). Overall implications of these maps can be very useful in targeting specific areas of poor or rich fertility and fertiliser recommendation, which is more economically viable to small-holder farmers to put in what is needed.

Key Words: Farm typology, Fertility gradients, Small-holder farmers, Spatial variability, Spatial dependency

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IN LOVING MEMORY OF MY LATE FATHER MR L.B MANQANA. ULALE NGOXOLO NTSHANGASE.

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1. CHAPTER ONE: GENERAL INTRODUCTION

1.1 Background

Poor and declining soil fertility is a major limiting factor for crop productivity in small-holder farms in Africa (Tittonell *et al.*, 2005a). The decline in soil fertility is driven by processes that are not homogenously distributed in space thus resulting in spatial and temporal variations from field to regional scale. At farm level soil fertility largely depends on soil management including nutrient management and their export via crop harvest (Onwonga and Freyer, 2006; Kuivanen *et al.,* 2016).

Soil management differs between and within farms mainly due to socio-economic factors affecting resource allocation strategies (Tittonell *et al.*, 2005a). Such differences in resource allocation in small-holder farms have consequently led to development of soil fertility gradients between and within farms (Bucagu *et al.*, 2014). Strong soil fertility gradients have been reported on small-holder farms and lead to a decrease in crop yield with increasing distance from homesteads (Muthamia *et al.,* 2011; Kuivanen *et al.,* 2016).

A decrease in chemical fertility (e.g. organic C, total N and available P) from resource endowed to resource constrained fields was recorded in small-holder farms of Zimbabwe (Zingore *et al.*, 2007; Nyamangara *et al.*, 2013). Zingore *et al.* (2007) found that wealthy farmers used substantial amounts of mineral fertilisers, which were distributed evenly across farms resulting in strong gradients between these farms and those owned by poor farmers. Social class is thus a crucial factor influencing the presence or absence of fertility gradients on small-holder farms. Due to different resource availability, there is a difference in terms of gradients between the poor and wealthy farmers (Mugwe *et al.*, 2009; Raiasekharan *et al.,* 2014).

Small-holder farms often consist of multiple fields that are managed differently. Fields closer to the homesteads receive more input of nutrients either as inorganic fertiliser and/or manure, which consequently impact on soil nutrient balances. Giller *et al.* (2011) argued that the continuous concentration of nutrients in homefields, at the expense of nutrient depletion in outfields, leads to overall negative nutrient balances (uneven distribution between the fields). Higher fertility was reported in home-fields than fertility on outfields in western Kenya

(Tittonell *et al.*, 2005b). Negative nutrient balances threaten the long-term sustainability of small-holder agriculture (Tittonell *et al.*, 2013; Kaur *et al.*, 2021).

Several authors have reported higher soil pH in homefields than in outfields (Tittonell *et al.*, 2005b; Zingore *et al.*, 2007; Masvaya *et al.*, 2010). This increase is influenced by the addition of domestic waste, like ash from firewood, kitchen waste and chicken droppings. While soil type differences generally explain variability in cation exchange capacity (CEC),with significantly greater values on clay soils than sandy soil (Masvaya *et al.*, 2010), gradients could also be a result of management. Higher CEC values have also been reported in homefields compared to outfields due to a larger concentration of soil organic matter (SOM) in these fields (Zingore *et al.*, 2007; Masvaya *et al.*, 2010).

A study conducted by Roberts *et al.* (2003) in KwaZulu-Natal, South Africa on two different climatic zones and soils, showed higher soil fertility status for homefields compared to outfields, which was attributed to differential management in these respective fields. They reported that the median adjusted-P was 14 mg L^{-1} in the homefields and 4 mg L^{-1} in the outfields of Obonjaneni and 11 and 3 mg L^{-1} in the Valley of a Thousand Hills for homefields and outfields, respectively. Similar trends were observed for K, pH, and Mg. While they did not study SOC and N, it would be expected that these parameters would also be affected by management, within and across the fields.

Soil fertility gradients in small-holder farms should thus be a research priority to ensure efficiency in resource utilisation within farm systems. Small-holder farms in KwaZulu-Natal occur under different climatic conditions and on different soil types, with respect to the extent of weathering. In addition, the farmers also vary in terms of the extent of resource endowment, and sources of livelihoods, with some depending on remittances and social grants and less on agriculture. This variation determines how soil fertility is managed on these small-holder farms.

A combination of climatic conditions, soil types and management could influence the strength of soil fertility gradients and the need for targeted fertiliser applications on small-holder farms of KwaZulu-Natal. While soil fertility gradients have been shown on small-holder farm settings, there is a paucity of studies on spatial variability of these soil fertility gradients. Understanding such variability in soil fertility is necessary to improve sustainable management, considering that some areas may be fertile and would not need fertilisers, while deficient areas require more additions (Yasrebi *et al.*, 2008; Kaur *et al.*, 2021).

Soil fertility maps are essential for highlighting the nutrient needs, based on fertility status of soils and adverse soil conditions which needs improvement to realise good crop yield (Lelago *et al.*, 2016). Agricultural areas usually have soil chemical fertility that is highly variable (Bogunovic *et al.*, 2017), irrespective of management practices. Farm fields are not homogeneous and appropriate sampling techniques have been recommended to describe field variability (Lelago *et al.*, 2016). Describing these spatial variabilities has been very difficult across the fields until the introduction of new technologies such as global position system (GPS), geographic information system (GIS) and remote sensing (Cambardella and Karlen, 1999; Lelago *et al.*, 2016).

The GIS software package of tools is useful for collecting, storing, retrieving, transforming, and displaying spatial data (Van der Perk *et al.*, 1998). Maps of soil fertility produced using GIS tools help us to understand the spatial and temporal fertility status of the soil and will help in formulating site specific balanced fertiliser recommendation (Patil *et al.*, 2011). Many studies have been done that are based on geo-statistical analysis to designate the spatial variability of different soil properties (Huang *et al.*, 2007; Cao *et al.*, 2011).

Amongst many other geo-statistical methods, the ordinary kriging method is considered the most accurate method in mapping spatial variation of soil fertility, using either exponential or spherical models (Song *et al.*, 2013; Manyevere *et al.*, 2017). The spatial patterns of soil properties namely, pH, OM, P and K that are also commonly measured by Inverse Distance Weighed (IDW) and Spline which are less accurate than Kriging that provides a higher level of prediction accuracy (Song *et al.*, 2013).

1.2 Objectives

The aim of this study was to understand farm typology, examine and map spatial variability of soil fertility gradients on small-holder farms of KwaZulu-Natal. The findings from this study will help find suitable adaptation technique for complex typology systems in small-holder cropping areas. The specific objectives of this study were to:

- Establish farm typology in uMbumbulu and Msinga small-holder farms.
- To assess soil chemical fertility gradients within small-holder farms.
- To map the within field spatial variability of selected soil fertility parameters on small-holder farms.

2. CHAPTER TWO: SOIL FERTILITY GRADIENTS AND SPATIAL VARIABILTY IN SMALL-HOLDER FARMS: A REVIEW

2.1 Background

Nutrient imbalances are a major problem on small-holder farms in the sub-Saharan Africa (SSA) (Tittonell *et al.*, 2005a; Haileslassie *et al.*, 2006). Such imbalances have been observed both within and across farms (i.e., homefields vs. outfields). Zingore *et al.* (2007) defined homefields as fields of less than 50 meters from household and outfields as fields ranging from 100 to 500 meters from household. The difference in nutrient levels within these fields constitute to soil fertility gradients, characterised by an increase or decrease in soil nutrients from homesteads as reference points (Tittonell *et al.*, 2005a).

Several authors have documented higher soil fertility in homefields than in the outfields (Mtambanengwe and Mapfumo, 2005; Tittonell *et al.*, 2005b; Haileslassie *et al.*, 2006; Vanlauwe *et al.*, 2007; Zingore *et al.*, 2007). The greater fertility on homefields was attributed to human-induced variations related to farmer's resource endowment and socio-economic conditions as well as biophysical environment. Farmer driven variations are associated with management practices (field prioritisation in allocation of resources) dependent on the farm typology. Farm typology is often used as a mechanism to simplify the heterogeneous farming systems into small coherent groups (Dunjana *et al.*, 2018). There is strong evidence of differences in nutrient balances between different wealth groups and farms of different distances from homesteads (Zingore *et al.*, 2007). This is mainly because small-holder farm management depends on farmer resource endowment (rich vs. poor) (Tittonell *et al.*, 2005a; Zingore *et al.*, 2007).

Rich farmers have access to resources, like tractors, some irrigation systems, labour availability, capital, and livestock, while the poor have no or minimal livestock and capital (Tittonell *et al.*, 2005a; Vanlauwe *et al.*, 2007; Zingore *et al.*, 2007). Moreover, small-holder farmers tend to adapt various management techniques mostly based on indigenous knowledge, and/or financial constraints (Snapp *et al.*, 1998; Tittonell *et al.*, 2005b; Mugwe *et al.*, 2009).

Most small-holder farmers rely on organic fertiliser inputs such as crop residues and cattle manure (Snapp *et al.*, 1998; Zingore *et al.*, 2007). Livestock ownership leads to easy access to manure often resulting in low investment in mineral fertilisers (Vanlauwe *et al.*, 2007; Zingore *et al.*, 2007; Mugwe *et al.*, 2009). Relying more on manure contributes significantly to soil fertility gradients as this has transport implications resulting in fields closer to homestead receiving more in comparison to outfields.

Literature shows that inherent soilscape fertility gradients are also related to the position of a field along a toposequence. Factors relating to soil fertility gradient along a toposequence can be the differences in soil types and slope terrain. For example, sandy soils tend to have low water holding capacity (WHC), hence water available for crop uptake is limited (Kome *et al.*, 2018). Soils on foot-slopes experience a problem of waterlogging while in mid-slope fields sheet erosion can occur. These effects tend to contribute significantly to soil fertility gradients along slopes.

It is necessary to explore farmer typology and soil heterogeneity with respect to magnitude as well as relating it to landscape and specific management practices in order to understand the complexity of small-holder farming systems. The objectives of this review were thus to investigate (i) the magnitude of soil fertility gradients in small-holder farms, (ii) the relationship between soil management practices, inherent soil-landscape variability, and soil fertility gradients on small-holder farms, (iii) to understand the spatial variability of nutrients in small-holder farms.

2.2 Small-holder farms and their characteristics

Small-holder farmers are rural cultivators practicing intensive, permanent and diverse agriculture on relatively small-scale farms of 0.2 to 2 ha, but vary throughout localities (Tittonell *et al.*, 2005a; Zingore, 2006). Small-holder farms constitute the largest proportion of the farms worldwide (Giller *et al.*, 2011). Family is responsible for managing and facilitating farm activities such as labour, production, consumption and the marketing of the produced goods (Netting, 1993; Mugwe *et al.*, 2009). Women are often a key source of information about on-farm seed conservation, cultivation, and local crop-based gastronomy in their respective communities (Mugwe *et al.*, 2009; Altieri *et al.*, 2012). Small-holder farmers rely on indigenous knowledge which has been transferred from one generation to another (Mugwe *et al.*, 2009). This knowledge has enabled them especially from developing countries, to develop and/or inherit complex farming systems adapted to the local conditions assisting them to sustainably manage harsh environments and to meet their subsistence needs (Altieri *et al.*, 2012). Some farmers achieve this with no or limited mechanisation, chemical fertilisers, pesticides, or other technologies of modern agriculture (Altieri *et al.*, 2012) and contribute significantly to both crop and livestock production.

2.3 Farm typology

Farm typology is an instrument utilised to simplify the diversity of complex small-holder farming systems (Alvarez *et al.*, 2018; Dunjana *et al.*, 2018) . Farm typologies have been used by Musafiri *et al.* (2020) when studying agricultural greenhouse gas emissions in Kenya, (Dunjana *et al.*, 2018) in the characterisation of small-holder food-cash crop production systems in Zimbabwe by Kuivanen *et al.* (2016) in characterising small-holder farming systems and their constraints and opportunities for innovation in Ghana. It was also used in exploring farms' heterogeneity at regional farm scale (Tittonell *et al.*, 2005a) and due to within-farm variability in resource allocation, nutrient flows and soil fertility status in Kenya (Tittonell *et al.*, 2005b). Technological interventions precision, applicability and adoption of new technologies could be improved by understanding these complex systems (Tittonell *et al.*, 2010; Dunjana *et al.*, 2018).

Common typologies presented by literature can vary as Tittonell *et al.* (2005a) defined 3 typologies namely (i) high resource endowment (HRE) which is defined as market oriented larger land size, high livestock ownership and the only constraint is labour, with main source of income salary, pension and other external financial inputs (ii) Medium resource endowment (MRE) defined as self- consumption with low inputs, it is also market oriented with capital and labour constraints, with main source of income coming from cash crop produce from farm. (iii) low resource endowment (LRE) these are subsistence farmers, with land, capital and labour as main constraints and their main source of income is by selling their labour. Similarly, Nyamangara *et al.* (2011) named these typologies as resource groups. Resource group 1 (RG1) are wealthy farmers, resource group 2 (RG2) nor wealthy and nor poor, resource group 3 (RG3) these are poor farmers. Though the terminology may differ, but the definitions are the same, depending on different countries. Later Dunjana *et al.* (2018) used the same definition but different terminology. They identified (i) resourced endowed, commercial oriented farms, (ii) medium resourced and (iii) resource constrained farms which are subsistence.

2.4 Soil management in small-holder farms

2.4.1 Nutrient management

Organic manure, such as cattle manure and compost are the primary sources of nutrients in small-holder farms largely because farmers cannot afford adequate amounts of mineral/chemical fertilisers to apply on their farms (Snapp *et al.*, 1998; Zingore *et al.*, 2007). The application of nutrient amendments in small-holder farms is largely field specific. Commonly, homefields tend to be prioritised since they are used to grow crops for the sustenance of the homestead livelihood. Homefields thus often receive most of the organic resources and commonly used to produce vegetables (Tittonell *et al.*, 2005b; Zingore *et al.*, 2007). However, this is not observed in wealthier farms who can afford to transport significant amounts of manure to distant fields. Wealthier farmers own livestock (Zingore *et al.*, 2007) and can afford large amounts of mineral fertilisers (Tittonel *et al.*, 2005a) compared to poor farmers. Consequently, such differences result in significant soil fertility variation between wealth classes with higher accumulation and positive nutrient balances reported in wealthier farms (Vanlauwe *et al.*, 2015).

Generally, no or limited organic resources are applied to the remote fields (outfields), due to the extra efforts and labour required to transport materials to distant fields resulting on additional costs depending on the distance (Vanlauwe *et al.*, 2005). Organic N additions is achieved through green manuring, legume rotations or fallowing with leguminous crops (Smithson and Giller, 2002; Tittonell *et al.*, 2005b). Higher inputs of C, N, P and K (whether from green manures or fertilisers) result in an increase in soil organic carbon and nitrogen, available phosphorus, and potassium and hence increasing the production rates (Clark *et al.*, 1998).

2.4.2 Cropping techniques

Common cropping techniques in small-holder farms include crop rotation, intercropping, residue management, intensity and frequency of cropping (Mikha *et al.*, 2006). Legume crops are used as part of rotations and intercropping as they aid in the production and supply of nitrogen to the soil (Zingore, 2006). High-quality crop residues from the yield, have a low C: N ratio, hence are easily degraded by micro-organisms, resulting in more nutrients being released to the soil for crop uptake (Snapp *et al.*, 1998). Low C:N ratios also enhance soil microbial activity, phosphorus (P) and micronutrients availability, and the soils buffering capacity to resist change in pH (Snapp *et al.*, 1998; Zingore, 2006). Leguminous crops are essential in nutrient recycling as they increase the supply of nutrients within the rooting zone of crops through input of nitrogen (N) by biological nitrogen-fixation. Roots aid in absorption and transportation of nutrients from the rooting zone of crops and reduction in nutrient losses by leaching and erosion (Buresh *et al.*, 1996).

A research done on *Sesbaniasesban* (leguminous crop) grown in rotation with maize showed an enhanced recovery of subsoil N by an estimated 25 kg/ha/yr (Snapp *et al.*, 1998). Crop rotations are an important practice for maintaining soil fertility for the farmers with (Snapp *et al.*, 1998). In addition, maize-grain legume rotations exhibit substantial benefits to soil fertility under favourable environment of good management practises (Snapp *et al.*, 1998). Residues are either fed to livestock, burnt or mulched to clear the fields, as they lead to weed manifestation (Giller *et al.*, 2009).

2.4.3 Tillage management

There are various types of tillage systems and the use of each is farmer dependent based on socio-economic status (Mugwe *et al.*, 2009). Cultivation of soils results in the disruption of soil aggregates and loss of soil organic matter in the aggregates compared to virgin land (Beare *et al.*, 1994). Conventional tillage includes ploughing and harrowing which mixes the soil with fragments and the incorporation of residues (Beare *et al.*, 1994; Fabrizzi *et al.*, 2005). These effects of tillage tend to moderate water, air and temperature in the incorporated residues and increases their ability to avail nutrients for plant uptake. This is due to the enhanced residue decomposition and organic matter transformations (Beare *et al.*, 1994). Conversely, conservation tillage includes no-tillage (NT) in which specialised equipment are used to cultivate the land with minimum disturbance of the soil (Havlin *et al.*, 1990). Beare *et al.* (1994) reported higher organic carbon, nitrogen and CEC under no-tillage (NT), in the topsoil (0-5 cm) in a study done in southern Appalachian Mountains near Athens. Contrary, under conventional tillage the proportions were lower both in the upper 0-5 and 5-15 cm depth. This is attributed to the depletion of organic matter in the soil as the conditions are always conducive for microbial activities (Zingore, 2006).

Conservational tillage has shown to have positive outcome for the environment and soil health more than conventional tillage (Zingore, 2006). However, in small-holder farms conservational tillage does not yield good results, this is because affordability of appropriate machinery and the labour intense nature of this method (Swanepoel *et al.*, 2018; Jena, 2019). Also, adopting these practices for small-holder farms is still a problem as farmers are not well informed and hence, more education is needed about these technologies (Fabrizzi *et al.*, 2005; Wang *et al.*, 2016).

2.4.4 Weed management

Lack of effective weed management strategies is one of the major constraints that small-holder farmers experience in Southern Africa. Weed management can be managed mechanically by conventional tillage and hand-hoes or chemically by the use of herbicides, and biological practices (Nyamangara *et al.*, 2013). According to Kumar *et al.* (2013) mulching, crop rotation and crop residues are biological controls of weed management that small-holder farmers have adopted. Crop rotation supresses weed growth and development (Mikha *et al.*, 2006; Kumar *et al.*, 2013). Rotating crops with different planting dates and growth periods, opposing competitive characteristics and dissimilar management practices disrupt the regeneration of different weed species and prevent an increase of weed species (Nyamangara *et al.,* 2013).

2.5 Farmers soil fertility perceptions

Understanding farmer’s perceptions of soil fertility, knowledge and management is essential. Various studies show that the majority of small-holder farmers in SSA perceive fertile soils as those having high crop quality and yield without or little fertiliser or manure used (Tittonell *et al.*, 2005b; Kome *et al.*, 2018). Based on studies on small-holder farms, black, red, and deep soils, good soil tilt, which results in low labour costs on tillage, presence of microbes like worms/worm casts, and litter abundance on the field, are some of the common characteristics of good and fertile soils (Tittonell *et al.*, 2005b; Karlen *et al.*, 2006; Zingore *et al.,* 2007; Kome *et al.*, 2018).

Farmers also distinguish between fertile and infertile soils through the presence/absence of particular weeds species on their fields (Kome *et al.,* 2018). In most parts of west and central Africa, plant species like, *Chromoloena odorata* spp., *Aframomum* spp. and *Thaumatococcus* spp. which mostly grow on high moisture, deep soils are classified as good plant indicators of fertile soils, while *Imperata cylindrical* spp. growing in water scarce, dry, coarse, and infertile soils indicate poor and non-productive soils (Ngobo *et al.*, 2004; Enang *et al.*, 2016; Norgrove and Hauser, 2016; Kome *et al.*, 2018)

Infertile soils are mostly described by coarse-texture (sandy and gravel) resulting in low water and nutrient retention capacity (Rodríguez Rodríguez *et al.*, 2002; Tittonell *et al.*, 2005b; Kome *et al.*, 2018). Areas with stones and gravel are considered infertile as they limit the root growth and development of crops (Enang *et al.*, 2016). Compacted soils with low bulk density and high sand content are susceptible to erosion and eroded soils are a major limiting factor to agricultural production. The multiple factors considered as indicators of soil fertility suggests that farmers also recognise soil fertility gradients using these parameters, although it is not clear whether they would use them to purposefully plan nutrient management.

2.6 Soil fertility gradients in small-holder farms

Soil fertility gradients can be defined as an increase or decrease of nutrients in the soil over time based on various conditions, such as inherent soil parameters, management practices and socio-economic factors which occur between and within farms (Zingore *et al.*, 2007; Giller *et al.*, 2009; Giller *et al.*, 2011; Tittonell *et al.*, 2013). Inherent soil parameters refer to soil type/texture, depth, and drainage. While socio-economic factors refer to resources such as capital, labour and market (Mugwe *et al.*, 2009). All these parameters henceforth forge certain management practices within small-holder farmers that result in the availability of nutrients in the soil and induce different yield outputs from the farms.

2.6.1 Soilscape

Different fertility patterns found within SSA agricultural systems (soil fertility gradients) are associated with soilscape position, soil type and erosion (Stoop, 1987). Table 2.1 illustrate the soil fertility gradients in relation to location of the field along a toposequence. Lower slope positions or valley parts of the toposequence are often associated with high soil fertility. This is due to the lower valley being a soil deposition site, nutrients can be eroded from top to bottom. Available P, which records high values in the lower or valley parts on number of case studies (Salako *et al.*, 2006; Tittonell *et al.*, 2013). There are several factors influencing the soil gradients along a toposequence. Various positions in the toposequence experience presents of various soil type which have different inherent soil fertility status. An example would be sandy soils naturally have low water holding capacity, hence low available water for crop uptake, in the valleys waterlogging could occur, hence not favourable for crop growth Also sheet erosion can occur on steeper slopes (Salako *et al.*, 2006). Therefore, these factors significantly influence the soil fertility gradients from top to the bottom of the slope. In addition to natural variability, differences in management practices also contribute to soil fertility gradients.

Table 2.1: Soil fertility gradients across landscape position in the field of the SSA small-holder agriculture. Adapted from (Siriri *et al.*, 2005; Salako *et al.*, 2006; Tittonell *et al.*, 2013).

Case study area	Landscape characteristic/position	Characteristics position and soil	Fertility indicators								Sources
								Exchangeable bases (cmol$_+$/kg)			
			Clay+Silt (%)	pH (H_2O)	SOC (g/kg)	Total N (g/kg)	Available P(mg/kg)	K^+	Mg^{2+}	Ca^{2+}	
Central Kenya (Meru South district)	Positions along toposequence	Upslope	46	5.8	20.3	n.d	15.6	0.64	1.5	5.6	
		Midslope	48	5.6	19.7	n.d	17.2	0.54	1.4	4.9	(Tittonell *et al.*, 2013)
		Footslope	47	5.5	19.1	n.d	21.2	0.53	1.3	4.8	
		Valley bottom	51	5.3	20.3	n.d	24.6	0.56	1.4	4.4	
		SED*	3.9	0.03	0.2		0.77	0.017	NS	NS	
South-West Nigeria	Positions along toposequence	Upper slope	44.7	5.9	3.40	0.40	3.82	0.25	0.50	1.96	(Salako *et al.*, 2006)
		Middle slope	32.1	5.7	3.96	0.43	5.22	0.18	0.64	1.92	
		Lower slope	26.8	5.5	4.89	0.50	6.06	0.28	0.76	2.42	
		LSD(p>0.05)	NS	0.38	NS	0.07	NS	NS	NS	NS	
South-West Uganda	Position across bench terrace	Strip 1(upper)	28.4	n.d	20.1	0.22	5.34	0.35	n.d	5.89	
		Strip 2	26.8	n.d	20.3	0.21	4.71	0.33	n.d	6.88	
		Strip 3	22.4	n.d	20.5	0.27	4.15	0.31	n.d	6.90	(Siriri *et al.*, 2005)
		Strip 4	20.5	n.d	20.7	0.29	4.47	0.29	n.d	7.34	
		Strip 5(lower)	18.6	n.d	20.8	0.30	4.84	0.25	n.d	7.36	
		SED*	2.01		0.08	0.01	0.80	0.02		0.25	

LSD – Least significant Difference, SED – Standard Error Difference of means, NS – Not significant.

2.6.2 Field type and farmer typology effect on soil fertility gradients

There is a huge nutrient imbalance that can be observed between fields in a farm, which result in substantial differences in soil fertility status between different fields (Mtambanengwe and Mapfumo, 2005; Muthamia *et al.*, 2011). Numerous studies showed that homefields are more fertile than the outfields (Tittonell *et al.*, 2005b; Zingore *et al.*, 2007; Kome *et al.*, 2018b). Farmers tend to prioritise productive and low labour cost fields (Muthamia *et al.*, 2011). Prudencio (1993) reported a variation in soil carbon at the farm level, from 0.2 to 2.2% from the outfields to homefields. Homefields mostly have a wide variety of crops with diversity of crop types decreasing as you move away from homestead (Tittonell *et al.*, 2005b; Muthamia *et al.*, 2011; Tellen and Yerima, 2018). Highest yields are attained in the homefields, as a result of fertiliser application and the use of improved seeds (Tittonell *et al.*, 2005b). These gradients are influenced by different management practices farmers use and resource endowment as well as inherent soil properties such as soil type. This is because wealthy farmers have more resources (labour, chemical/mineral fertilisers, irrigation systems) and higher income and hence are able to maintain high crop productivity (Mugwe *et al.*, 2009).

Fields that are identified as productive and non-productive by farmers are inclusive of the major physicochemical and biological factors influencing crop growth at field-level, and qualitatively reflect laboratory-based indices (Mtambanengwe and Mapfumo, 2005). Productive fields are mostly homefields where high fertility levels have been reported. For example, researchers have reported high soil pH and exchangeable cations in these fields often associated with the effects of ash and kitchen solid waste inputs to the home gardens (Tittonell *et al.*, 2005b; Zingore *et al.*, 2007). Similarly, several studies in the SSA and tropics show that pH is associated with management, and it tends to be higher in the homefields than the outfields (Table 2.2). Changes in soil pH in short time periods makes it a good indicator of change in the soil (Smith and Doran, 1996; Zingore, 2006). The variation in nutrients with distance from homefields to outfields is mainly related to difficulties in the transportation of manure further away from the homesteads thus discouraging farmers to apply required large amounts of inputs to fields far away from the homestead (Vanlauwe *et al.*, 2005).

In Zimbabwe, Zingore *et al.* (2007) reported a decline in cation exchange capacity (CEC) with distance from the homesteads which was largely attributed to differences in soil and field type. The CEC and pH are largely influenced by the type and amount of clay in the soil, soil type, nutrients, cropping and tillage management (Tittonell *et al.*, 2005b; Zingore *et al.*, 2007). According to Vanlauwe *et al.* (2005) the CEC on the clayey soils was significantly greater than on the sandy soil. Clayey soils across all farm types had a CEC of 24.2 and 22.0 cmol_c/kg for homefield (HF) and outfield (OF) respectively. Sandy soils showed low CEC values of 2.2 and 1.6 cmol_c/kg for HF and OF, respectively, on all the fields in sandy soils can be explained by low nutrient holding capacity because of their low clay contents and associated with low soil organic matter (SOM) concentrations. High CEC on homefields results from a high concentration of SOM, which is often initiated by the disposal of organic waste like left over food, chicken droppings, ash, and sweepings from the house, whereas the fields further away from the homesteads have low CEC due the low SOM concentrations. Available P concentrations usually follow a similar trend of the bases in the soil (Muthamia *et al.*, 2011).

A study done by Tittonell *et al.* (2005b), indicated that the P concentrations in the home gardens of Emuhaia and Shinyalu reflected the inputs of ash, composted crop residues and manure, together with kitchen wastes and house sweepings normally containing chicken droppings. The combined use of mineral fertiliser and manure improves the soil organic carbon content in the soil more than that of mineral fertiliser alone (Bandyopadhyay *et al.*, 2010) explaining higher fertility in wealthier farmers and in homefields where these are often co-applied. In Kenya, Meru South districts there were no visible soil fertility gradients between the fields, but it was between the resource groups, showing that the wealthy/rich farmers have higher pH than that of poor farmers (Table 2.2). Other studies from Western and Central Kenya showed similar trend (Table 2.2).

Table 2.2: Soil fertility gradients across, field type, farmer perceived fertility class, distance and farm typology or resource group in SSA small-holder agriculture**.** Adapted from (Mtambanengwe and Mapfumo, 2005; Tittonell *et al.*, 2005a; Tittonell *et al.*, 2005b; Zingore *et al.*, 2007; Muthamia *et al.*, 2011; Nyamangara *et al.*, 2011; Tittonell *et al.*, 2013; Bucagu *et al.*, 2014).

Case study area			Fertility indicators								Sources
								Exchangeable bases (cmol+/kg)			
			Clay+Silt (%)	pH (H_2O)	SOC(g/kg)	Total N (g/kg)	Available P (mg/kg)	K^+	Mg^{2+}	Ca^{2+}	
Central Kenya (Meru South district)	Farmers Fertility class	Distance (m)									
	Good	52	n.d	5.9	20	2.18	18.2	0.66	n.d	n.d	(Tittonell *et al.*, 2013)
	Medium	68	n.d	5.6	19.6	2.19	14.7	0.55	n.d	n.d	
	Poor	110	n.d	5.5	19.7	2.22	16.9	0.52	n.d	n.d	
		SED*		0.04	0.3	0.03	0.9	0.021			
Zimbabwe, Gokwe District	Field type	Resource group									(Nyamangara *et al.*, 2011)
	HF	RG1	4.3	5.7	n.d	n.d	n.d	1.67	5.75	16.75	
	OF	RG1	4	5.7	n.d	n.d	n.d	0.51	1.10	4.2	
	HF	RG2	3.3	5.3	n.d	n.d	n.d	0.22	1.95	2.7	
	OF	RG2	4	5.0	n.d	n.d	n.d	0.51	1.85	10.7	
	HF	RG3	5	4.8	n.d	n.d	n.d	0.51	0.40	4	
	OF	RG3	4	5.8	n.d	n.d	n.d	0.56	0.45	1.95	
		SED*	0.35	0.26				0.31	1.16	3.67	
Western Kenya	Field type	Resource group									(Tittonell *et al.*, 2005a; Tittonell *et al.*, 2005b)
	HF	RG1	53.1	6.1	9.7	1.1	4.8	0.4	1.5	2.8	
	OF	RG1	49.8	5.1	10.6	1.0	2.4	0.4	1.1	2.9	
	HF	RG2	76.4	5.7	17.5	1.5	4.5	0.2	1.4	4.2	
	OF	RG2	76.2	5.2	17.4	1.6	2.1	0.5	2.2	7.9	
	HF	RG3	36.1	5.4	10.8	0.6	4.6	0.3	1.1	3.8	

	OF	RG3	39.4	5.2	4.8	0.2	2.2	0.2	0.2	0.9	
		SED*	1.95	0.60	0.1	0.14	4.1	0.09	0.2	0.5	
Zimbabwe, Chikwaka	Farm type										(Mtambanengwe and Mapfumo, 2005)
	Rich		67(4.0)	4.4(0.24)	7.1(0.64)	0.7(0.10)	7.8(1.43)	0.03(0.001)	0.6(0.14)	1.2(0.32)	
	Poor		58(4.2)	3.7(0.09)	4.6(0.17)	0.5(0.05)	4.3(0.78)	0.02(0.001)	0.3(0.03)	0.4(0.06)	
	Field type	Farm type									
Central Kenya	HF	Rich		5.7b	2.75b	0.28b	16.5a	1.01ab	0.74ab	2.64cd	(Muthamia *et al.*, 2011)
	OF	Rich		5.12c	2.2e	0.22f	10.7d	0.57de	0.34cd	0.88de	
	HF	Mid		5.9ab	2.51cd	0.26cd	13.63bc	0.92bc	1.21a	3.05b	
	OF	Mid		5.04cd	2.46cd	0.24e	12.06cd	0.5e	0.24d	0.56e	
	HF	Poor		5.65b	3.01a	0.31a	16.7a	1.04ab	2.31b	2.3a	
	OF	Poor		4.83d	2.52cd	0.24e	11.27d	0.43e	0.16d	0.55e	
Zimbabwe	Field type	Distance (m)									(Zingore *et al.*, 2007)
	HF	<50	15	5.1	0.50	0.4	7.2	0.21	0.32	0.91	
	OF	100-500	12	4.9	0.31	0.3	2.4	0.11	0.19	0.26	
	HF	<50	54	5.6	1.43	0.8	12.1	0.8	6.2	11.5	
	OF	100-500	58	5.4	0.75	0.5	3.9	0.3	6.3	8.4	
		SED*		0.2	0.37	0.06	7.4	0.55	1.69	2.39	
	Field type	Distance (m)							CEC		(Bucagu *et al.*, 2014)
Rwanda	HF	10 – 30	40.0	5.5	25.2	2.5	12.5	0.7	8.6		
	OF	100 – 800	38.7	5.2	16.0	1.5	5.1	0.4	12.5		
		SED*		0.1	1.5	0.2	1.9	0.1	1.0		

HF – Homefield, OF – Outfield, RG – Resource Group, SED – Standard Error Difference of mean, nd – No data, Alphabets notify significancy.

There is a strong relationship between management practises, soil chemical properties and crop yields (MacColl, 1989; Snapp *et al.*, 1998; Giller *et al.*, 2009). In Aludeka, Kenya the homefields were managed differently as nutrient-demanding crops were produced on inherent soil fertility and seasonally rotated within the farm (Tittonell *et al.*, 2005b). In all sub-locations, homefields often received P-containing fertilizers, particularly di-ammonium phosphate (18:46:0) (Tittonell *et al.*, 2005b; Zingore *et al.*, 2007). However, the low soil P concentrations on these fields reflects low application rates of fertilizer used by the farmers and the P-fixing capacity of these soils.

Another study by Zingore (2006) in Zimbabwe, which assessed the interaction between soil types, fertility status and application of different sources of nutrients on maize production and nutrient use efficiencies showed that, an increase in P availability in the second season and third season of planting does not come from P applied in that season only, but also as a residual effect of manure and single superphosphate (SSP) in the previous season. Estimation of residual P effects of SSP and manure indicated that P applied in the first season contributed 1-13% of P recovered by maize in the second season, whilst P applied in the first and second seasons contributed 2-18% of the P recovered in the third season.

The work done at Domboshava in Zimbabwe comparing a maize-groundnut rotation with continuous maize, with inorganic fertilizer (providing 92 kg N ha^{-1}, 17 kg P ha^{-1} and 16 kg K ha^{-1} per year) and without fertilizer, showed that the groundnuts crop almost doubled the grain yield of the maize crop in the subsequent season as it was estimated that up to 86 kg of inorganic N ha^{-1} would have been needed to obtain that yield increases with continuous maize production. While differences were observable between fields, within field spatial variability could also occur.

2.7 Spatial variation of fertility in small-holder farms

Spatial variability in soils occurs naturally from pedogenic factors, as a results of the complex interactions between geology, topography and climate (Yasrebi *et al.*, 2008; Song *et al.*, 2013). Additionally, land use and different soil management strategies also influence the soil spatial variability (Yasrebi *et al.*, 2008). Intensive agriculture as well as irrigation has led to a significant and rapid decline of nutrients (Binita *et al.*, 2010). Where such spatial variability occurs within-field, precision agriculture (PA) would be required to optimise crop production. The benefits of precision agriculture are the precise identification and mapping of small-scale variability (Bernardi *et al.*, 2016). Hence site-specific management is required as it possesses a high potential benefit in increasing input efficiency, improving the economic margins of crop production and in reducing environmental hazards risks (Yasrebi *et al.*, 2008; Bernardi *et al.*, 2016). While the need for special equipment for application of materials could be a major limiting factor in PA, the determination of the spatial variability is also limited by the tedious nature of the procedures.

Determining soil spatial variability in the field has been challenging, consequently new innovative technologies such as; global position system (GPS), geographic information system (GIS) and remote sensing were implemented (Cambardella and Karlen, 1999; Lelago *et al.*, 2016). These technologies are used to map spatial and temporal fertility status of the soil. Geographic Information System aids in formulating site specific balanced fertiliser recommendation (Cambardella and Karlen, 1999; Patil *et al.*, 2011; Lelago *et al.*, 2016).

Many studies have been done that are based on geo-statistical analysis to designate the spatial variability of different soil properties (Huang *et al.*, 2007; Cao *et al.*, 2011). Unlike conventional statistical analysis that treat observations as independent based on a chosen experimental design, geo-statistics allows for modelling of spatial dependence in data thus showing the spatial scales at which they vary (Hengl *et al.*, 2017). Kriging is the most widely used method for mapping soil fertility properties. Kriging guarantees a minimum-variance unbiased prediction as well as an estimate of the prediction variance, hence it is the most preferred method for interpolation of fertility (Huang *et al.*, 2007; Fu *et al.*, 2016; Denton *et al.*, 2017). Robinson and Metternicht (2006) argued that continuous soil property maps cannot be given by one main interpolator. Hence, some interpolators perform better than others in interpolating soil variables/ properties. For example, Robinson and Metternicht (2006) found that kriging method was more accurate in interpolating pH and electric conductivity in the top soil outperforming the inverse distance weighed (IDW) and spline, but IDW in the sub-soil showed greater accuracy. Sampling time and method pose a great influence in fertiliser recommendation (Wollenhaupt *et al.*, 1997). Low intensity sampling generally increases prediction error, while greater intensities only improve prediction error but does not account for the geometric increase in sampling costs (Mueller *et al.*, 2001; Usowicz *et al.*, 2017).

2.7.1 Mapping of soil fertility variation in small-holder farms

Farm management practises like cultivation and fertiliser application have an impact in the spatial variability in the soil (Vasu *et al.*, 2017). This varies in small-holder farming due to differences in farm typology and biophysical factors. As such great spatial variability has been reported at fields of small-holder farms (Soropa *et al.*, 2021). However, there is little information on variation of soil fertility parameters in the fields of small-holder farms despite evidence of soil fertility gradients resulting from differential management. Vasu *et al.* (2017) observed inconsistent outliers from the dataset which were attributed to farm management practises such as intensive cultivation and fertiliser inputs. This is in correlation with what Huang *et al.* (2007) concluded that the spatial and temporal variability of nutrients is affected by soil farming or management practices such as residue incorporation, land use change as well as technology adaptations in China. Also, spatial variability maps could be used in identifying areas or plots with nutrient deficiency/ adequacy (Hengl *et al.*, 2017).

An example, Figure 2.1 illustrate mapping of variability of pH and OC of agricultural soil of a village in India (Vasu et al., 2017). They reported a slightly acidic to neutral pH for most villages (Vasu *et al.,* 2017). Organic carbon showed to be high in the southern villages and low in the northern villages. Figure 2.1 illustrate how pH and OC are distributed spatially (Vasu *et al.*, 2017). This aid in nutrient management to not over-compensate for abundantly available nutrients and hence, regulate and flatten the differences in the fields. Spatial dependency of measured soil fertility variables is determined by the nugget to Sill (N:S) ratio. An N:S ratio of <25% (0.25) indicate a strong spatial dependency, 25 – 75% (0.25 - 0.75) indicate moderate spatial dependency and >75% (>0.75) indicate weak spatial dependency. Majority of fertility parameters, such as pH, OC and P showed a moderate spatial dependence (0.25 - 0.75), While N and K showed weak spatial dependence (>0.75) (Table 2.3).

Table 2.3: Semivariogram parameters of soil fertility properties. Adapted from (Vasu *et al.*, 2017).

Fertility parameter	Lag distance (m)	Range (m)	Sill	N:S ratio	Spatial dependence
pH	324	1272	0.031	0.68	Moderate
OC	413	1538	0.272	0.72	Moderate
N	292	1167	0.259	0.85	Weak
P	455	1160	0.405	0.73	Moderate
K	511	1291	0.356	0.81	Weak

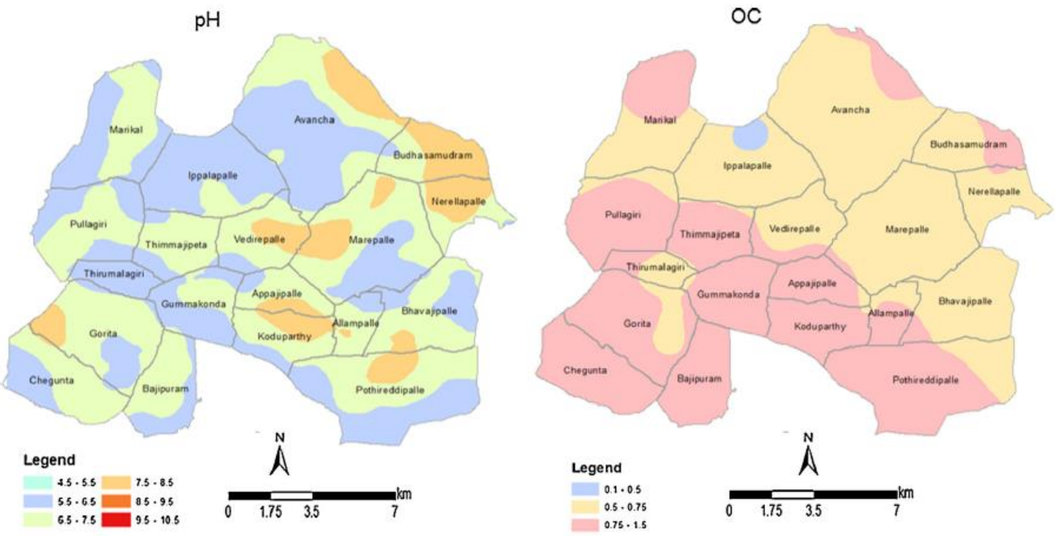

Figure 2.1: Spatial variability map of pH and organic carbon of a village in Telangana, India (Vasu *et al.*, 2017).

2.8 Conclusion

The review shows that fertility declines as you move away from the homestead. Different management strategies and resource endowment are some of the leading causes of fertility gradients. Wealthy farmers have low fertility gradients than the poor due to availability of resources and finance. The poor farmers tend to prioritise homefields due to the amount of labour and costs associated with management, such as fertiliser/manure application, tillage, cropping strategies and weeding, thus resulting to higher fertility gradients in their fields.

A good strategy to monitor, assess and manage nutrient variability in the field is through soil mapping. Geostatistical models such as Arc-GIS, with different mapping methods of which kriging is the most and widely used method to map these spatial variabilities in the soil. The technology has been used for some time and is ever improving and making farmers lives better. However, the costs associated with these technologies is high and that limits small-holder farmers to adapt to it.

Small-holder farming in KwaZulu-Natal is practiced in different areas that vary in climate and soil type, such as uMbumbulu and Msinga. The farmer typologies and their effects on soil fertility gradients and spatial variability need to be clearly understood if resource allocation for improved crop productivity is to be optimised.

3. CHAPTER THREE: FARMER TYPOLOGY AND RESOURCE MANAGEMENT OF SMALL-HOLDER FARMS IN SELECTED REGIONS OF KWAZULU-NATAL

3.1 Introduction

Farmers in the Sub-Saharan Africa have adapted to different soil management systems, in their highly diverse farming systems, which are affected by socio-economic and biophysical factors (Zingore, 2006). The important biophysical factors that affect soil and crop management include differences in micro-climate, parent material, soil texture, nutrient availability and other soil properties while the socio-economic factors include access to education, capital, market, labour availability, and population growth (Zingore *et al.*, 2007; Giller *et al.*, 2009; Kome *et al.,* 2018). These socio-economic factors determine how farmers manage their soils in small-holder farming areas, with effects on crop productivity and soil quality.

Farm typology determines types of production constraints at farm scale and the management of soil resources, fertiliser materials and types of crops grown in small-holder agricultural understanding aggregate groups of farms (i.e., farm typology) based on these varied factors could be helpful in decision making on appropriate interventions for improved farm productivity. Solutions to the production constraints will depend on clear understanding of the complexities of the different farm typologies in the small-holder setting. In addition, applicability and adoption of modern technologies could be improved by understanding these complex systems. Multivariate statistical techniques are used for in-depth understanding of these complex systems to aid in decision making.

Principle component analysis (PCA), multiple correspondence analysis (MCA) and cluster analysis (CA) are common multivariate analytical techniques. The PCA identifies non-correlated variables (quantitative data) and are used for categorisation criteria of the households, MCA mainly classifies categorical data (Rusinamhodzi *et al.*, 2012), while CA minimises the variance within clusters which are relatively equal in size (Bidogeza *et al.*, 2009). These techniques are useful in understanding farm typologies of small-holder agricultural sector of South Africa.

There are limited studies that explore resource management strategies and farmer typology within and across small-holder farmers in South Africa. Typical small-holder agricultural settings in South Africa vary due to differences in biophysical factors including climatic conditions and soil types. In addition to biophysical factors, farmer management also impacts crop productivity and soil quality. The overall soil quality could depend on resource endowment of the farmers in a particular area. Extensive research is needed to understand the farmer typology, management of available resources and constraints under different complex resource management systems and the effect of biophysical factors. To address the above-mentioned issues, the following objectives for this chapter was to (i) identify farm characteristics, soil fertility management techniques and crop production practices, (ii) determine farm typologies, and (iii) determine the constraints and effects of crop production and soil management on each typology in uMbumbulu and Msinga regions of KwaZulu-Natal.

3.2 Methodology

3.2.1 Site description

The study was conducted at Ezigeni, Pitela and Nungwane villages of uMbumbulu and three sub-areas of Nocomboshe village of Msinga in KwaZulu-Natal (Figure 3.1). The uMbumbulu (29.9846° S; 30.7041° E) site are located in a coastal area, with mean annual rainfall of 956 mm year^{-1} and temperature ranging from 18.2 to 25.2°C (Buthelezi, 2010). The dominant soil forms were Hutton and Glenrosa and some of the commonly grown crops are sugarcane, amadumbe (taro), maize and dry beans (Buthelezi *et al.*, 2013). Msinga (28.5608° S; 30.4358°E) receives an annual rainfall of 670 mm year^{-1} and temperatures of 22°C to 35°C (Zindove and Chimonyo, 2015). The area is dominated by Mispah, Glenrosa and Milkwood soil forms (Nyiraruhimbi (2012), with mostly low to moderate productive potential due to problems of high erosion hazard, shallow depth and very poor drainage (Institute of Natural Resources, 2007). Drought tolerant crops such as millet, dry beans, maize, sorghum, and groundnuts are commonly grown (Letty, 2007).

3.2.2 Farm household survey

Two key informant (KI) per study site were identified, resulting into four in total. Interviews were conducted in both study areas to identify the general knowledge of the management practises and agricultural practises they used. The KIs included the chairpersons of the co-operatives. These KI helped in identifying the farmers who were interested in participating in the project. Following the KI interviews, fifty farmers were selected for survey questionnaires from each study site. The farmers were sampled randomly, with no specific age group or gender of farmers and response to the questionnaire.

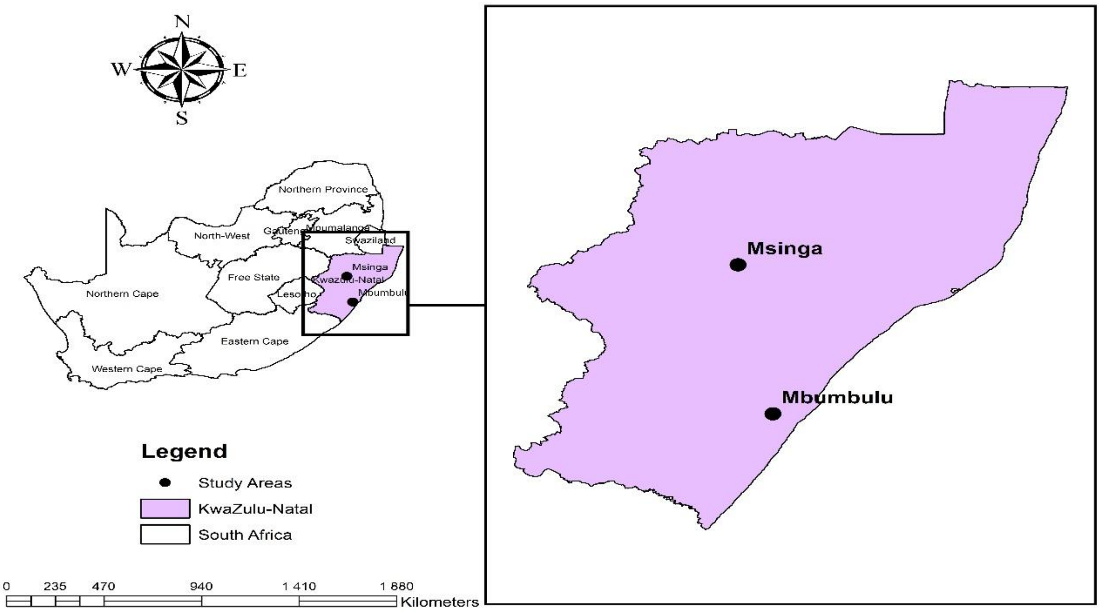

Figure 3.1: uMbumbulu and Msinga research sites in KwaZulu-Natal.

A detailed open-ended questionnaire, developed in English and later translated to IsiZulu, was used in this study. One questionnaire was used for all KIs. The questionnaire covered various aspects from socio-economy, crops grown, inorganic and organic fertiliser use, management practices, labour, crop residue management, farmers perceptions and production constraint such as climate variability (history of heavy storms), variety of crops grown as well as input labour. The data was used in the construction of farmer typology. In this study the major characterising variables for farmer typology construction were land size, livestock ownership and income from farming which are more relevant to nutrient management (Tittonell *et al.*, 2005a; Vanlauwe *et al.*, 2007; Zingore *et al.*, 2007; Tittonell *et al.*, 2010). These data were collected between August and December 2019.

3.2.3 Statistical analysis

All the data were analysed for variability using R-studio version 3.5.2 2018. Factor variables in qualitative data was converted to numerical values by the *as.numeric* functions to be analysed. For open ended questions similar answers were grouped into one category and quantified (Table 3.3). Dimension reduction on the quantitative and qualitative variables was executed by the principal component analysis (PCA) and multiple correspondence analysis (MCA) methods. Data exploration included obtaining means, ranges and quartiles for quantitative data and frequencies for qualitative data (Alvarez *et al.*, 2018; Dunjana *et al.*, 2018).

3.2.3.1 Principal component analysis (PCA)

Principal Component Analysis (PCA) was used in the selection and grouping of quantitative variables that influence farm productivity into principal components (PCs). Variables were standardised by getting rid of anomalies in the data to deal with the complexity of analysing data of different measurement scales (Mooi and Sarstedt, 2011; Dunjana *et al.*, 2018). Data satisfactory for PCA was checked with Kaiser-Meyer Olkin (KMO) as to test data sampling adequacy and Bartlett for sphericity. A KMO value of > 0.5 indicated adequacy of data to be analysed using PCA. The Z-scores of the data were used to run the PCA. To eliminate multi-collinearity, correlation matrix was rotated with a varimax rotation when generating the principal components (PCs). The significance of PC selection was determined by eigenvalue which defines the variance of each PC generated. (Lattin *et al.*, 2003; Dunjana *et al.*, 2018; Stephen *et al.*, 2019). Eigenvalues > 1 show significant variability and only factor loadings of > 0.5 were retained for PCs variables. The highest loading coefficient variables represented the PC correlated variable (Jagadamma *et al.*, 2008).

3.2.3.2 Multiple correspondence analysis (MCA)

Correspondence analysis is based on the computation of a data matrix of frequencies (Savary *et al.*, 1995). Categorical variables have many dimensions and to reduce these data dimensions multiple correspondence analysis needs to be done. Eigenvalues are used to determine the significance of variability in the same way as PCA. The Inertia, which represents the chi-square statistic divided by the total number of observations is based on the sum of eigenvalues (Alvarez *et al.*, 2018). An inertia value > 0.2 and a Cronbach's alpha score, were used as basis for dimension selection and retention (Stephen *et al.*, 2019). These scores show consistency in the dataset, which ranges from 0 - 1.0, where a score of 0 shows no consistency, 1.0 shows perfect consistency and reliable variance within range. (Costa *et al.*, 2013).

3.2.3.3 Cluster analysis (CA)

Principal component analysis (PCA) and MCA variables were used in cluster analysis to identify homogenous groups of farms. A 2-step cluster analysis was performed to include both hierarchical and non-hierarchical (K means) principle methods (Mooi and Sarstedt, 2011). This analysis groups cases by mixing continuous and categorical variables. Hierarchical cluster analysis utilises multi-dimensional distances between variables for separation and selection of cluster numbers. In K means clustering, cluster solutions maximises homogeneity optimisation within clusters is achieved by reassigning cases to clusters (Hair *et al.*, 2010).

3.3 Results

3.3.1 General village characteristics

The uMbumbulu village is dominated by female headed households (63%), and showed low literacy with 12, 60 and 27% of farmers having no formal education, primary and senior education, respectively (Table 3.1). Family sizes ranges from 2 up to 35 family members for uMbumbulu, household with high number of people in a household in polygamous households. Most of the farmers (53%) are older than 55 years, with 18 and 29% being 26 – 40 and 41 – 55 years old, respectively. While 55% of the farmers are married, 37 and 8% are single and widowed, respectively. Most of the farmers use their own labour (73%) while the rest uses hired labour, either solely or in combination with own labour, in their agricultural activities. Majority of these farmers depend on social grants and pension as their primary source of income, while only a few generate enough money from the sale of their produce. These farmers farm for subsistence, with the major crops cultivated in the area include amadumbe (taro), potatoes, beans, maize, cabbage, spinach, and sugarcane. Amadumbe and sugarcane are sold for profits in the households.

Table 3.1: General farm information of uMbumbulu.

General Information	Variable	
Gender (%)	Male	37
	Female	63
Age (%)	< 25	0
	26 – 40	18
	41 – 55	29
	> 55	53
Marital status (%)	Single	37
	Married	55
	Widowed	8
Education (%)	No education	13
	Primary education	60
	Senior education	27
Household members		2-35
Labour (%)	Hired labour	12
	Own labour	73
	Both hired and own labour	15
Common crops		Amadumbe (Taro)
		Potatoes
		Beans
		Maize
		Cabbage
		Spinach
		Sugarcane
Other crops		Sweet potatoes
		Groundnuts
		Chillies

In Msinga, most of the farms (92%) were female headed households (Table 3.2). At least 4% of the sampled population had a tertiary qualification while the 36 and 48% had no and primary education, respectively, with household members ranging from 4 to 15 people. the outfields of these villages are communal, where several farmers use one large field, and each has a plot and are supported by extension officers. Most farmers were older than 55, the youngest age group involved in farming was 26 – 40 years at 7%. Majority of these farmers (92%) used their own labour and land size ranged from 0.1 to 2 hectares and 26% of the population owned livestock (Table 3.2). Common crops grown in the fields range from maize, potatoes, beans, spinach, carrot, onions, and cabbages.

Table 3.2: General farm information of Msinga.

General Information	Variable	
Gender (%)	Male	8
	Female	92
Age (%)	< 25	0
	26 – 40	7
	41 – 55	33
	> 55	60
Marital status (%)	Single	44
	Married	56
Education (%)	No education	36
	Primary	48
	Senior	12
	Tertiary	4
Household members		4 to 15
Labour	Own labour	92
	Both (Hire and Own)	8
Common crops		Beans
		Maize
		Potatoes
		cabbage
		Spinach
Other crops		Chillies

	Carrots

3.3.2 Crop and residue management, fertiliser use and land preparation

Majority of farmers (62%) in uMbumbulu rotate crops on their fields, while a small percentage practice mixed and monocropping (Table 3.3). Crop residue is mostly retained at the surface as mulch (42%) while 23 and 21% burn residues and feed to livestock, respectively (Table 3.3). Most farmers rely on animal manure from the livestock kraals, even those that do not own livestock also use manure, while only 12% use chemical fertiliser only and 13% co-apply chemical and organic fertilisers. Majority of the farmers (67%) apply the fertiliser materials annually. Most of the farmers prepare the land before (40%) and at the start of (45%) rains. While 33 and 17% of the farmers prioritise homefields and outfields, respectively, while 50% did not have a priority.

Table 3.3: Management strategies of uMbumbulu.

Management practices	Variables	Frequency (%)
Cropping systems	Monoculture	13
	Mix cropping	13
	Rotation	62
	Inter-cropping	12
Crop residue management	Burn	23
	Feed livestock	21
	Mulch	42
	(Feed + Mulch)	13
Fertiliser type	Compost	2
	Animal manure	73
	Chemical fertiliser	12
	Mix manure & fertiliser	13
Yearly fertiliser application	Yes	67
	No	33

Land preparation	Before rain start	40
	After rain start	15
	As rains begin	45
Vary in land preparation for outfields & homefields	Yes	12
	No	88
Field priority	Homefield	33
	Outfield	17
	None	50

Majority of farmers (68%) in Msinga, rotate their crops, while 28% intercrop and only 4% practice monoculture (Table 3.4). Majority of farmers (70%) manage their crop residues by feeding to livestock (cattle and goats) and mulching, meaning the residues are divided into two, the other portion goes to livestock and the other to mulching. While 24% only mulch all their crop residues and 6% only feed their crop residues to livestock. Majority of farmers (64%) co-apply organic manure and commercial fertilisers and are applied yearly in all their fields (Table 3.4). Eighty four percent of the farmers start preparing their fields before the rains start. Majority of farmers (64%) do not priorities any field in terms of fertiliser allocation.

Table 3.4: Management strategies in Msinga.

Management	Variables	Frequency (%)
Cropping systems	Monoculture	4
	Mix-cropping	28
	Rotation	68
Crop residue management	Feed livestock	6
	Mulch	24
	Both Feed & Mulch	70
Fertiliser type	Compost	8
	Animal manure	24
	Chemical fertiliser	4

	Mix manure & fertiliser	64
Yearly fertiliser application	Yes	100
Land preparation	Before rain start	84
	After rains start	16
Vary in land preparation for outfields & homefields	Yes	46
	No	54
Field priority	Homefield	36
	Outfield	64

3.3.3 Perceptions of farmers on soil fertility and yield trends

All the farmers at uMbumbulu, perceive workable, dark soils as fertile, with the majority emphasising on earthworms (77%), while the rest consider crop yields (23%). Infertile soils are perceived to be those that produce poor yields with stony fields. Majority of farmers have seen a decline in yields (52%) while 40% have reported an increase over the past 10 years. A large proportion (67%) of the farmers recorded yield increase while 31% reported a decline, in the previous season (2018), compared to long-term average (Table 3.5).

Table 3.5: Farmer's perceptions on soil fertility and crop yield trends at uMbumbulu**.**

Farmers Perception	Descriptors	
	Indicators	
Fertile soils (%)	Workability, dark colours, Yield	23
	Workability, dark colours, worms	77
Infertile soils (%)	Poor yield	40
	Both Poor yield & Stoney fields	60
Crop yield in the past 10 years (%)	Increasing	40
	Decreasing	52
	Constant	8

Previous season (2018) yield (%)	Increasing	67
	Decreasing	31
	Constant	2

All farmers (100%) at Msinga perceive fertile soils to be easily workable, dark coloured and worm-infested. While infertile soils are classified by poor yields and stony fields by 96% of the farmers. Majority of farmers (64%) in this area have seen an increase in yield in a 10-year period including the previous season yield (Table 3.6).

Table 3.6: Famer's perceptions of Msinga.

Farmers Perception	Descriptors	
	Indicators	
Fertile soils (%)	Workability, dark colours, worms	100
Infertile soils (%)	Poor yield	4
	Poor yield, stony fields	96
Crop yield in the past 10 years (%)	Increasing	64
	Decreasing	32
	Constant	4
Previous season (2018) yield (%)	Increasing	52
	Decreasing	32
	Constant	16

3.3.4 Principal component analysis

The KMO value for uMbumbulu was 0.67, which gave adequacy for a PCA. Eighteen PCs were generated, and 3 PCs with eigenvalue of greater than 1, together accounted for 60% of the variability, were selected and used in this study (Figure 3.2). The PCs 1, 2 and 3 accounted for 26, 21 and 13% of the variability, respectively. Under PC1, homefield area and external income had significant loading values of 0.601 and 0.68 respectively (loading values >0.5). On

PC2, the homefield and outfield areas significantly loaded with values of 0.611 and 0.506, respectively (loading values >0.5). Only outfield area significantly loaded on PC3, with a loading value of 0.742 (>0.5). Income from farming, and ownership of cattle, goats and sheep showed no significant loadings on all the selected PCs (Table 3.7).

Table 3.7: Loading values in the selected principal components of uMbumbulu.

Variables	PC1	PC2	PC3
Homefield area	0.601	0.611	-0.34
Outfield area	-0.04	0.506	0.742
Income from farming	-0.38	0.167	0.275
Cattle ownership	-0.2	-0.011	-0.02
Sheep & goat ownership	-0.01	-0.02	0.095
External income	0.68	0.012	0.018

Extraction method: Principal Component Analysis. Rotation method: Varimax with Kaiser normalisation. Rotation converged in 4 iterations.

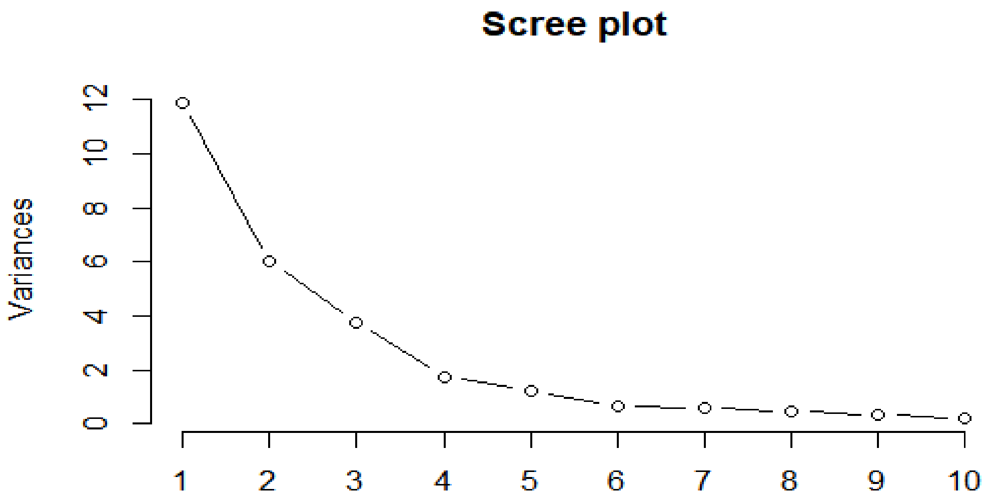

Figure 3.2: Screeplot of uMbumbulu showing eigenvalues/variance of principal components.

The KMO value for Msinga was 0.51, which was adequate for PCA. Fourteen PCs were generated, and 3 PCs with eigenvalue of greater than 1 (Figure 3.3), which accounted for

83% variability were used. The PCs 1, 2 and 3 accounted for 49, 28 and 6%, respectively. For PC1 homefield area and cattle ownership had significant loadings of 0.982 and 0.623, respectively, with income from farming being the least (<0.5). On PC2 the outfield area had the highest loading (0.922) while outfield area (0.765) and sheep & goat ownership (0.507) significantly loaded on PC3 (Table 3.8). External income had no significant loadings for all three PCs.

Table 3.8: Loading values in the selected principal components in Msinga.

Variables	PC1	PC2	PC3
Homefield area	0.982	0.098	0.079
Outfield area	-0.0646	0.922	0.765
Income from farming	-0.0206	-0.0725	-0.367
Cattle ownership	0.623	-0.0195	0.177
Sheep & goat ownership	0.581	0.624	0.507
External income	0.0392	0.028	-0.0583

Extraction method: Principal Component Analysis. Rotation method: Varimax with Kaiser normalisation. Rotation converged in 4 iterations.

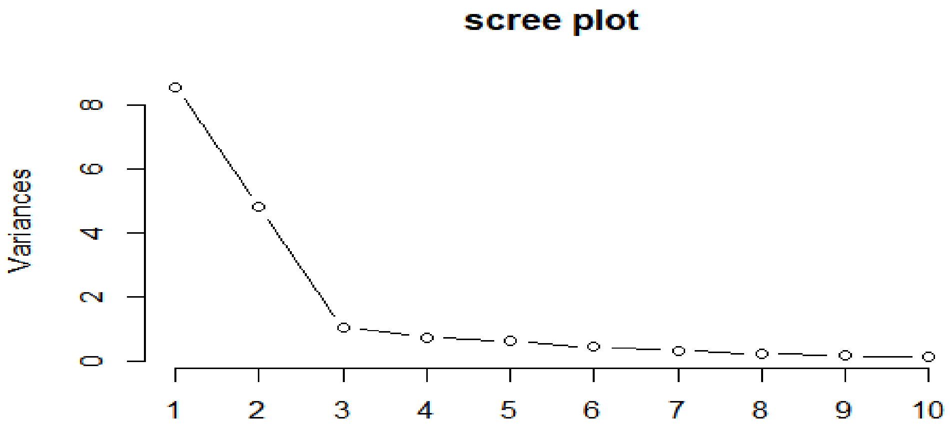

Figure 3.3: Screeplot of Msinga showing eigenvalues/variances of principal components.

3.3.5 Cluster profiles and farm typology

The cluster profile for uMbumbulu were fair when measured for cohesion and separation. The 2-step cluster analysis of PCA and MCA derived variables generated 3 farm typologies.

Type I: Rich resource endowment

Type I farmers were classified as rich/ resource-endowed, and they accounted for 22% of the farmers surveyed. They have the least land accessibility on average at 0.5 ha and make 20% of their income from farming, with majority of income being external for this group. The 20% source of income from farming is the highest of the three typologies, and 2.3% own cattle but majority are crops (Table 3.9). Majority of these farmers (53%) have senior education (matric), while 47% ended at primary school level (Table 3.1), and like all the other typologies, none of the farmers had tertiary qualifications. As for marital status, 60% of this group (typology) were single, while 40% were married, with male headed households being higher (53.6%) than female headed households (46.4%). They practice monoculture (56%) more than the other cropping systems. Most of this group have a wide range variety of crops like taro (amadumbe), potatoes, beans, maize, spinach, cabbage, sweet potatoes are common (Table 3.1) and use 85% of their hired labour while the other 15% is their own. Type I owns livestock (2.3%), (less than type II 4.2%) and afford synthetic fertilisers. Sixty three percent (63%) mix organic manure and the synthetic fertilisers for maximum yield and they all (100%) fertilise their fields yearly, also 2% of this typology use compost, unlike type II & III (Table 3.9).

Type II: Medium resource endowment

This group was classified as the moderately-resourced farmers and represented the largest group (64%). They own more land (0.7 ha) than type I with higher percentage (4.2%) owning livestock than both Type I & III. The percentage of farmers in this group having income from farming was significantly lower (14%) than type I (20%) and higher than type III (8%) (Table 3.9). In this group most farmers (60%) have primary education while 27 and 13% have senior education and are uneducated, respectively. The majority in this group (73%) use their own labour while 27% use hired labour. Most of farmers rotate their crops (62%), use organic fertilisers from the livestock kraal (73%) and apply fertilisers annually (63%) (Table 3.5). Also, type III grows less variety of crops than type I. These crops are taro, potatoes, spinach and cabbage.

Type III: Poor resource endowment

This group is the smallest (14%) and was classified as the poorly resourced group. They possess the highest amount of land at 1.3 ha and the least livestock ownership (0.8%). The lowest proportion of farmers (8%) derive their income from farming while the rest rely on social grants and external jobs compared to type I & II (Table 3.9). In this group 69 and 27% of the farmers had primary and senior (matric) education, respectively. All the farmers (100%) use their own labour and cannot afford to hire labour. Majority of these farmers (71%) intercrop, while 12% practice monoculture. Type II, type III farmers did not use any compost on their farming activities. Synthetic fertilisers are used by 58% of these farmers, while 40% use organic fertilisers whether from their own kraals or from neighbours, who belong to the more resource-endowed groups. A substantial proportion of these farmers (82%) apply fertiliser yearly, while the other 18% do not (Table 3.9).

Table 3.9: Cluster characteristics derived from 2-step clustering in uMbumbulu.

Variables	Clusters		
	1 Type II (n=64)	2 Type I (n=22)	3 Type III (n=14)
Average land size (ha)	0.7	0.5	1.3
Average livestock ownership (%)	4.2	2.3	0.8
Income from farming (%)	14	20	8
Categorical variables	% of n		
Gender (%)			
Male	37	53.6	2
Female	63	46.4	98
Marital status (%)			
Single	37	60	0
Married	55	40	24
Widowed	8	0	76
Education (%)			
None	13	0	4
Primary	60	47	69
Senior	27	53	27

Tertiary	0	0	0
Labour (%)			
Hire	27	85	0
Own	73	15	100
Cropping system (%)			
Monoculture	13	56	12
Mixed cropping	13	15	9
Crop rotation	62	29	8
Intercropping	12	0	71
Type of fertiliser (%)			
Compost	2	0	0
Organic	73	26	40
Chemical	12	11	58
Mix organic & chemical fertiliser	13	63	2
Yearly fertiliser application (%)			
Yes	67	100	82
No	33	0	18

The cluster profiles of Msinga were fair when measured for cohesion and separation. Like for uMbumbulu three farm typologies were generated after the 2-step cluster analysis of PCA and MCA derived variables.

Type I: Rich resource endowment

This is the smallest group (8% of the farmers) at Msinga and is considered as rich/resource-endowed group, higher land size 0.7 ha, than the others. Of the farmers 10% of in this group owned livestock and 6% made income from farming activities (Table 3.10). The majority of the households were female-headed and 53, 36 and 3% having no, primary, and tertiary education. As a proportion of the group 12% hire labour while 88% use their own labour. Farmers mostly relied on monoculture cropping (92%), while 5% rotated. They apply fertilisers yearly and majority (57%) rely on organic fertilisers from their kraals and a small percentage (4%) use compost (Table 3.10) with none using mineral fertilisers.

Type II: Medium resource endowment

Type II consist of 20% of the farmers in Msinga, with the least land size (0.2 ha), average livestock ownership of 7% and 2% derive their income from farming (Table 3.10). Primary, senior and no education account for 70, 22 and 8% of the farmers in this. Only 2% hire labour while the rest use their own labour The majority of farmers (83%) rely on monoculture with only 10% rotating their crops. The farmers rely on the co-application of synthetic fertiliser and organic manures from livestock, with only 2% relying solely on synthetic fertilisers, and 22% on organic fertilisers, which were all applied yearly (Table 3.10).

Type III: Poor resource endowment

This group was classified as the poorly resourced group accounting and for 72% of the farms. They have access to 0.3 ha of land on average, with 9% cattle ownership. Only 1.5% making income from farming, while the other > 90% depend on social grants and remittances (Table 3.10). Of all the farmers in this group, 92% are female headed, with 56% of the farmers being married while the remainder were single. Primary, senior, tertiary and no education accounted for 48, 12, 4 and 36%. The majority (68%) rotate their crops, while 28% practice mixed cropping. Majority of farmers in this group 64% co-apply fertilisers and 24% apply organic fertilisers only (Table 3.10). All the farmers in this group use their own labour.

Table 3.10: Cluster characteristics derived from 2-step clustering in Msinga.

Variable	Clusters		
	1 Type III (n=72)	2 Type II (n=20)	3 Type I (n=8)
Average land size (ha)	0.3	0.2	0.7
Average livestock ownership (%)	9	7	10
Income from farming (%)	1.5	2	6
Categorical variables	% of n		
Gender (%)			
Male	8	15	0
Female	92	85	100
Marital status (%)			
Single	44	26	32
Married	56	74	68
Widowed	0	0	0
Education (%)			
None	36	8	53
Primary	48	70	36
Senior	16	22	8
Tertiary	0	0	3
Labour (%)			
Hire	0	2	12
Own	100	98	88
Cropping system (%)			
Monoculture	4	83	92
Mixed cropping	28	5	3
Crop rotation	68	10	5
Intercropping	0	2	0
Type of fertiliser (%)			
Compost	8	0	4
Organic	24	22	57
Chemical Fertiliser	4	2	0

Mix Organic & chemical fertiliser	64	76	39
Yearly fertiliser application (%)			
Yes	100	100	100
No	0	0	0

3.4 Discussion

This study showed that most of these small-holder farmers lack resources such as fertilisers and livestock ownership, specifically cattle (Table 3.9 & 3.10). The higher proportion of female-headed households in both uMbumbulu (63%) and Msinga (92%) (Table 3.1 & 3.2) emphasise the importance of women in farming activities, particularly in rural areas. The findings are in agreement with other studies in the literature (Mugwe *et al.*, 2009; Altieri *et al.*, 2012; Baiphethi & Jacobs, 2009), which showed that women are the key source of information about on-farm seed conservation, cultivation and local crop-based gastronomy, and they lead crop production in their communities. The lower proportion of male-headed households could be because most males go out in the city in the search for jobs and women are left to look after the family. The findings showed that most of the farmers are >50 years of age (53% in uMbumbulu; 60% at Msinga) suggesting that less younger people lead in the farming activities, and many pursue other sources of income in the cities. This finding may suggest that, with lower involvement of younger people, farming activities may decrease in the future, especially considering that the majority (73% at uMbumbulu; 92% at Msinga) use their own labour due to poverty. Most of the farmers do not derive income from farming activities, and poverty is a serious challenge in these small-holder farming areas with many farmers depending on social grants and pensions. Previous studies have however focused more on small-holder farms where crop production is done for income generation (Zingore *et al.*, 2007; Mugwe *et al.*, 2009; Baiphethi & Jacobs, 2009). In this study the population pool of farmers produces mainly for own consumption and only sell access suggesting that small-holder agriculture is key to food security and livelihood sustenance in studied villages. The use of own labour may affect management of fields and crop productivity, especially in outfields where more effort is required due to distance from the homestead. The predominance of poverty in these communities could explain most farmers having a maximum of primary education (72% at uMbumbulu and 84% at Msinga), which could affect their understanding of extension services on soil management and crop production activities, especially with the variety of crops they grow.

Technical support in terms of extension officers is provided to all the farm types in these two sites to transfer knowledge and technology to improve farming systems and sustain farmers livelihoods. Most of these farmers have limited information regarding compost preparation, hence few farmers prepare and use it. This could be due to farmers reluctancy to adopt new technologies in their system, or the extension services are not as intensive as they should. The production of maize, potatoes, spinach, cabbages, and beans both at uMbumbulu and Msinga highlight the importance of these crops for food security in the small-holder farming sector of South Africa. The amadumbe (taro) and sugarcane produced at uMbumbulu are sold at the market in uMbumbulu for income generation, and the lack of these crops at Msinga could be because of lower rainfall, considering that these crops were grown under dryland conditions.

Small land plots (Table 3.9 & 3.10) may constrain crop production to support commonly large families (Table 3.1 & 3.2) in studied areas. Majority of farmers in both uMbumbulu and Msinga thus practice crop diversification and rotation to maximise benefit from the land by improving soil fertility subsequently maximising crop yield on smaller plots. Type II & III of Msinga farms is highly dominated by monoculture system. Also, the dominance of crop rotation compared to monocropping (62% at uMbumbulu; 68% at Msinga) showed that the farmers were aware of the benefits of the practice. Crop rotations aids in breaking the weed and disease cycles, as well as nutrient recycling (Snapp *et al.*, 1998; Mikha *et al.*, 2006; Zingore, 2006). Crop rotation between Egyptian pea a leguminous crop and maize showed an increase in recovery of subsoil nitrogen by 25 kg/ha/year and hence production yield enhanced (Snapp *et al.*, 1998). Moreover, crop residues aids in keeping the soil healthy, with higher organic carbon concentrations for higher quality yields, whether in a mulched or burnt state (Giller *et al.*, 2009). The lower proportion of farmers who use crop residues for mulching only at Msinga (24%) than uMbumbulu (42%) could be because of fewer livestock at uMbumbulu. This view was supported by the higher proportion of farmers who both feed livestock and mulch the soil with the residues at Msinga with 70% (uMbumbulu had 13%).

The lower proportion of farmers who only apply chemical fertilisers (12% at uMbumbulu and 4% at Msinga) could be a result of the inflated cost of fertiliser. As a result, most farmers at Msinga co-apply chemical and organic fertilisers. On the other hand, the majority of Msinga farmers rely more on the co-application of fertilisers and organic manure as they are provided with seedlings and fertilisers from Farmers Support Group (FSG) and they also own livestock (cattle and goats), of which goats are more dominant (Table 3.10) because the area is predominantly dry. They also have cooperatives which are supported by FSG from the University of KwaZulu-Natal which gives them training on proper adaptation strategies for management for different crops, but management advancement adoption is dependent on individual farmers socio-economic status. The majority of uMbumbulu farmers mostly rely only on organic manure because they are under cooperate farming called Ezomvelo Farmers Organisation (EFO). They cultivate most of their land for Taro (amadumbe) production and are strictly organic. The main reason for this organic production is a market base requirement. Furthermore, taro is extremely sensitive to synthetic fertilisers, which decreases the yield and quality. A study by Mare and Modi (2012) showed that addition of nitrogen base fertiliser to taro significantly decreased the starch content. Hence, these farmers invest more on organic manures as to maintain excellent quality. On other crops farmers use synthetic fertiliser as they are for household consumption and using organic manure is labour intensive as some of the farmers do not own livestock.

Management strategies are mostly influenced by regional climate. Msinga is a predominantly dry and hot area in the north while uMbumbulu is humid and near the coast and is cooler. In these two sites most farmers rotate their crops, from cereal (maize) to legumes (beans) and tubers (potatoes), also mix-crop beans with maize for both the sites. In Msinga because of elevated temperatures farmers do not burn crop residues but use as mulch since the method aids in moisture retention of the soil and limits water loss (Table 3.3). While in uMbumbulu some residues are burnt for immediate nutrient release to the soil and conditions are cooler than Msinga (Table 3.4).

In addition, uMbumbulu farmers have larger fields than homefields reserved for sugarcane plantations which are monoculture. The management techniques for production of these crops are based on Indigenous knowledge, with reference to crop allocation, weeding and, fertilisation. Experience in working in the field and understanding previous season yields helps these farmers to make informed decisions and they seem to be common in the Sub-Saharan Africa (SSA) (Tittonell *et al.*, 2010; Nyamangara *et al.*, 2011; Vanlauwe *et al.*, 2015). Small-holder farmers rely on these management practices because it is what they know and has been passed from generation to the other and cheaper to operate, but with extensive technical support farmers are slowly adapting to new technologies (Vanlauwe *et al.*, 2015). To replenish fertility of the soil and decrease degradation, management strategies and extension approaches that are suitable need to be implemented. Hence, understanding farmer's soil fertility perceptions, knowledge and management is essential (Masvaya *et al.*, 2010).

The finding that all the farmers (100%) from both uMbumbulu and Msinga perceive fertile soils to be dark, workable and with earthworms could be related to high soil organic matter. While the farmers perceptions on this study come from Indigenous knowledge which is transferable from one generation to the other, the relationship with organic matter appears obvious. Soil organic matter makes the soil darker in colour, improves soil consistency, provides substrate for earthworms, making the soil healthy resulting in better yields. The colour, workability, yield, type of weeds and microbe's aid in informing the farmers of the soil fertility status (Michel *et al.,* 2015; Manyevere *et al.,* 2016). Majority of Msinga perceived fertile soils as soils that are easy workable i.e., does not require high energy to work it and not stony, dark colours and present of microbes like worms in the soil is a good indication of the of fertility (Table 3.5 & 3.6). Also, in uMbumbulu majority (77%) believed the same excluding high yields. As both areas use poor yields and stony fields as an indicator of infertile soils. Similar results have been reported for small-holder farmers in in Zimbabwe, Kenya, Ethiopia, and Cameroon (Mikha *et al.*, 2006; Masvaya *et al.*, 2010; Salami *et al.*, 2010; Tittonell *et al.*, 2010; Muthamia *et al.*, 2011; Nyiraruhimbi, 2012; Michel *et al.*, 2015; Manyevere *et al.,* 2016). The consideration of stony soils as infertile could be related to difficulty to work, potential shallow depth and low water-holding capacity.

The PCAs produced in this study showed significant loading values for land area, livestock ownership and external income for farmers. These factors are the main determinants of PCs, which reduced multi-dimensional data and allow for construction of farm typologies. The farmer typologies determined with the aid of multivariate analysis to understand some overlapping features and depict similar or varying crop management constraints/opportunities within the area. Improvements can be made easily once the constraints have been identified (Alvarez *et al.,* 2018).

Type I farms are perceived as the more resourceful and commercially driven typology. These farms have access to more land, and hence can produce more yield and make significantly amounts of income by definition (Vanlauwe *et al.*, 2015). However, in uMbumbulu 20% of farmers derived their income from farming while they have smaller land plots, than type II and type III farmers (and when compared with Msinga), which could be due to the market-oriented farming at uMbumbulu site, resulting more intensive use of land (Table 3.9 & 3.10). This finding at uMbumbulu could be because a larger proportion in this group (53%) had senior education than type II (13%) and type III (27%). The higher resource-endowment and level of education explain the co-application of chemical and organic fertilisers and composts and growing diversity of crops including those for the market, resulting in greater proportion of type I farmers making income from farming than the other typologies. Although these farms are more resourced than others in this study, their average land sizes are much lower than an average commercial farm size. In Msinga this group showed to be female dominated and uMbumbulu male dominated (Table 3.1). The reason behind male domination in uMbumbulu area could be that as their production is market orientated and men tend to get involved more. The observation in Msinga, generally women tend to be more knowledgeable about farming than men, due to the ratio of men vs women (Table 3.2) involved in farming. Women in small-holder agriculture know more about crop choice, field priority, weeding and gastronomy (Mugwe *et al.*, 2009).

Contrary to Dunjana *et al.* (2018) who found that farming was the main source of income for most small-holder farmers in Zimbabwe, only ≤ 20% of farmers derive their income from farming in both uMbumbulu and Msinga. Current results suggest that farmers mostly farm for own consumption despite the assistance and training provided by extension services and private agricultural organisations. This may be attributed to socio-economic factors, such as land access and financial constraints as extension services provide more technical support than input support. Moreover, older age groups (>55 years), comprising a majority of farmers in studied typologies (Table 3.1 & 3.2), do not adapt easily to change (Shikuku *et al.*, 2017). Hence, more educational workshops and investment with youth participation will benefit these farm as they have potential (Shikuku *et al.*, 2017).

Type I in uMbumbulu has less land (0.5 ha) than in Msinga (0.7 ha) and the dominant cropping system used in both these sites within this group is monoculture which is the easier system to manage. Also, in uMbumbulu they do not use or prepare compost as farmers see composting as time consuming, while the females in Msinga prepare and use it due to the affordability of chemical fertilisers and moisture retention. The other distinguishing factor between these two sites is the higher livestock ownership in Msinga (10%) though it is a female dominated group as now they are the head of household, while in uMbumbulu only 2.3% had livestock and is male dominated, but the uMbumbulu site has low livestock ownership (Table 3.9 & 3.10).

Type II are intermediate farms in terms of resource availability. These farms neither rich nor poor but maintain a balance to strive in the production cycle (Alvarez *et al.,* 2018). This farm type was most dominant (64%) in uMbumbulu compared to 20% in Msinga suggesting that most small-holder farms at uMbumbulu can maintain satisfactory farm productivity. This suggests that majority of uMbumbulu farmers are striving towards the type I farm type only limited by a few socio-economic factors. Msinga has small land sizes than in uMbumbulu in this group, hence smaller fields are easier to manage or work with in terms of fertiliser application, different cropping systems and labour inputs. According to Mugwe *et al.* (2009) larger land sizes require more labour and inputs hence one must spend more money for high productivity, while a smaller land can produce high yields at minimum costs with proper management in place. Here land utilisation is lesser than that of type I but more than that of type III as well as productivity follows the same trend. These farmers lack mechanisation as well as significant amount of land to effectively be more rigorous in their productivity and hence improve their livelihoods through farming. According to Dunjana *et al.* (2018) it is important to invest in mechanised systems, to compensate for the little labour they can afford.

Type III is the poorly resourced group and was dominant (72%) in Msinga. Farmers in this class produce strictly for own consumption. This is attributed by affordability of input costs and labour as majority of the farmers are old and cannot commit themselves in working the entire available land as land availability it is not the major constrain in this case. Previous studies show that land availability is the major constraint in this group (Zingore *et al.,* 2007; Giller *et al.,* 2011; Vanlauwe *et al.,* 2015; Manyevere *et al.,* 2017; Dunjana *et al.,* 2018). At Msinga, land area was in the order type II <type III <type I. Some of the reasons for this trend external income and can afford to pay for extra labour (12%) as they have extra sources of income, while type II & III are resourced constrained. Also, type I majority use monoculture (92%) which is a relatively easily managed cropping system even in larger fields and more productive if managed properly. They have the largest average livestock (10%) hence more organic manure usage. Though, land availability is not the only limiting factor, production factors such as labour, also contribute. This leads to farmers opting to less variety of crops for instance majority of farmers in this group tend to rotate same crops over the years. These farmers are more susceptible to food insecurity.

3.5 Conclusion

Farms in uMbumbulu and Msinga areas were characterised by size of the land, livestock ownership, and income from farming. The main soil fertility management in these two sites were similar and comprised of the use of synthetic fertilisers, organic manure from livestock, mulching of crop residues and composting.

Three farm topologies were determined in this study, namely resource-endowed (Type I), who possess more land and with larger proportion deriving income from farming; moderately resourced group (Type II), which is neither rich nor poor, with a balance in resources to maintain their livelihoods; and poorly resourced group (Type III), which is highly resource limited, but this group in Msinga has the largest average land size and minimum income from farming.

Land availability is not the only factor affecting farm typology but also socio-economic as well as management factors. uMbumbulu was dominated by the type II farm typology. This means that majority of uMbumbulu farmers are neither rich nor poor, hence they can maintain themselves through farming activities specifically crops. Type I farmers in Msinga cannot qualify as type I farmers in uMbumbulu due to a range of factors from income from farming, labour, input cost and external income inputs. Majority of Msinga falls on the type III farm typology, this is mostly attributed by their big arable land plots, but lack of input costs.

Findings above lead to a question of could the differences in management as affected by farm typology results in differences/ result in fertility gradients and spatial variability of soil fertility parameters?

4. CHAPTER FOUR: SPATIAL VARIABILITY OF SOIL FERTILITY PARAMETERS UNDER DIFFERENT FARMER TYPOLOGIES IN UMBUMBULU AND MSINGA, KWAZULU-NATAL

4.1 Introduction

Small-holder farms are characterised by multiple fields with a majority of farms being between 1 – 2 ha (Zingore *et al.*, 2007) contributes significantly to food production and sustenance of rural livelihoods. Unfortunately, soil fertility in Sub-Saharan Africa (SSA) is rapidly deteriorating with adverse effects on agricultural productivity and food security. In addition to the decline, soil fertility variation, due to differential management of fields within farms, is also a major factor in small-holder farms (Muthamia *et al.*, 2011). Soil fertility management on small-holder farms is not only controlled by the inherent soil potential but also by socio-economic status of the farmer. Social inequality among small-holder farmers produces complex soil fertility outcomes which have been observed in the agricultural landscape as the gradient of decreasing nutrient inputs with increasing distance from the homestead (Prudencio, 1993; Michel *et al.*, 2015). Moreover, depending on inherent properties of the soil such as soil type, texture, slope as well as the prevailing climate, farmers tend to prioritise or exploit productive fields and disregard the less productive (Zingore *et al.*, 2007; Tittonell *et al.*, 2013; Michel *et al.*, 2015). This prioritisation/exploitation may affect soil fertility, crop productivity and their variability and may depend on the resource- endowment of the farmers. Thus, understanding the impact of farmer typology on soil fertility and its variability on small-holder farms, is important for optimum management and productivity of the fields under local conditions.

Fields on the small-holder farms are defined based on distance from homestead, where homefields are the closest to the household buildings <50m to 100m and outfields are further than 100m (Tittonell *et al.*, 2005b; Zingore *et al.*, 2007). Some researchers use farmers perceptions of soil fertility to distinguish fertile from infertile ones by knowing productive soil colour, insects, and workability of the fields (Corbeels *et al.*, 2000; Michel *et al.*, 2015). Several studies on fertility gradients have shown that outfields are often less fertile than homefields due to farmer's preference, affordability, and management (Tittonell *et al.*, 2005b; Vanlauwe *et al.*, 2007). Farmers often prioritise homefields that are less labour intensive and are highly productive, resulting in positive nutrient balance, hence farmers understand the interaction of edaphic and non-edaphic and inform their management decision factors (Ramisch, 2005;

Altieri *et al.*, 2012; Buthelezi-Dube *et al.*, 2020). The higher soil fertility on homefields than outfield has been reported to be due to more greater resource allocation (Mtambanengwe and Mapfumo, 2005; Tittonell *et al.*, 2010; Nyamangara *et al.*, 2011), with domestic waste significantly contributing to the fertility of home-fields (Tittonell *et al.*, 2005b). Vanlauwe *et al.* (2005) showed a significant difference in CEC of 2.2 and 1.6 cmolc/kg for homefield and outfields, respectively, while Bucagu *et al.* (2014) reported soil pH of 5.5 and 5.2 for homefield and outfield, respectively. Soil organic carbon also differed from 25.2% on homefield to 16 % on outfield (Bucagu *et al.*, 2014). According to Ramisch (2005) these gradients tend to be more significant for larger fields while smaller fields show less as distribution is almost similar for both fields.

According to Zingore *et al.* (2007) the major source of nutrients in small-holder farmers is livestock manure, as mineral fertilisers are too expensive hence rarely adopted by farmers. Moreover, adoption of fertiliser recommendations is limited as these rates are often too high for farmers' affordability (Nyamangara *et al.*, 2011). Results in Chapter 3 also showed the importance of organic fertiliser as major crop nutrients in small-holder areas of uMbumbulu and Msinga. Distance from home is thus a significant factor as manure must be transported to reach distant fields. Moreover, resource poor farmers may not have access to adequate manure quantities as they often do not own livestock. Inputs from mulching, inter-cropping and mixed cropping are secondary sources of nutrient recycling (Rusinamhodzi *et al.*, 2016). Field management in small-holder farms thus largely depends on farmer typology defined by extent of resource endowment (Alvarez *et al.*, 2018).

Soil fertility management strategies rely on resources such as access to livestock, labour and finance which are dependent on farmers' endowment characterised by diverse and unequally distributed resources (Scoones, 2001). The availability and allocation of resources is determined by household wealth status, priorities, and production objectives (Chikowo *et al.*, 2014). As such farmer heterogeneity with regards to resource endowment significantly contributes to soil fertility variations observed in farms on similar soil types (Masvaya *et al.*, 2010). Resource endowed farms resemble high fertility because of affordability of labour, inputs, land, mechanisation, and adaptation to new technologies as these farms derive income from their fields (Mtambanengwe and Mapfumo, 2005; Dunjana *et al.*, 2018). Poorly resource endowed farmers show low fertility with limited resources, they sell their labour to the wealthy farmers and mostly produce for subsistence farming (Zingore *et al.*, 2007; Innazent *et al.*, 2022). Results in Chapter 3 also showed three major farmer typologies and the use of chemical and organic fertilisers depended on the farmer typology which was depended on the level of education and resource endowment. Effects of farmer typologies on spatial variability of soil fertility on small-holder farms need to be clearly understood if production practices are to be optimised on the different fields.

Spatial variability in soils occurs naturally from the complex interactions between geology, topography and climate (Yasrebi *et al.*, 2008; Song *et al.*, 2013; Buthelezi-Dube *et al.*, 2020). Additionally, land use and management strategies also influence the spatial variability of soil properties (Yasrebi *et al.*, 2008). For example, intensive agriculture and irrigation may lead to rapid decline of nutrients (Binita *et al.*, 2010), and management strategies that account for the spatial variability are required to increase input efficiency, improve the economic margins of crop production and reduce environmental risks (Yasrebi *et al.*, 2008; Bernardi *et al.*, 2016). Precision agriculture (PA) becomes the answer under these conditions, with the benefits of ability to precisely managing each identified mapping unit in the most appropriate way (Bernardi *et al.*, 2016). Challenges in determining soil spatial variability in the field has necessitated the use of new innovative technologies such as global position system (GPS), geographic information system (GIS) and remote sensing were implemented (Cambardella and Karlen, 1999; Lelago *et al.*, 2016). These technologies have been used to map spatial and temporal fertility status of the soil (Lelago *et al.*, 2016), including formulating site specific balanced fertiliser recommendation (Cambardella and Karlen, 1999; Patil *et al.*, 2011; Lelago *et al.*, 2016).

Various studies done using geo-statistical analysis to designate the spatial variability of different soil properties have mostly used the kriging method (Huang *et al.*, 2007; Cao *et al.*, 2011; Manyevere *et al.*, 2017). Kriging guarantees a minimum-variance unbiased prediction and an estimation of the prediction variance; hence it is the most preferred method for interpolation of fertility (Huang *et al.*, 2007; Fu *et al.*, 2016; Denton *et al.*, 2017). Usowicz *et al.* (2017) found that kriging method was more accurate in interpolating pH and electric conductivity in the topsoil, outperforming the inverse distance weighed (IDW) and spline. Sampling time and method pose a great influence in fertiliser recommendation (Wollenhaupt *et al.*, 1997; Manyaevere *et al.*, 2017). Low intensity sampling generally increases prediction error, while greater intensities only improve prediction error but does not account for the geometric increase in sampling costs (Mueller *et al.*, 2001).

Many studies on fertility gradients have been done across the SSA, but no published work has been done in South Africa. Also, there are no studies that map fertility spatial variability under different typologies, such as those identified in the small-holder areas of uMbumbulu and Msinga (Chapter 3). For purposes of optimising management and crop productivity, it is essential to establish the different management practices, as affected by farmer typology, would affect spatial variability of soil fertility. The objectives of this study were thus to: assess (i) the fertility gradients on small-holder farms of uMbumbulu and Msinga, (ii) effect of farmer typology on soil fertility gradients and (iii) to map spatial variability in relation to farmer typology of selected fertility parameters in homefields of uMbumbulu area.

4.2 Methodology

4.2.1 Study site and farm selection

Farms were randomly selected based on farm typology and soil type. Following farm typologies as described in Chapter 3, soil classification was done in all farms according to the Soil Classification Working Group (Group, 2018). Only farms with the same soil type were considered for the study of soil fertility gradients to minimise high variations of variables due to natural differences in soil characteristics. Farms with a Hutton soil form in uMbumbulu, and Glenrosa soil form at Msinga were selected. Three farms were selected for each typology (i.e., Type I, II and III).

4.2.2 Soil sampling

Two fields were used from each selected farm in both Msinga and uMbumbulu. At Msinga these fields were defined as homefields (≤ 100m from homestead) and outfields (>100m from the homestead). At uMbumbulu, all the fields studied were within 100m of the homestead (homefields) and therefore differences in cropping were considered instead, i.e monocropping and mixed cropping. Soil samples were collected from 0-20cm depth using an auger. Six soil samples were taken per typology and duplicated as homestead and outfield for Msinga, while for uMbumbulu were duplicated as monoculture and mixed cropping. This resulted in 18 samples from all the typologies for each of uMbumbulu and Msinga. A total of 36 soil samples were collected, air dried, ground, and passed through the 2mm sieve prior analysis.

4.2.3 Soil fertility variability mapping

Soil fertility variability mapping was only done for homefields and one farm per typology. Only uMbumbulu farms were considered for mapping due to financial constraints for the analysis and ease of access. For this a 5 × 5 m (Manyevere *et al.*, 2017) grid layer was constructed over both monocropping and mixed cropping fields from the 3 previously selected uMbumbulu farms. The grid points were tracked by GPS co-ordinates and a total of 150 samples were collected at each grid intersection at 0-20cm. Soil samples collected were air-dried, ground, and passed through a 2mm sieve before analysis.

4.2.4 Soil analysis

Soil pH was determined using the electrode pH meter, using a 1:5 soil 1M KCl ratio in proportion of 10 g of soil and 25 ml of 1M KCl and solution was stirred at 400rpm for 5 minutes. The suspension was allowed to rest for 30 minutes before measuring the soil pH (Mekaru and Uehara, 1972). Samples were analysed at the Soil Fertility Analytical Services of the KwaZulu-Natal Department of Agriculture and Rural Development (Cedara) using standard methods as detailed by (Manson and Roberts, 2000). For soil fertility parameters (Ca, Mg, K, total C, total N, exchangeable P). Exchangeable P and potassium (K) are analysed from the Ambic-2 extraction method, consisting of 0.25 M NH_4CO_3 + 0.01 M Na_2EDTA and 0.01 M NH_4F + 0.05 g/L superfloc. Exchangeable P was determined by the molybdenum blue procedure. Exchangeable calcium (Ca), magnesium (Mg) and acidity were extracted with 1M KCl and analysed in the Atomic Adsorption Spectrophotometer (ASS). Total carbon and nitrogen were analysed using Trumac Leco_CNS. Acid saturation (AS) was calculated using equation 1. For particle size analysis, 20g of soil was treated with hydrogen peroxide to oxidise organic matter and 400 ml of de-ionised water was added and left overnight. A pipette method was used to measure clay and silt fractions of the soil, while for the sand fraction was determined by sieving and textural class was determined using the textural triangle.

$$\boldsymbol{Acid\ saturation}\ (\%) = (\boldsymbol{Acidity/CEC}) * \mathbf{100} \qquad \textbf{Equation (1)}$$

4.2.5 Statistical and geostatistical analysis

Soil data was subjected to the analysis of variance using Genstat 18th edition to establishment differences in measured soil fertility parameters across different fields and farmer typologies. Mean separation was done using the least significance difference (LSD) and Tukey-Kramer method at 5% level of significance.

Geostatistical analysis was done to assess spatial variability and dependency of selected soil fertility variables using ArcMap GIS version 10.8 (2020). Firstly, descriptive statistics for the mapping data including min, max, mean, standard deviation (S.D), coefficient of variance (C.V), skewness and kurtosis were calculated for variables using R-Studio version 3.5.2 (2018). Normality of the data was tested using the Jargue Bera test (Jarque and Bera, 1980), and variables not normally distributed were log transformed, before kriging. Standard normal distribution should have a skewness of between -1 to 1, and a kurtosis value of between -0.5 to 0.5 (Hair *et al.,* 2017). The semivariogram function model fitting was performed using Ordinary Kriging (OK) method which estimates values of unsampled location of each of the selected soil properties (Vasu *et al.*, 2017) (pH, exchangeable P, exchangeable bases, acid saturation, total C, and clay percent). The spherical model was used in this study as it shows higher accuracy even with limited sampling and minimise sampling cost (Mueller *et al.*, 2001; Vasu *et al.*, 2017). Also, for the maps the following scales were used for pH (<4, 4 – 5 & > 5), acid saturation (<10, 10 – 50 & >50%), calcium (<2, 2 – 5 & >5 cmolc/kg), magnesium (<1, 1 – 3.5 & >3.5 cmolc/kg), potassium (<0.1, 0.1 – 1 & >1 cmolc/kg) phosphorus (<10, 10 – 20 & >20 mg/kg), total carbon (<2, 2 – 4 & >4%) and clay percentage (<30, 30 – 50 & >50%).

In a semivariogram, the lag size is defined as the distance between two points in a field. The range is defined as the distance in which the semi-variance stops increasing or find equilibrium. Sill is the semi-variance at the range and nugget is a measure of error (Vasu *et al.,* 2017). Spatial dependency of measured soil fertility variables was determined by the nugget to Sill (N:S) ratio. The N:S ratio of <25% (0.25) indicated a strong spatial dependency, 25 – 75% (0.25 - 0.75) indicated moderate spatial dependency and >75% (>0.75) indicated weak spatial dependency(Xin-Zhong *et al.*, 2009; Vasu *et al.*, 2017; Manyevere *et al.,* 2017).

4.3 Results

4.3.1 Fertility parameters across fields/cropping systems and farm typology

There were no significant differences ($p>0.05$) in measured soil parameters across all typologies and cropping systems in uMbumbulu (Table 4.1). However, soil pH ranged from 4.33 to 4.88 while exchangeable P ranged 6.56 - 10.9 mg/kg across typologies and between cropping systems. Potassium and calcium had narrow ranges of 0.26 - 0.3 and 4.16 - 6 cmol$_c$/kg, respectively.

Table 4.1: Soil fertility parameters of different farm typologies and cropping systems in uMbumbulu.

Factor	pH	Exchangeable P (mg/kg)	Exchangeable bases (cmol$_c$/kg)		
			K	Ca	Mg
Typology					
Type I	4.33	10.9	0.30	4.16	2.13
Type II	4.73	6.56	0.26	4.96	2.67
Type III	4.88	7.64	0.31	6.00	2.84
LSD	1.2	9.43	0.44	7.39	0.97
Cropping					
Mixed	4.93	7.89	0.24	4.33	2.13
Monoculture	4.36	8.85	0.34	5.76	2.97
LSD	0.98	1.36	0.16	1.54	0.92

There was no significant difference ($p>0.05$) in measured soil parameters except for exchangeable P across all typologies and field type no gradients were observed in Msinga (Table 4.2). Soil pH for outfields ranged from 3.94 – 4.17 for type I and II respectively, while for homefields ranged from 4.17 – 5.27 for type I and II respectively. Exchangeable bases had narrow ranges.

Table 4.2: Soil fertility parameters of different farm typologies and cropping systems in Msinga.

Factor		pH	Exchangeable bases (cmolc/kg)		
			K	Ca	Mg
Typology	*Field type*				
Type I	Homefied	4.41	0.53	3.29	1.46
	Outfied	3.94	0.26	1.67	1.08
LSD		1.03	0.55	4.13	2.28
Type II	Homefied	5.27	0.76	5.96	2.07
	Outfied	4.18	0.41	4.22	2.39
LSD		1.17	0.89	4.35	2.07
Type III	Homefied	4.97	0.49	3.79	1.52
	Outfied	4.97	0.40	4.14	1.72
LSD		1.57	0.59	2.31	1.1

Interaction effect of farm typology and field type was only significant for exchangeable P at Msinga (Figure 4.1). Exchangeable P was significantly higher in homefields than outfields for the type I (rich) farms, while no significant difference between homefields and outfields of the other typologies. For the homefields, the type I had higher exchangeable P than type III, while type II was not significantly different from the other two typologies (Figure 4.1).

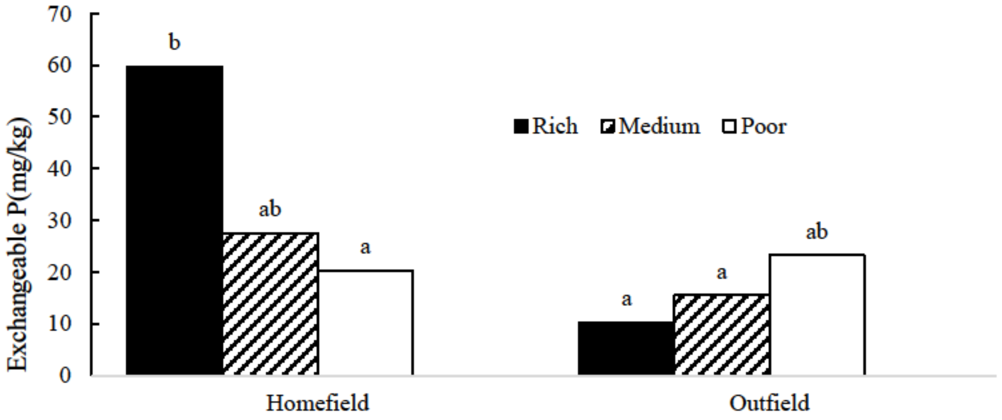

Figure 4.1: Bar graph showing exchangeable P as affected by interaction of field types (homefield and outfield) and farm typology (Type I, II and III) in Msinga.

4.3.2 Summary statistics of mapped soil fertility parameters.

Type I typology soils were acidic with mean pH of 4.48. Phosphorus showed a mean of 12.69 mg/kg in this typology. Type II typology showed similar trends to typology I with acidic pH and P as their means were 4.53 and 12.02 mg/kg respectively. Type III typology also showed acidic soils with a mean pH of 4.09 with low mean 8.61 mg/kg for exchangeable P. Total carbon ranged from 1.32 % to 2.94 % with a mean clay percentage of 30.59 % in type I homefields. Type II typology had high mean carbon content of 4.62%. However, clay content was very high in this typology with a mean of 54.46 %. Total carbon mean concentration in type III homefields was 2.06 %, which is the lowest compared to type I & II typologies. Clay content averaged 27.5% (Table 4.3).

Soil pH was normally distributed while available P, TC, and clay percentage (Clay %) were not normally distributed hence were log transformed and the skewness decreased after the transformation (Table 4.3). Extractable P had high variation (CV values ranging from 43% to 88%) meaning high level of dispersion for type I. Extractable P showed high variation/dispersion (CV ranging from 47 to 100+%) was the only one which showed no normality (2.92 skewness), while all the other parameters were normally distributed in type III. After log transformation all parameters were normally distributed (Table 4.3). The pH, P and TC showed low dispersion in type III with a CV range of 2 to 30%. Soil pH and phosphorus were not normally distributed, and all the variables were normalised after log transformation i.e., decreased the skewness (Table 4.3).

Table 4.3: Descriptive statistics for pH, exchangeable P, total carbon, and clay content of homefields at farm types I, II & III of uMbumbulu using 5 x 5m grid to a depth of 20 cm.

Variable	Min	Max	Mean	SD	CV	Skewness	Skewness^c	Kurtosis
pH								
Type I	3.88	5.94	4.48	0.68	0.15	0.89 a	-0.05	-0.70
Type II	4.27	4.90	4.53	0.17	0.04	0.40 a	-0.40	-0.71
Type III	3.98	4.33	4.09	0.10	0.02	1.10 b	0.04	0.04
Exchangeable P								
Type I	8.11	31.19	12.69	6.04	0.48	1.67 b	0.22	1.85
Type II	8.89	32.61	12.02	5.69	0.47	2.92 b	0.47	7.77
Type III	5.09	15.70	8.61	2.55	0.30	1.16 b	0.06	1.00
Total C (%)								
Type I	1.32	2.94	2.39	0.29	0.12	-1.97 b	0.29	6.50
Type II	4.11	5.29	4.62	0.38	0.08	0.59 a	-0.23	-1.09
Type III	1.67	2.43	2.06	0.21	0.10	-0.18 a	-0.75	-0.88
Clay (%)								
Type I	24.00	33.00	30.59	2.04	0.07	-1.88 b	0.27	3.36
Type II	49.00	65.00	54.56	2.29	0.04	1.00 a	0.00	-0.43
Type III	25.00	31.00	27.45	14.56	0.53	0.50 a	-0.30	-1.38

Skewness^c – Skewness after log transformation, a – normally distributed, b – not normally distributed.

Exchangeable Ca in homefields of types I, II and III ranged 0.89 - 7.08, 3 - 6.60 and 1.23 - 5.36 cmolc/kg, respectively, while exchangeable Mg ranged 0.40-1.60, 2.22 to 4.25 and 0.74 to 2.02 cmolc/kg respectively. Exchangeable K ranged from 0.07 – 1.72, 0.13 – 0.61 and 0.07 – 0.53 cmolc/kg respectively, while acid saturation ranged from 0.54 – 64.73, 0.69 – 7.82 and 1.87 – 43.37 % respectively. The means of exchangeable Ca, Mg, K and AS were 2.94, 0.90, 0.52 and

27.26 for type I, 4.66, 3.16, 0.27 and 3.03 for type II and 2.89, 1.22, 0.22 and 18.84 for type III (Table 4.4).

Exchangeable Ca, Mg and acid saturation were normally distributed in type I. Exchangeable K was not normally distributed hence were log transformed and the skewness decreased after the transformation (Table 4.3). Exchangeable Ca, Mg, K and AS had high variations (CV values ranging from 43 to 88%) with high level of dispersion. Exchangeable K and AS in type III showed high variation/dispersion (CV ranging from 47 to >100%). Only phosphorus showed no normality (2.92 skewness), while all the other parameters were normally distributed. After log transformation all parameters were normally distributed (Table 4.4). Exchangeable Mg and AS in type III showed low dispersion with a CV range of 2 to 30%. All the variables were normalised after log transformation i.e., decreased the skewness (Table 4.4).

Table 4.4: Descriptive statistics for exchangeable bases and acid saturation of homefields at farm types I, II & III of uMbumbulu with the field grid of 5 x 5m to a depth of 20 cm.

Variable	Min	Max	Mean	SD	CV	Skewness	Skewness^c	Kurtosis
Ca (cmolc/kg)								
Type I	0.89	7.08	2.94	2.09	0.71	0.80 a	-0.09	-0.83
Type II	3.00	6.60	4.66	1.01	0.22	0.38 a	-0.42	-0.88
Type III	1.23	5.36	2.89	1.36	0.47	0.36 a	-0.44	-1.46
Mg (cmolc/kg)								
Type I	0.44	1.60	0.90	0.39	0.43	0.40 a	-0.39	-1.51
Type II	2.22	4.25	3.16	0.54	0.17	0.15 a	-0.82	-0.77
Type III	0.74	2.02	1.22	0.37	0.30	0.62 a	-0.21	-0.69
K (cmolc/kg)								
Type I	0.07	1.72	0.52	0.40	0.77	1.44 b	0.16	1.64
Type II	0.13	0.61	0.27	0.14	0.52	0.97 a	-0.01	0.14
Type III	0.07	0.53	0.22	0.13	0.59	0.92 a	-0.03	-0.26

AS (%)								
Type I	0.54	64.73	27.26	23.93	0.88	0.01 a	-1.89	-1.76
Type II	0.69	7.82	3.03	5.11	1.69	1.05 a	0.02	-0.37
Type III	1.87	43.37	18.84	1.70	0.09	0.42 a	-0.38	-0.91

Skewness^{c} – Skewness after log transformation, a – normally distributed, b – not normally distributed.

4.3.3 Spatial variability maps of soil fertility parameters

Spatial variability of pH in type I varied across the field with the highest pH of greater than 4.5 closer to the homestead and the least of less than 4 furthest from the homestead. Type II and III were on the same medium range (4 – 4.5) for the entire fields (Figure 4.2). Acid saturation (AS) showed similar trends of pH on type I & II fields, but slight difference for type III as it ranged from lowest (<10%) and majority of the field on medium range (10 – 50%) (Figure 4.3). Exchangeable calcium in type I showed a decreasing trend from closer to homestead going further, while majority of type II & III showed medium concentration (2 – 5cmolc/kg) (Figure 4.4). Type II field showed highest concentration of magnesium (>3cmolc/kg), while type I and III varied from lowest to medium (Figure 4.5). For potassium (K), type III field showed lowest concentrations (<0.2cmolc/kg), while type II showed medium concentrations (0.2 – 0.7cmolc/kg) and type I varied from highest (>0.7cmolc/kg) to majority of the field being the medium concentration (Figure 4.6). Type I farms were characterised by an extensive area with medium concentrations of TC (2 – 4%). Type II had the highest total carbon of greater than 4% the entire field, while type III varied from <2% and 2 – 4% (Figure 4.7). Type I & III showed majority of medium clay percentages of 25 – 40%, while type II showed highest clay percentage of greater than 40% (Figure 4.8). Type I & II fields showed medium concentrations (10 – 17mg/kg) of exchangeable phosphorus, while type III showed majority of the field lowest concentrations of less than 10mg/kg (Figure 4.9).

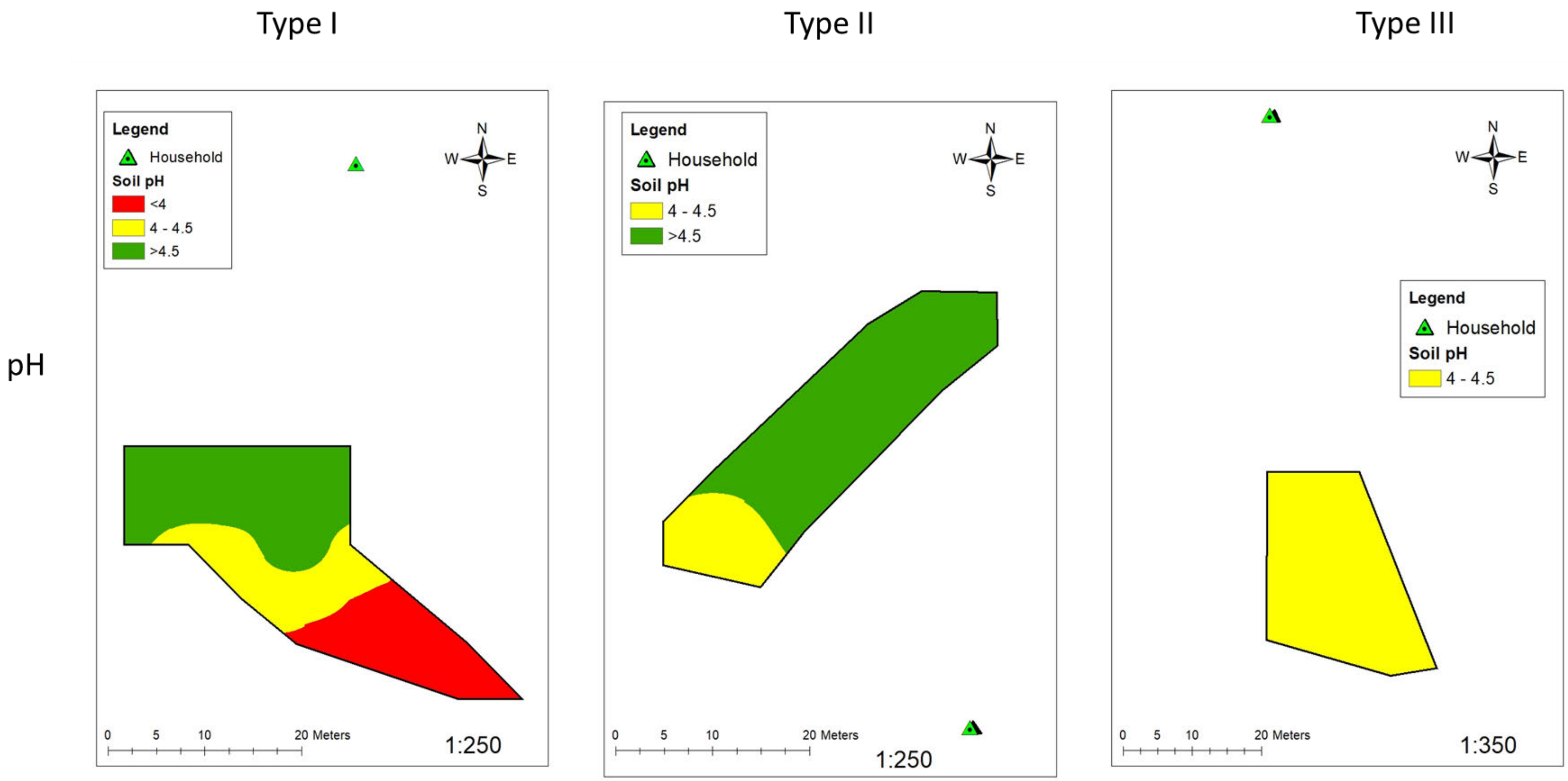

Figure 4.2: Maps showing spatial variability of soil pH on three farm typologies in uMbumbulu area.

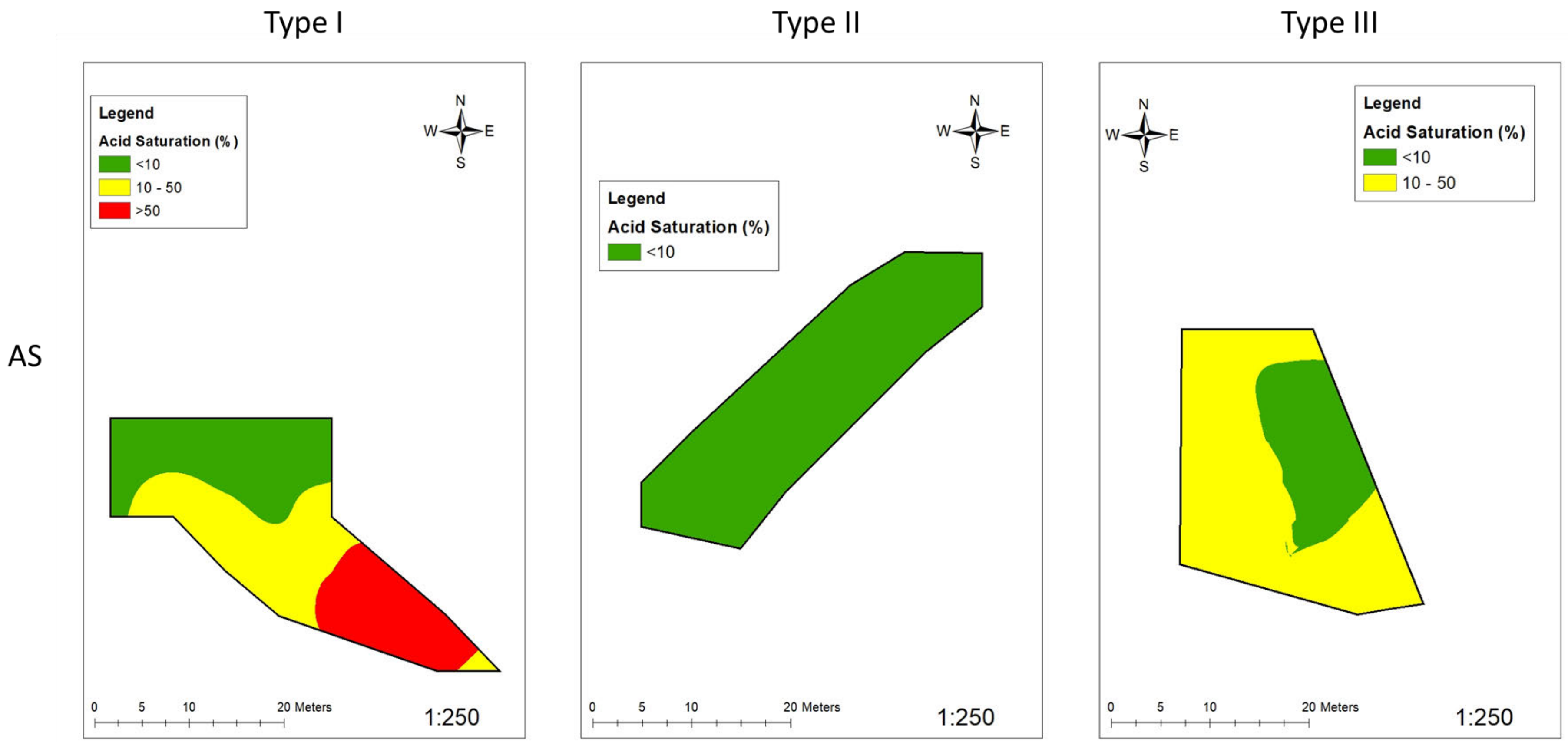

Figure 4.3: Maps showing spatial variability of acid saturation (%) on three farm typologies in uMbumbulu area.

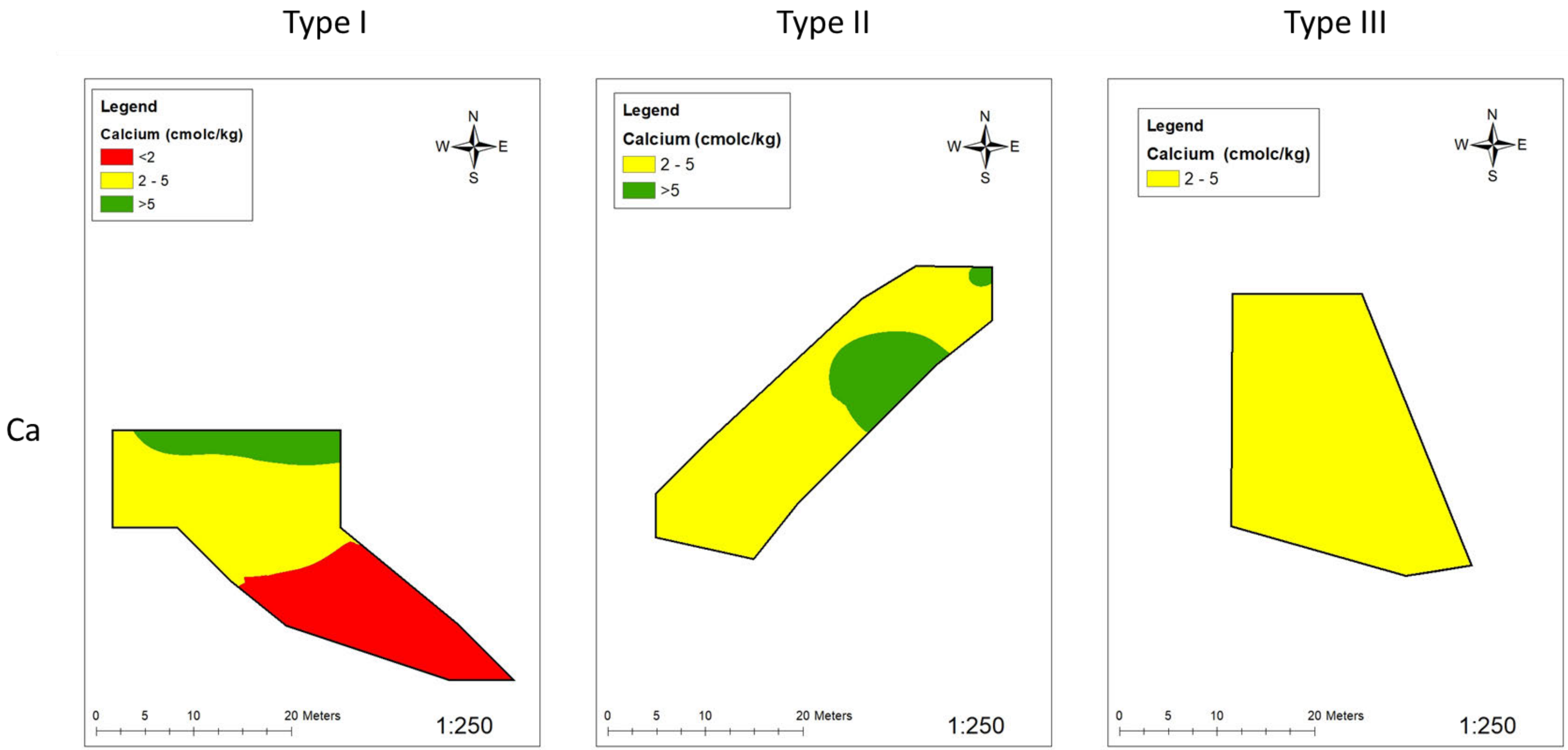

Figure 4.4: Maps showing spatial variability of calcium (Ca) in cmolc/kg on three farm typologies in uMbumbulu area.

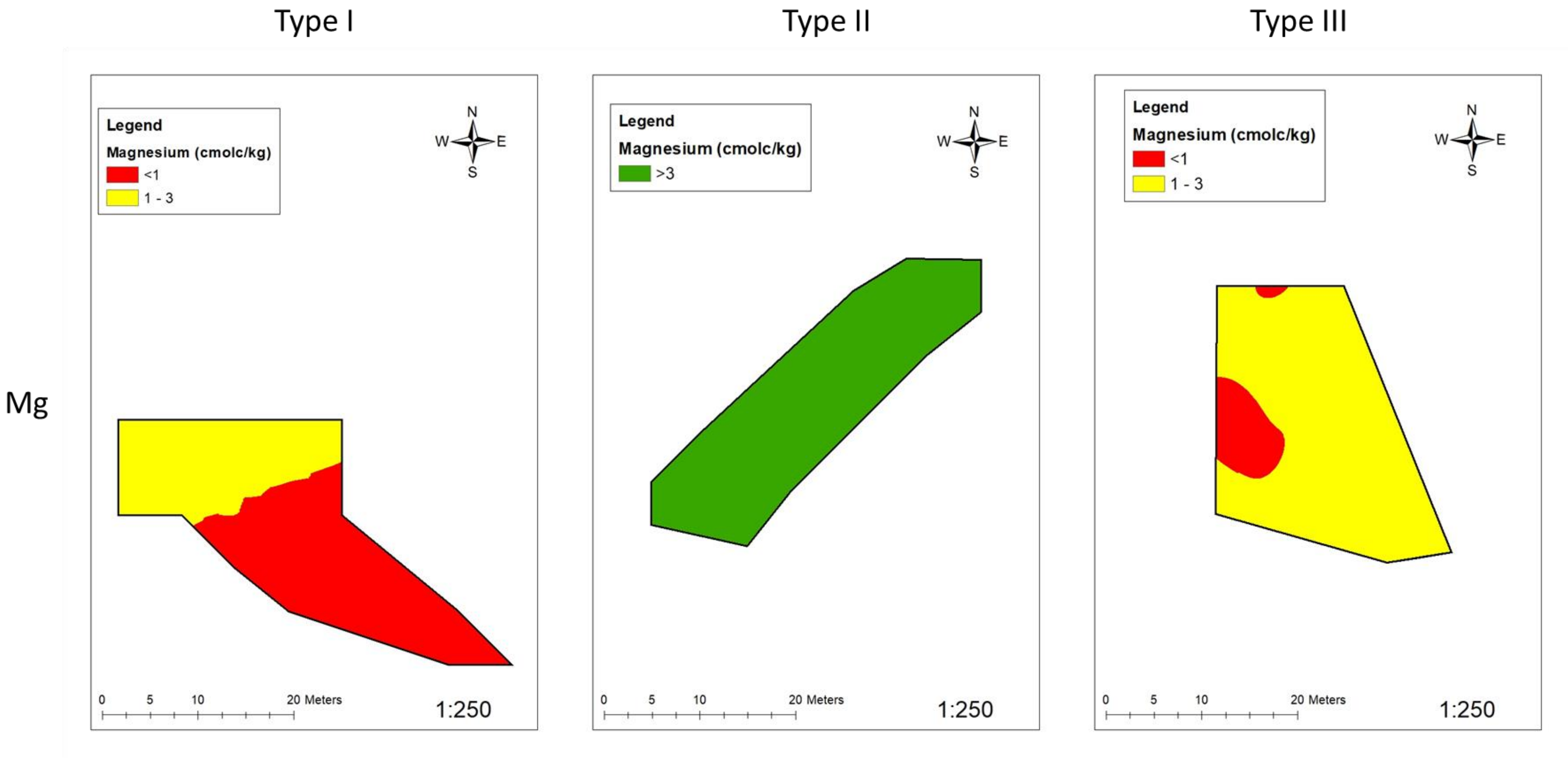

Figure 4.5: Maps showing spatial variability of magnesium (Mg) in cmolc/kg on three farm typologies in uMbumbulu area.

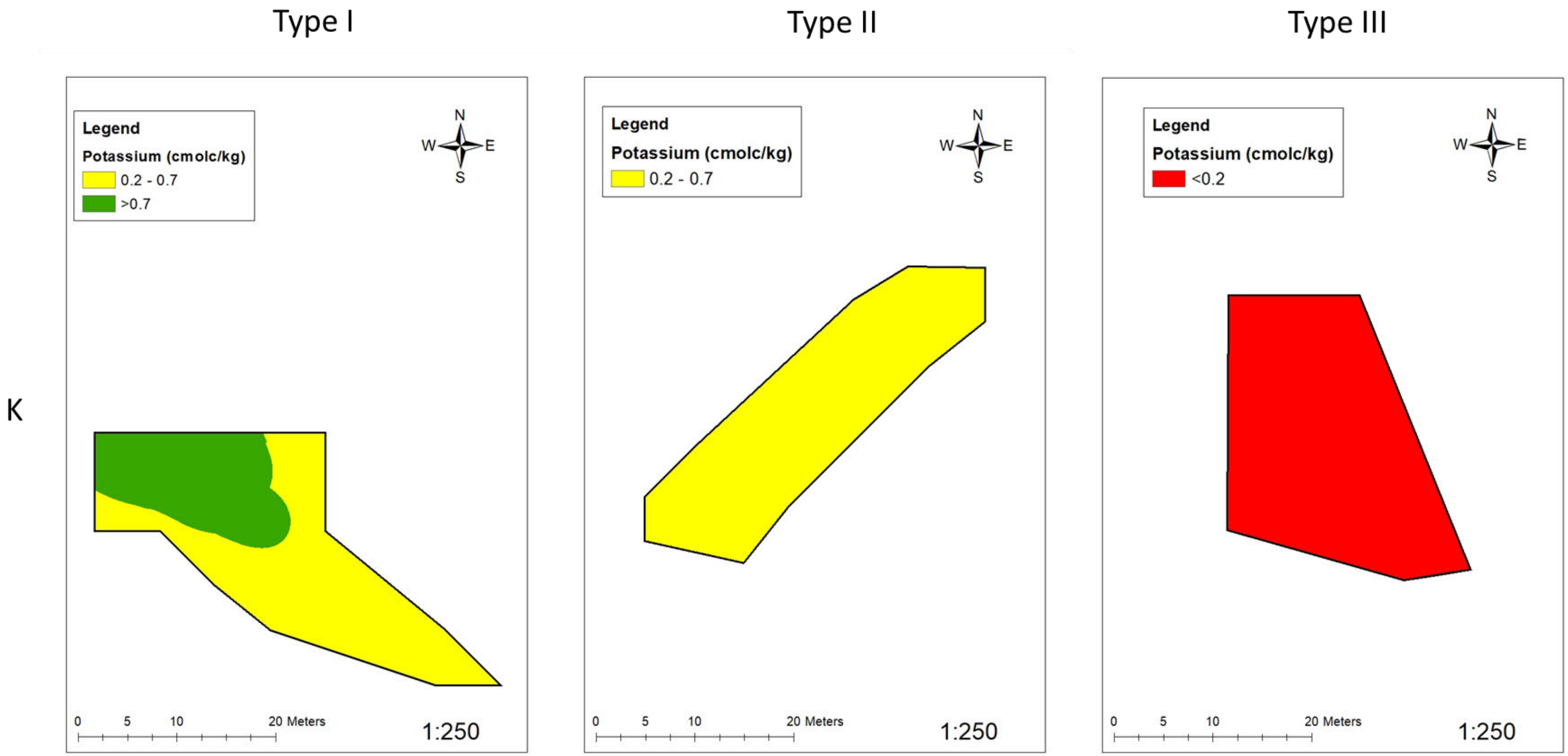

Figure 4.6: Maps showing spatial variability of potassium (K) in cmolc/kg on three farm typologies in uMbumbulu area.

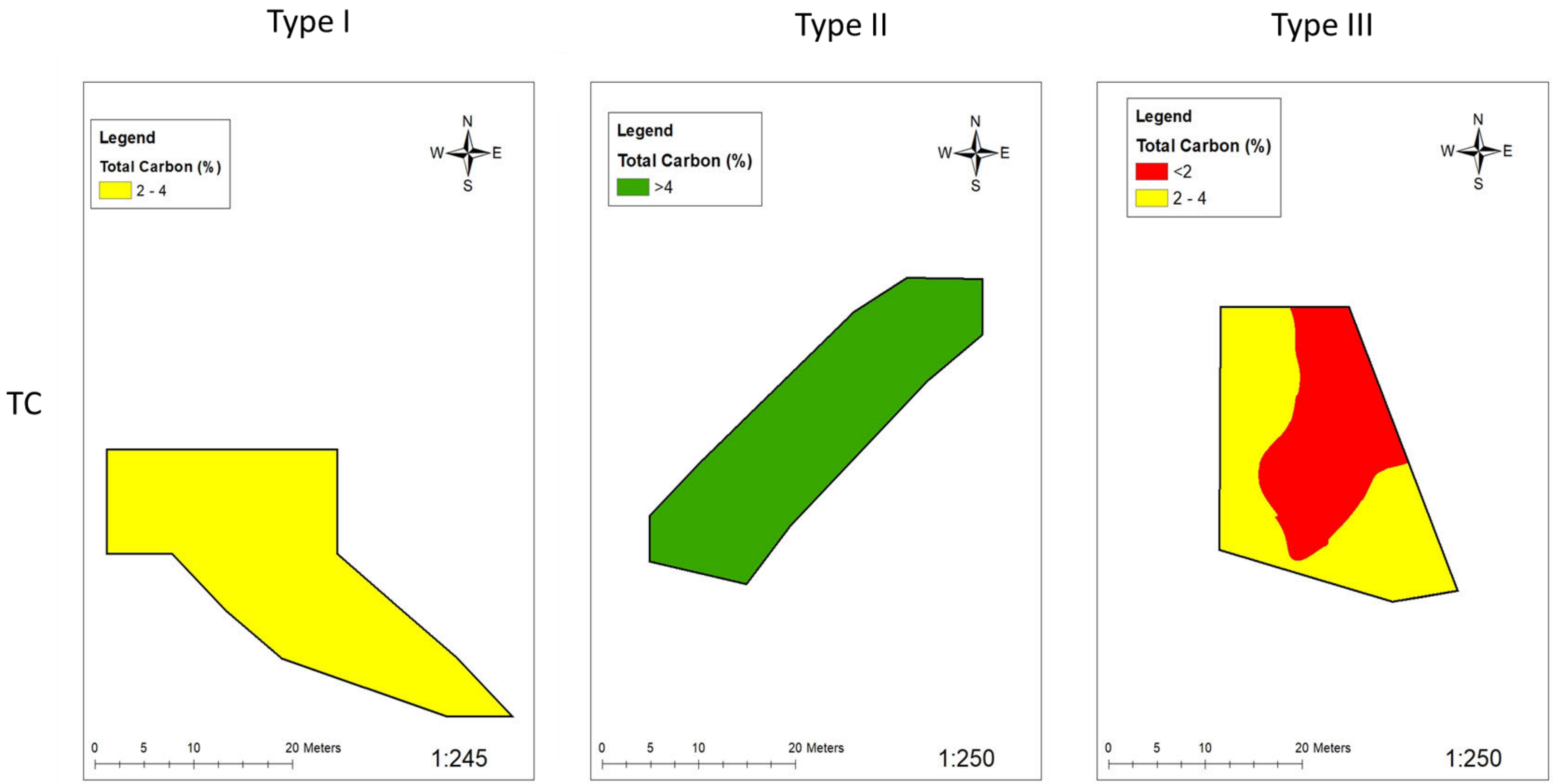

Figure 4.7: Maps showing spatial variability of total carbon (%) on three farm typologies in uMbumbulu area .

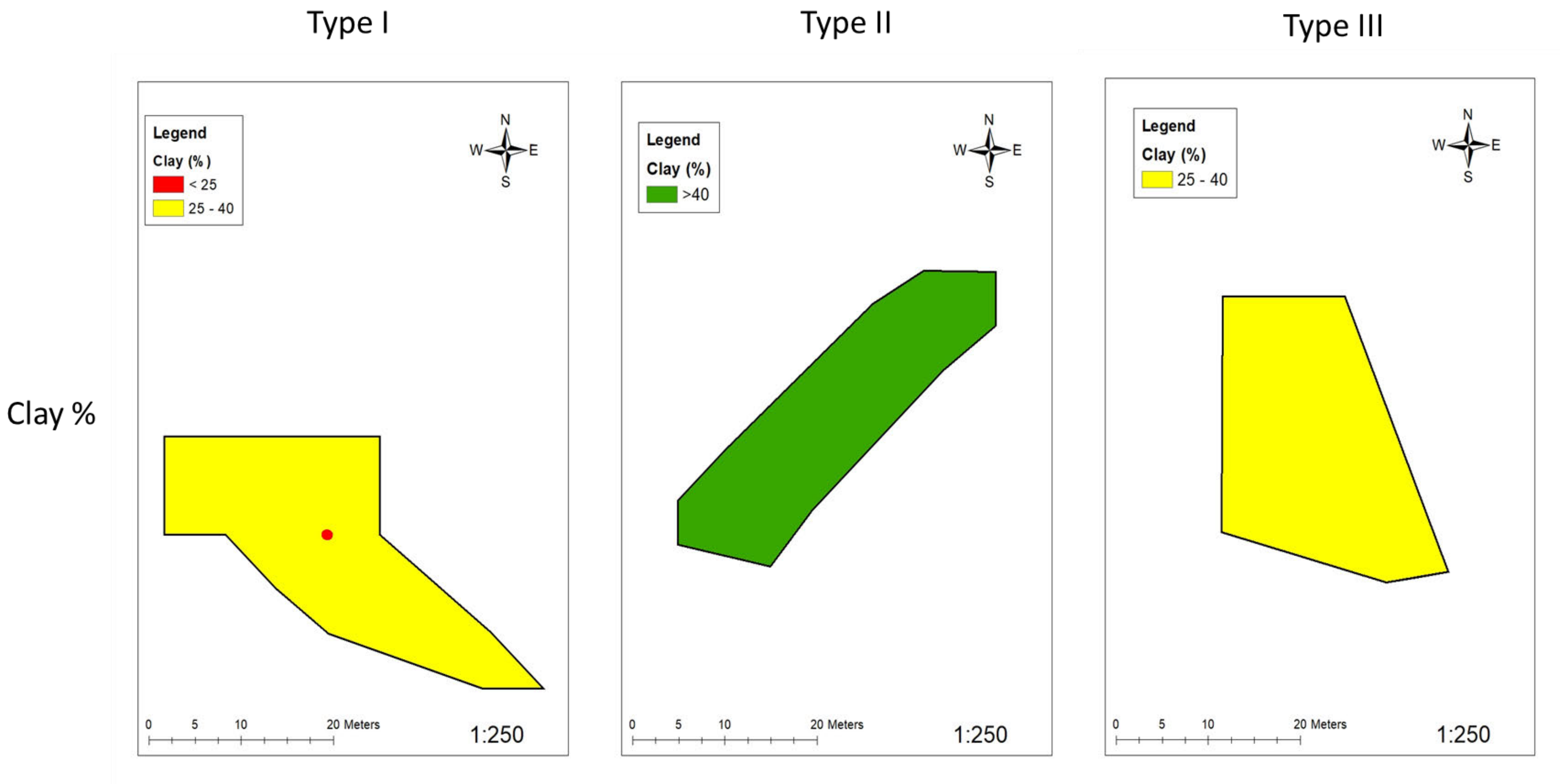

Figure 4.8: Maps showing spatial variability of clay percentage (Clay %) on three farm typologies in uMbumbulu area.

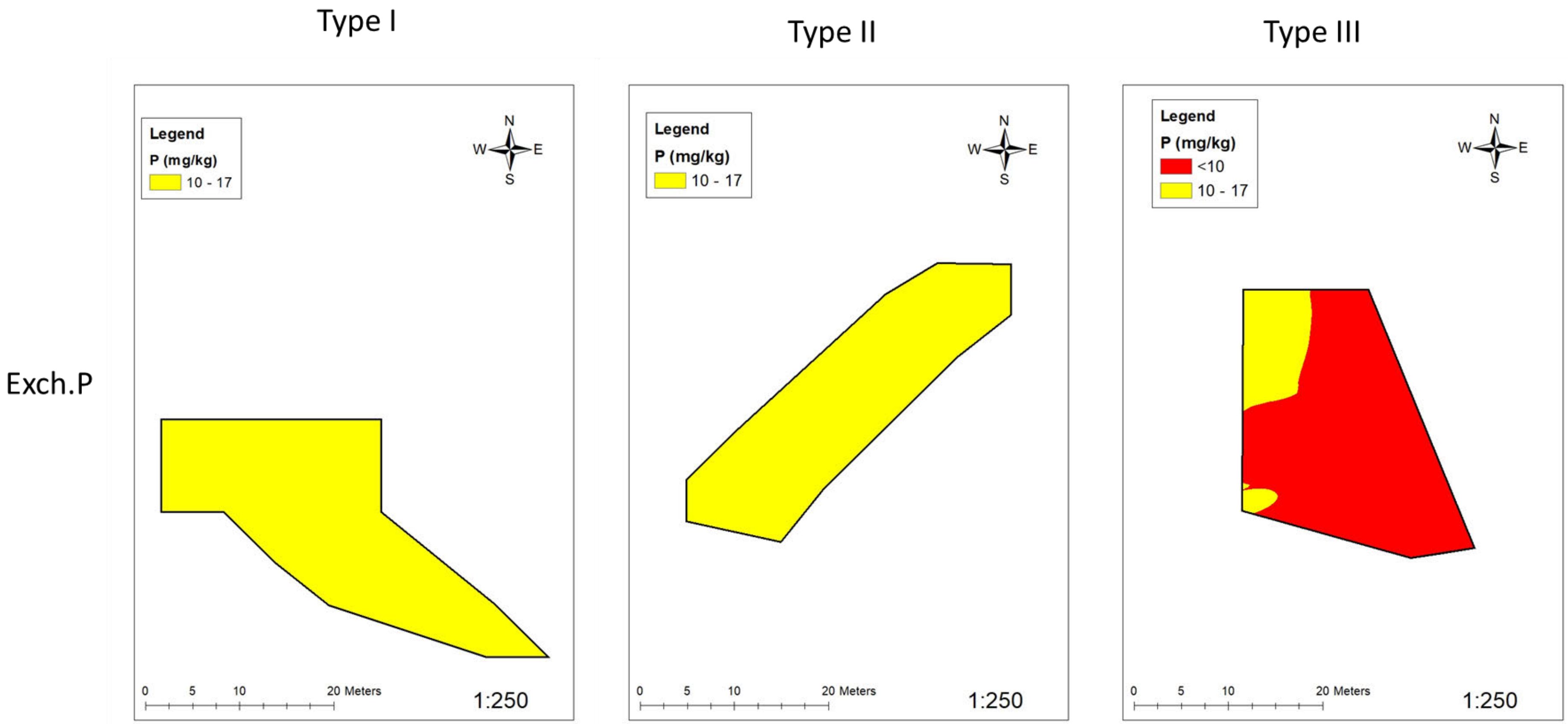

Figure 4.9: Maps showing spatial variability of exchangeable P (mg/kg) on three farm typologies in uMbumbulu area.

4.3.4 Summary of geo-statistics of farm typology and spatial dependency

The soil on all three typologies is constantly acidic for all 3 typologies. The spatial dependency for soil pH was strong (<25%) in type I and weak in both type II & III typology (>75%), while extractable P showed weak and strong dependency for type I and III respectively. Total carbon showed weak spatial dependency with N:S ratio of >75% for type I and II typologies, while moderate (25-75%) for type III. Clay percent showed strong, moderate, and weak for type I, II and III respectively. The range of spatial dependence varied from 10.60 m (TC) to 50.95 m (exchangeable P and clay %) (Table4.5).

Table 4.5: Semivariogram parameters of pH, exchangeable P, total carbon, and clay content of homefields at farm types I, II III of uMbumbulu.

Variable	Lag Size (m)	Range (m)	Sill	Nugget (C_o	N:S Ratio	Spatial Dependency	Model
pH							
Type I	4.25	45.35	0.66	0.04	0.06	Strong	Spherical
Type II	3.96	28.03	0.01	0.02	2.31	Weak	Spherical
Type III	1.37	16.38	0.00	0.01	5.04	Weak	Spherical
Exchangeable P							
Type I	4.25	50.95	5.91	34.65	5.86	Weak	Spherical
Type II	4.00	48.00	0.00	32.34	-	-	Spherical
Type III	3.38	40.51	10.98	0.45	0.04	Strong	Spherical
Total C (%)							
Type I	1.73	10.60	0.03	0.12	3.69	Weak	Spherical
Type II	3.17	30.12	0.08	0.09	1.14	Weak	Spherical
Type III	2.99	21.47	0.04	0.01	0.41	Moderate	Spherical
Clay (%)							

Type I	4.25	50.95	1.99	0.0	0	Strong	Spherical
Type II	3.25	28.61	25.25	8.70	0.34	Moderate	Spherical
Type III	2.16	25.94	1.33	1.76	1.33	Weak	Spherical

The – means value is undefined as number divided by zero gives infinity.

There is a different array in spatial dependency of exchangeable bases and acid saturation in all 3 typology (Table 4.6). Exchangeable Ca showed strong, weak, and moderate spatial dependency for type I, II and III, while the range was 38.19, 48 and 14.01 m respectively. Exchangeable Mg, K and AS showed strong spatial dependency for type I and III, while type II remained weak (Table 4.6). For exchangeable bases and acid saturation show same range of 48 m for type II, while the others vary (Table 4.6).

Table 4.6: Semivariogram parameters of exchangeable bases and acid saturation of homefields at farm types I, II III of uMbumbulu.

Variable	Lag Size (m)	Range (m)	Sill	Nugget (C_o	N:S Ratio	Spatial Dependency	Model
Exchangeable Ca (cmolc/kg)							
Type I	4.25	38.19	2.04	0.35	0.17	Strong	Spherical
Type II	4.00	48.00	0.61	0.70	1.15	Weak	Spherical
Type III	2.24	14.01	1.29	0.83	0.65	Moderate	Spherical
Exchangeable Mg (cmolc/kg)							
Type I	4.25	50.95	0.38	0.86	0.23	Strong	Spherical
Type II	4.00	48.00	0.00	0.29	156.32	Weak	Spherical
Type III	1.35	11.66	0.13	0.03	0.23	Strong	Spherical
Exchangeable K (cmolc/kg)							
Type I	1.73	12.68	0.39	0.33	0.09	Strong	Spherical
Type II	4.00	48.00	0.00	0.02	-	-	Spherical

Type III	2.90	23.33	0.02	0.00	0.23	Strong	Spherical
AS (%)							
Type I	4.25	50.95	23.38	0.16	0.18	Strong	Spherical
Type II	4.00	48.00	2.14	4.08	1.90	Weak	Spherical
Type III	2.43	17.28	205.60	37.24	0.18	Strong	Spherical

The (–) means value is undefined as number divided by zero gives infinity.

It was only pH and clay% that shows weak spatial dependency (>0.75), as depicted in the semivariogram which shows a higher starting slope (Figure 4.10 & 4.17). In type III typology, AS, Mg, K and exchangeable P show a strong spatial dependency (<0.25) and on the semivariogram (Figure 4.11, 4.13, 4.14, 4.15) they start from a lower slope which is much closer to zero if not equal to zero. As for Ca and TC, they are moderately spatial dependent (0.25-0.75). Hence, their slope on the semivariogram is nor high nor low (Figure 4.12 & 4.16).

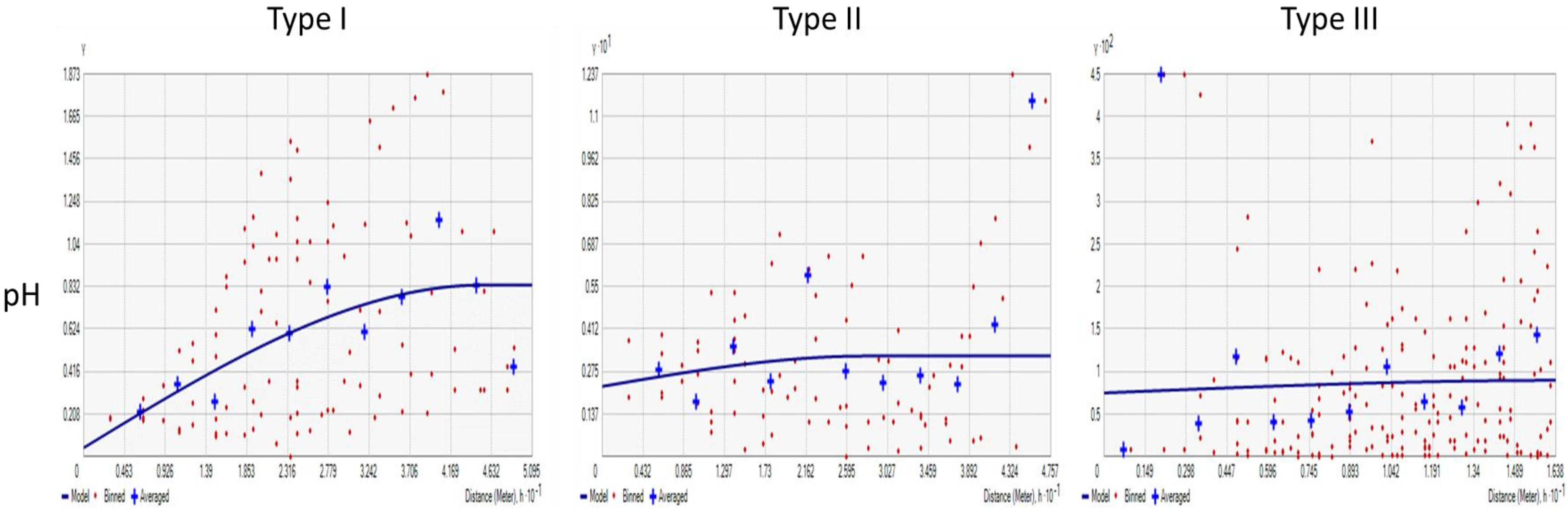

Figure 4.10: Semivariograms showing spatial variability of pH on three farm typologies in uMbumbulu area.

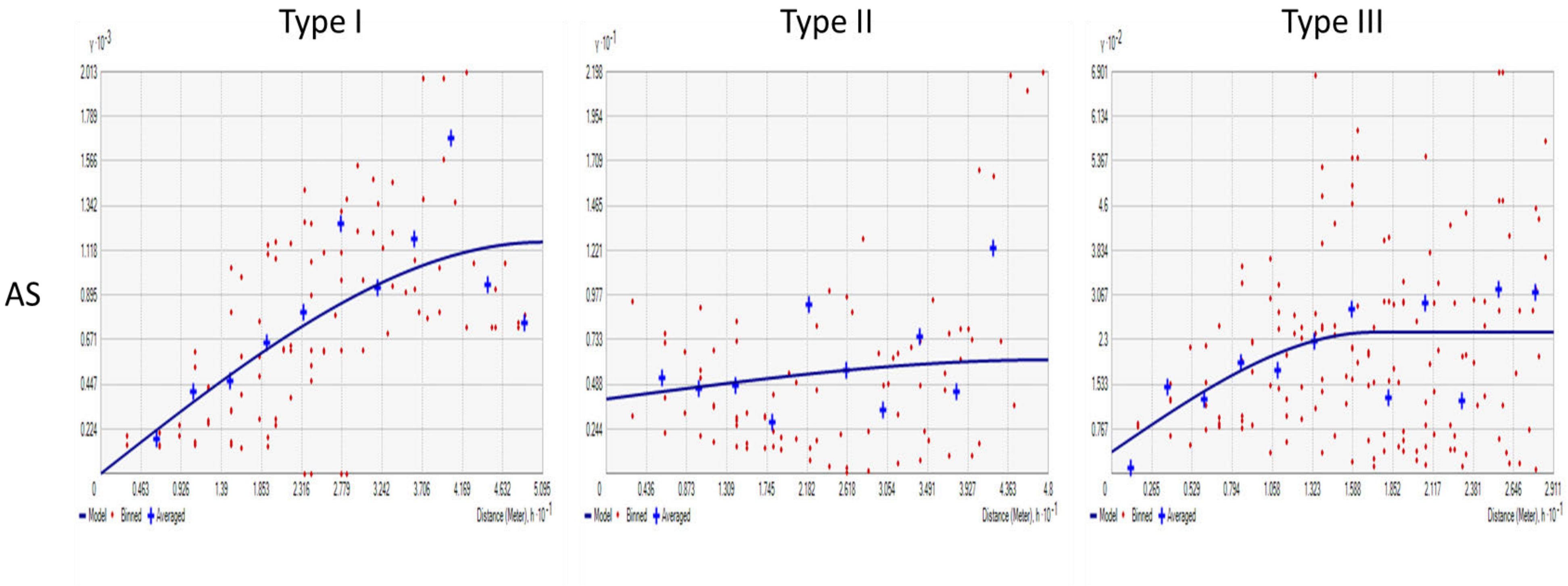

Figure 4.11: Semivariograms showing spatial variability of acid saturation (%) on three farm typologies in uMbumbulu area.

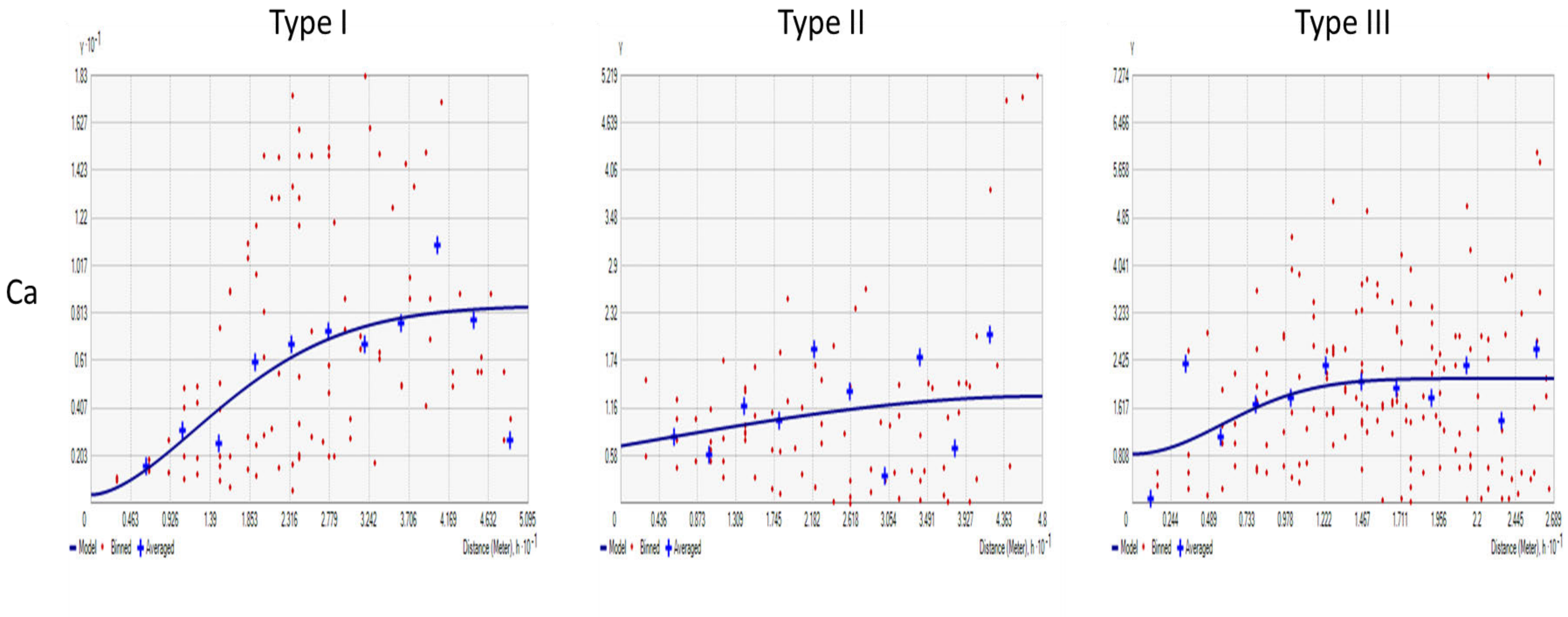

Figure 4.12: Semivariograms showing spatial variability of calcium (cmolc/kg) on three farm typologies in uMbumbulu area.

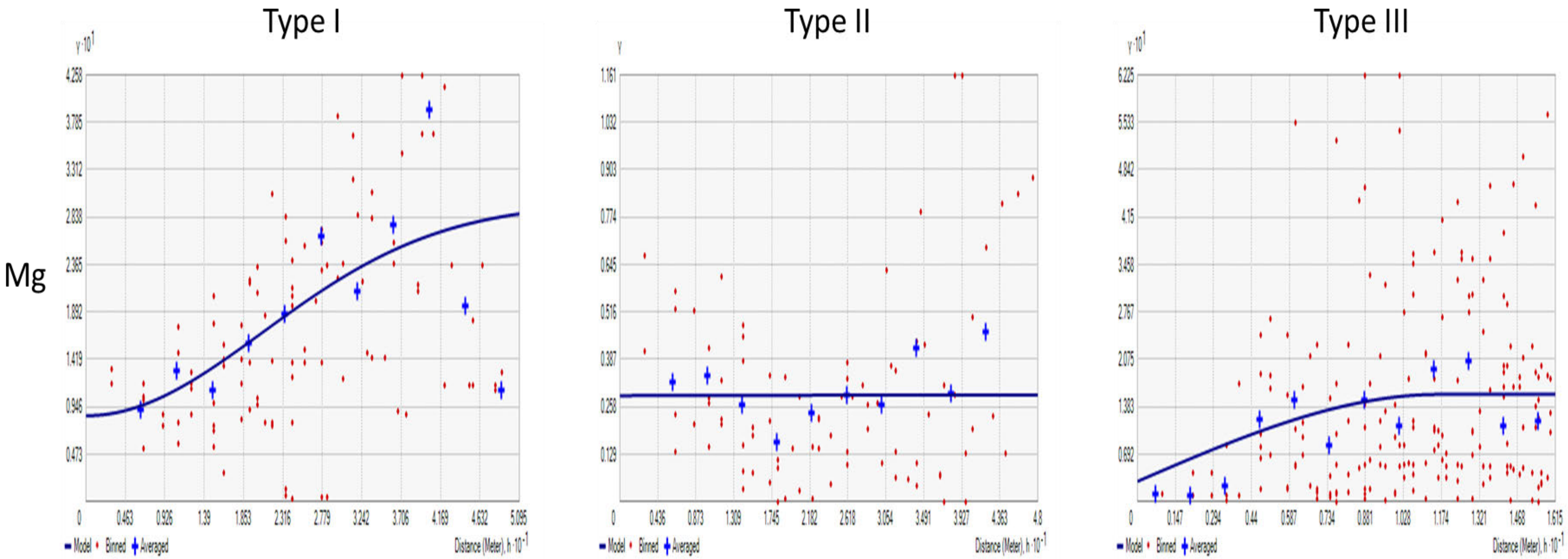

Figure 4.13: Semivariograms showing spatial variability of magnesium (cmolc/kg) on three farm typologies in uMbumbulu area.

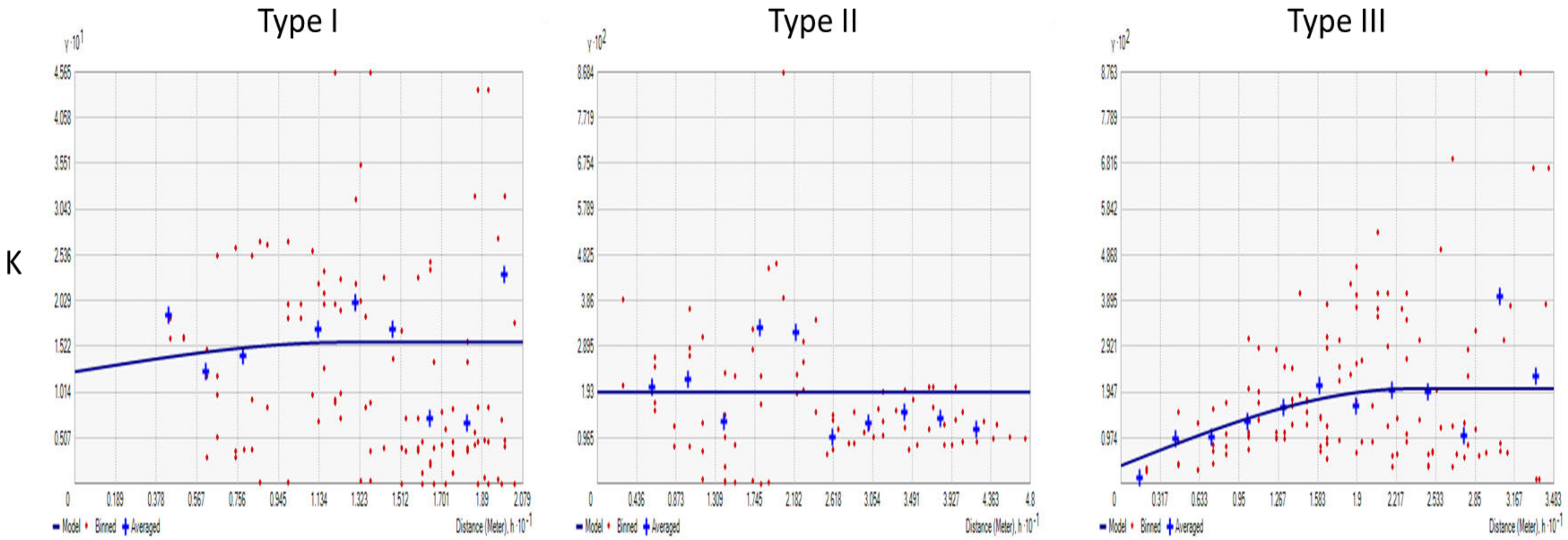

Figure 4.14: Semivariograms showing spatial variability of potassium (cmolc/kg) on three farm typologies in uMbumbulu area.

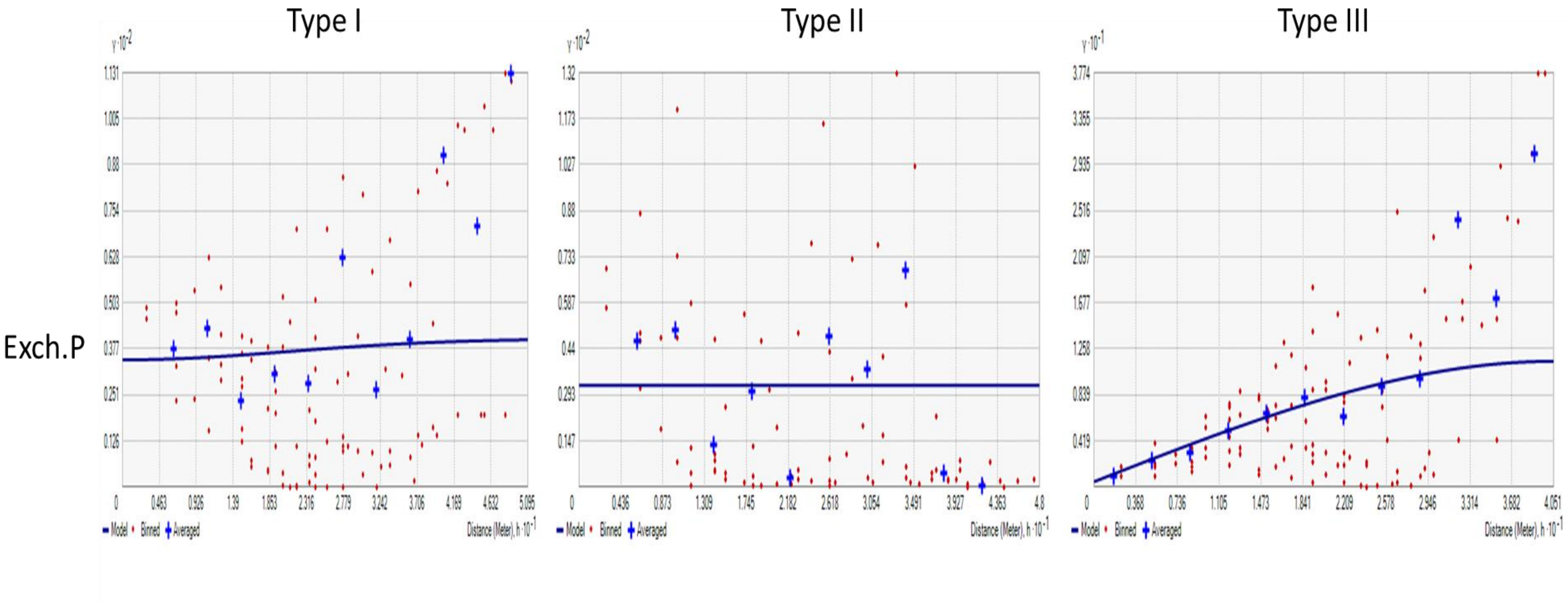

Figure 4.15: Semivariograms showing spatial variability of extractable phosphorous (mg/kg) on three farm typologies in uMbumbulu area.

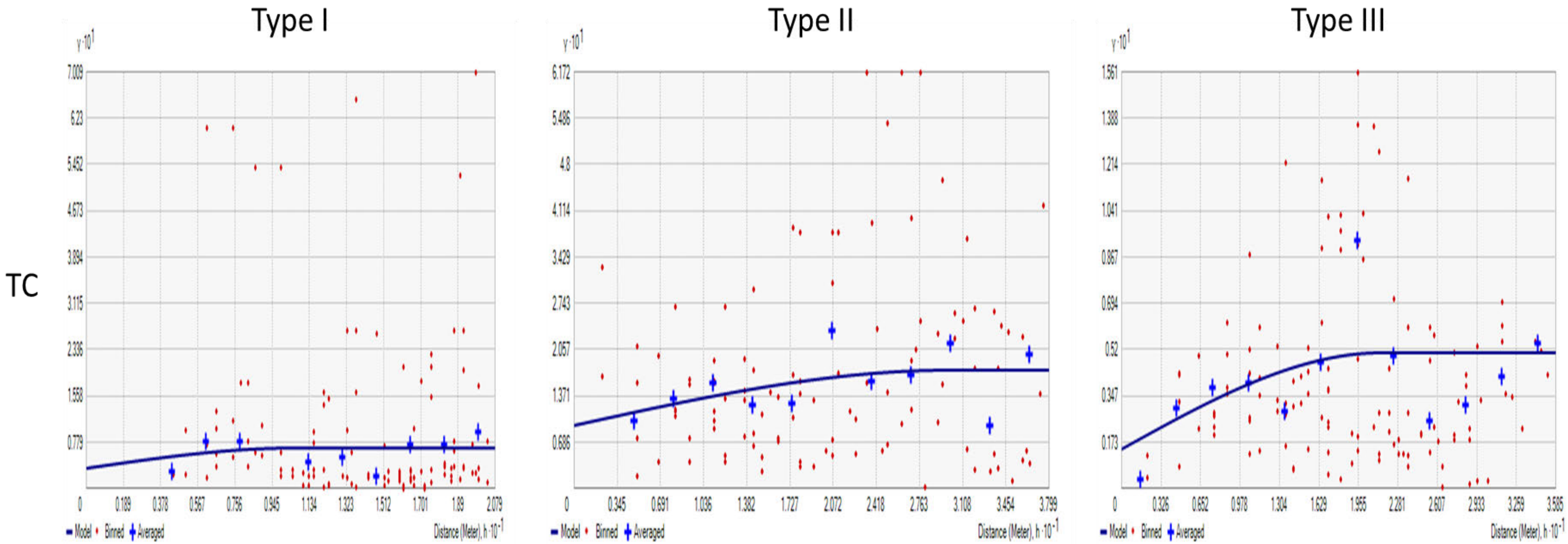

Figure 4.16: Semivariograms showing spatial variability of total carbon (%) on three farm typologies in uMbumbulu area.

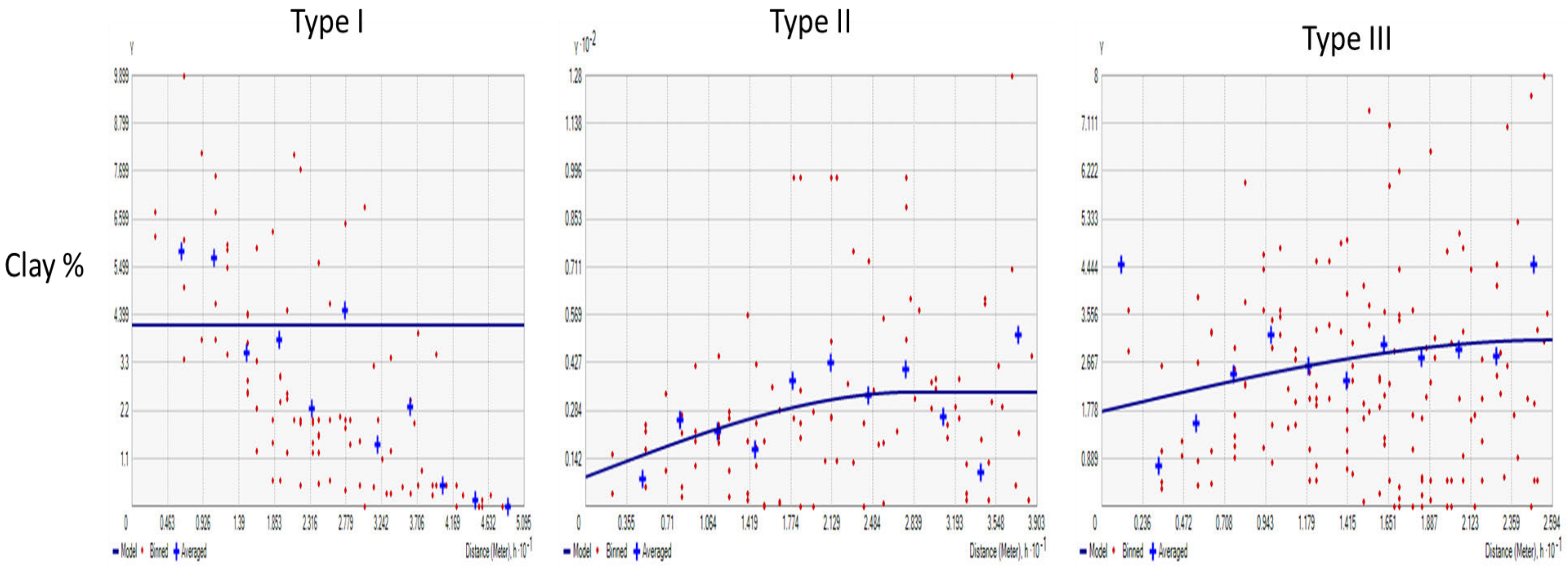

Figure 4.17: Semivariograms showing spatial variability of clay percentage (%) on s typologies in uMbumbulu area.

4.4 Discussion

The lack of significant differences in soil fertility results in ($p > 0.05$) between all three typologies and cropping systems at uMbumbulu could be a result of generally the use of organic amendments across all the typologies as supported by cooperative Ezemvelo Farmers Organisation (EFO) and the government, where they cultivate amadumbe on most of their land which are strictly organic and leads to positive impacts on soils. The main reason for this organic production is a market base requirement. Samples were taken from fields of the same soil type Hutton in uMbumbulu, which eliminated variability due to pedogenesis, but their management differs with each typology as affected by each typology characteristics.

The observed trend is inconsistent with previous studies (Tittonell *et al.*, 2005a; Zingore *et al.*, 2007; Tittonell *et al.*, 2010; Kome *et al.*, 2018) who found significant effect of farmer typology on soil fertility parameters. The difference between literature and the observed results for this study might be because of potentially lower rates of applications of amendments than of other countries and the market drive for more product. Moreover, in uMbumbulu majority of farmers rely on organic manure and with the help of extension services facilitated by several stakeholders from government to private institutions, adaptation to new technologies is easier and manage to minimise fertility gradients. From the results resource endowment did not affect soil fertility parameters, and no previous study on fertility gradient and resource endowment showed these findings. The only logical explanation would be extension services are doing a great job in minimising fertility gradients throughout the typologies both uMbumbulu and Msinga (Table 4.1 and 4.2). This is also clearly illustrated in the maps (Figure 4.2 to 4.9) that most soil parameters tested are spatially variable and/or correlated in the field.

However, the exchangeable P results agreed with what is in the literature, where homefields, especially of type I farms had higher levels, than outfields and home fields of other typologies. This effect could be explained by the relatively higher amendments applied in the homefields of the well-resourced group of farmers. The samples were taken from fields with the same Glenrosa soil type at Msinga, which eliminated variability due to pedogenesis, but their management differs with each typology as affected by each typology characteristics.

Management strategies are mostly influenced by regional climate and hence why no significance when relating factors of management. An example, in Msinga majority of farmers mulch their fields after harvest and in planting to retain moisture as the area is very hot, but in uMbumbulu farmers burn crop residues, by burning them the nutrients in the residues become readily available in the soil for plant uptake. The above statement indicates that management may seem to differ between fields and sites, but it all lies in the method of execution of these management strategies hence, some may be readily active and some slow.

Msinga, also has access to extension services from farmers support group (FSG) and the government. The significance of extractable phosphorus in Msinga is due to the soils are shallow and rock sediments are much closer to the surface as they impact the concentration of extractable phosphorus (Figure 4.1). This is more of a pedogenesis factor/implication rather than that of management. But also, from the previous chapter Msinga farmers had access to more livestock than uMbumbulu and their production is mainly based on subsistence for food security and hence more organic inputs put to the soil and induce these gradients of phosphorus. Also, uMbumbulu consist of Hutton soils which have a high P-fixing potential, hence the difference between uMbumbulu and Msinga on phosphorus availability (Fey, 2010). Moreover, Zindove and Chimonyo (2015) found that Msinga has nutritious veld and hence their livestock produced highly fertile manure. Farmers with access to manure/fertilisers usually have a variation in nutrient availability on their fields (Zingore *et al.*, 2007; Innazent *et al.*, 2022).

As shown in the descriptive statistics (Table 4.3). The acidic nature of uMbumbulu soils could be more of using manure and/or fertiliser continuously without liming (Kome *et al.*, 2018). Also, Hutton soils are generally acidic due to high leaching and advanced weathering (Fey, 2010). Acidic soils had a negative effect on exchangeable bases, leading to lower concentrations of bases. Total carbon values of less than 1.8 % (18 g/kg) are considered low and above 1.8 % depicts high total carbon (Fey, 2010). In this study total carbon under all typologies was high ranging from means of 2.06 % to 4.62 %. The distribution of the data for type I, II and III typologies need to be normally distributed for it to fit in the kriging method models (Xin-Zhong *et al.*, 2009; Vasu *et al.*, 2017; Manyevere *et al.*, 2017).

Most important aspects in geo-statistics are spatial dependency which is explained by the N:S ratio. Which means that variables or parameters with values close to each other are similar/ the same (strong dependence), but those with values far apart the relationship is more variable (weak dependence) (LeSage and Pace, 2001; Xin-Zhong *et al.*, 2009; Vasu *et al.*, 2017) and shows how dependent spatially the measured variables are. This phenomenon is seen closer graphically in a semivariogram where the slope of the graph closer to zero resembles a spatial continuity between neighbouring points which can be observed for pH, AS and Ca in type I typology. Clay % in type II typology, AS, Mg, K, and exchangeable P in the type III typology (Figure 4.2 to 4.9). In uMbumbulu, a slope close to zero implies that there is a narrow dispersion/less variability/ strong variability as indicated by the coefficient of variance, the opposite applies to a slope far from zero which shows wider dispersion and hence weak variability (Table 4.5 & 4.6).

Overall, type I majority of variables have strong dependency (Table 4.5). This means there is low variability of fertility parameters in this group, hence this is an effect of adequate management and the ability to afford inputs such as labour, fertiliser and more land as explained in chapter 3. In type II the overall majority showed weak dependency (Table 4.6). This is an indication of improper fertility management in the field and thus would result in poor yields. Contrary, type III was expected to have weak spatial dependency however majority of the variables were strongly spatial dependence or with narrow dispersion.

Such studies that map spatial variability versus different typologies do not exist in literature. However, previous studies have shown spatial variability of small-holder farmers on a single field with no different management implications (Lelago *et al.*, 2016), mapping variability under different agro-clamatic zones (Prabhavati *et al.*, 2015; Soropa *et al.*, 2021), an entire district of different villages (Vasu *et al.*, 2017), micro nutrients in different irrigation schemes (Manyevere *et al.,* 2017) yield of different crops under sandy soils (Usowicz *et al.*, 2017). Hence, more research needs to be done in the aspect to give out a clear view of this phenomenon both in uMbumbulu and Msinga as in this study only focuses on data from uMbumbulu.

The variability of parameters can also be explained by the range. The range give an indication of good or poor sampling density intervals. If the range is higher than the lag distances (average distance in meters between sample points), that means good or adequate sampling density and vice versa when the range is lower than the lag distance (Xin-Zhong *et al.,* 2009; Prabhavati *et al.*, 2015). Under all three typologies (Table 4.5 and 4.6) there was adequate sampling density as the sampling grid was 5 m × 5 m and the fields ranged from an average of 0.2 to 0.8 hectare which are relatively small fields.

The maps produced in this study (Figure 4.2 – 4.9) are in correlation with the statistics (Table 4.5 and 4.6), as they clearly indicate areas of low and high nutrient concentrations spatially in the fields with reference to the homestead. The high concentration of nutrients closer to the homestead in these results are in conjunction with previous studies that observed higher concentrations of nutrients closer to the homestead, due to chicken droppings, sweepings as well as prioritisation of fields due to minimum labour availability (Muthamia *et al.*, 2011; Michel *et al.*, 2015).

A minimum of 100 m × 100 m grid is usually used for larger area which entails one sample could be interpolated for 1 ha (Xin-Zhong *et al.*, 2009; Bogunovic *et al.*, 2017). In some studies they used larger grids like 300 × 300 m, 325 × 325 m grids (Prabhavati *et al.*, 2015; Vasu *et al.*, 2017). In which in these studies a wide range was established for different grids, the greater the range the more reliable or adequate the sampling interval (Fu *et al.*, 2010). The ranges in this study varied from 10.6 to 50.9 m as only one interval (5 m × 5 m) was used throughout the three typologies (Table 4.5 and 4.6), which gave an indication of adequate sampling for such small fields.

4.5 Conclusion

In this study we ought to see fertility gradients due to different management practices, field type and typology as evident in literature. No gradients were observed in between typologies, as well as between management practices, but exchangeable P in Msinga showed presence of gradients. This led to the spatial mapping of these nutrients.

For uMbumbulu, spatial variability was more dependent on the sampling range/ adequacy. Under type I and type II typologies there was weak spatial dependency, while type III typology varied from strong to weak spatial dependency for the different soil fertility parameters. Maximum spatial dependency range for type I, II and III were 50.95 m, 48 m, and 40.51 m respectively which are all greater than the lag size. Hence, the 5 m × 5 m sampling range was adequate to give an accurate spatial representation of parameters at hand. A recommendation would be to also map homefields of Msinga to give a clear indication and comparison of different typologies with reference to management and spatial variability of nutrients.

5. CHAPTER 5: GENERAL DISCUSSION AND CONCLUSIONS

5.1 General discussion

Socio economic factors such as education, capital, access to market, land, and labour availability played a pivotal role in the development of farm typologies in the small-holder sector on uMbumbulu and Msinga in this study. The study identified three farm typologies based largely on land size, livestock ownership and external income, and the farmers are largely female headed at both uMbumbulu (63%) and Msinga (92%), emphasising the importance of the leadership of women in small-holder agriculture. The dominance of female-headed households could be because man leave to the city in search employment. Similar observations were previously made in Zimbabwe, Central Kenya, and Northern Region in Ghana (Zingore *at al.,* 2007; Mugwe *et al.,* 2009; Alvarez *et al.,* 2016). The study focused on subsistence farmers at typical small-holder farming areas of uMbumbulu and Msinga, who largely produce maize, potatoes, spinach, cabbage, and beans, which largely form their diet and therefore the main source of food security, and only sell some portion of the produce for money. Most of the crops which may improve soil fertility and crop production at both uMbumbulu (62%) and Msinga (68%). Crop rotations aid in breaking the weed and disease cycles, as well as nutrient recycling (Snapp *et al.,* 1998; Mikha *et al.,* 2006; Zingore, 2006). Also crop residues aid in keeping the soil healthy, with higher organic carbon concentrations for higher quality yields, whether in a mulched or burnt state (Giller *et al.,* 2009).

The farmers studied had average land sizes ranging 0.2-1.3ha, and for uMbumbulu the poor farmers (type III- resource poor) had higher average land area then the rich (type I -resource endowed) while at Msingathe rich had more land. Type I farmers are more commercially driven (Dunjana *et al.,* 2018). but the low land size for cultivation, 0.5 to 0.7 ha were not big enough for commercial production and more intensive technical advisory is needed. Type II are intermediately resourced farms and are between highly resourced and poorly resourced farms (Alvarez *et al.,* 2018). This typology is the most dominant in uMbumbulu (64%) compared to Msinga, where type III (poorly resourced) is the most dominant typology (72%). In previous studies land availability is a major constrain for this group (Zingore *et al.,* 2007; Giller *et al.,* 2011; Vanlauwe *et al.,* 2015; Dunjana *et al.,* 2018). The average land size was higher for type II and type III farmers and lower for type I farmers at uMbumbulu than at Msinga. The higher proportion of type I farmers (on average), with higher land size for type II and III farmers, suggest that more produce may be sold from uMbumbulu than Msinga, generating income. This view was supported by the proportion of farmers who generated income from farming for types I, II and III, who were 14, 20 and 8%, respectively, for uMbumbulu while for Msinga they were1.5, 2 and 6%. While land availability is a major limiting factor, other production factors such as labour, also contribute, which leads to famers opting to less variety of crops. For instance, most of type III farmers tend to rotate same crops over the years. These farmers are more susceptible to food insecurity. These typologies tend to have a significant impact on fertility gradients and variability.

The differences in farmer typologies may imply that type I farmers may apply more resources to land, resulting in better soil fertility than the poorer typologies. This effect was clear for exchangeable P results at Msinga where homefields of type I farmers had high exchangeable P (up to 60 mg/kg) than type III (about 20 mg/kg), while there were no differences between outfields. The lack of differences between outfields emphasises the view that farmers, preferentially apply resources on homefields, which showed typological effects. Most of the farmers at Msinga indicated that they prioritised outfields (64%) while a small proportion gives priority to homefields (32%), and this perception could be because of the amount of effort they put in the management of the outfields due to distance. This could have been worsened by the fact that most of the farmers used their own labour for activities that included application of bulky organic manures. In Msinga, 96% of the farmers indicated that they relied on organic manures either solely (32%) or together with chemical fertilisers (64%). However, the higher exchangeable P on homefields than outfields of the rich (type I) farmers could be because of lower quantities of manure applied on the outfields due to greater labour requirements. The low levels of education (84% having primary as the highest level) could also have affected the soil management and the distribution of effort required.

The lack of differences in the fertility status (lack of gradients) of the field types (homefield and outfields) and typologies at uMbumbulu could be because (i) firstly all the fields were essentially homefields (close to the homestead), for which management was not affected by distance and (ii) secondly because of the assistance of extension services, which encouraged the use of organic manures, irrespective of typology and hence minimising these gradients. While the low levels of education (73% having primary as the highest educational level) could affect the soil management, the availability of extension services could have counteracted this effect. Technical support of extension officers led to an improvement of sustainable practise and livelihood of the farmers who are organised into a cooperative Ezemvelo Farmers Organisation (EFO), at uMbumbulu. As a result of this farmer organisation, the majority of uMbumbulu rely mostly on organic manure as they crop strictly organic taro (amadumbe) which is sensitive to synthetic fertiliser and is taken to the formal market. This view was supported by the findings that 73% of the farmers at uMbumbulu use sole organic manure, mostly annually, with a further 13% co-apply it with chemical fertilisers. Furthermore, majority of the farmers (50%) indicated that there was no prioritisation of fields in terms of management, while 17 and 33% indicated that they prioritised outfields and homefields, respectively.

The lower exchangeable P at uMbumbulu than Msinga, irrespective of farm typology could be explained by lower amounts and poorer quality of manure added in addition to higher acidity of the soils which may have resulted in P fixation. Farmers in Msinga have access to more livestock than uMbumbulu and hence more organic inputs put to the soil and induce these gradients of phosphorus found that Msinga has nutritious veld and hence their livestock produced highly nutrient-rich manure (Zindove and Chimonyo, 2015), and when applied at high rates, especially by type I (rich) farmers, soil exchangeable P is increased. The quality of manure at uMbumbulu could be poorer because of more highly weathered soils, and when applied at low quantities may not significantly influence available nutrients. Moreover, P fixation could have minimised the management effects on P availability in the more highly weathered uMbumbulu soils. Farmers with access to manure/fertilisers usually have a variation in nutrient availability on their fields (Zingore *et al.*, 2007). In addition to the addition of organic manures, most of the farmers (>65%) at both uMbumbulu and Msinga use crop residues as mulch and/or feed to livestock and the manure is returned to the land, with positive effects on soil fertility. However, the manures and crop residues of uMbumbulu and Msinga were not characterised for any potential quality differences and for their nutrient release patterns, which have significant implications to their contribution to soil fertility and crop productivity.

The lower exchangeable P suggest that more liming and P fertiliser may be required for uMbumbulu, than at Msinga. Also, organic inputs aid in phosphorus availability in the soil and hence improving soil health and yield (Opala *et al.*, 2013). However, the farmer management of the soil depends on their perceptions on soil fertility, and less on laboratory-based analytical results. The farmers in the study areas perceived fertile soils as those that were dark, workable and with earthworms, and to some extent yield. However, it was not clear what proportion of their land they considered fertile, and whether the farmers try to allocate better management to infertile soils to improve their productivity. While there were no effects of farmer typology on soil fertility at uMbumbulu, the spatial variability, based on more detailed sampling, could be significant.

As shown in the descriptive statistics (Table 4.3), the acidic nature of uMbumbulu soils could be a result the highly degraded nature of the soils due to high rainfall received in the area together with the use of manure and/or fertiliser continuously without liming (Kome *et al.*, 2018). Total carbon values of less than 1.8 % (18 g/kg) are considered low and above 1.8 % depicts high total carbon (Fey, 2010). In this study total carbon under all typologies of uMbumbulu was high and ranging from means of 2.06 % - 4.62 %.

Overall, type I majority of variables have strong dependency (Table 4.5). This means there is low variability of fertility parameters in this group, hence this is an effect of adequate management and the ability to afford inputs such as labour, fertiliser and more land as explained in Chapter 3. In type II the overall majority showed weak dependency (Table 4.6). This is an indication of improper fertility management in the field and thus would result in poor yields. On contrary, type III was expected to have weak spatial dependency. However, majority of the variables were strong spatial dependence or with narrow dispersion. Also, from this study a 5m × 5m sampling interval has shown to be adequate for smaller fields of less than 1 ha.

5.2 Conclusions

The aim of this study was to determine farm typologies and how their fertility gradients are related or affected by different management techniques. The findings from this study will help understand heterogeneity/complexity of rural small-holder farmers and finding suitable adaptation technique for resource management of complex typology systems as these.

Three resource groups or farm topologies were generated in this study, namely resource-endowed (Type I), who possess more land and with larger proportion deriving income from farming; moderately resourced group (Type II), which is neither rich nor poor, with a balance in resources to maintain their livelihoods; and poorly resourced group (Type III), which is highly resource limited, but this group in Msinga has the largest average land size and minimum income from farming. uMbumbulu is predominated by the type II farm typology. This means that majority of uMbumbulu farmers are neither rich nor poor, hence they can maintain themselves through farming activities specifically crops. Majority of Msinga falls on the type III farm typology, this is mostly attributed by their small arable land plots. To further understand the ingenuity of these resource groups per site, a proper soil analysis for fertility gradients was done.

While no soil fertility gradients were observed in between typologies, as well as between management practices, at Msinga homefields of type I farmers had higher exchangeable P than outfield.

After focussing on uMbumbulu for spatial variability of soil fertility, field under type I showed strong spatial dependency, while type II typologies had weak spatial dependency. For type III farmers, the fertility parameters showed spatial dependency that varied from strong to weak. Maximum spatial dependency range for type I, II and III were 50.95 m, 48 m, and 40.51 m respectively which are all greater than the lag size. Maps (Figure 4.2 - 4.9) clearly indicates areas of high and low nutrient concentrations.

These maps can be very useful in targeting specific areas of poor or rich fertility and fertiliser recommendation, which is more economically viable to small scale farmers to put in what is needed. Further work needs to characterise the manures and crop residues of uMbumbulu and Msinga to establish potential quality differences and nutrient release patterns, which significantly affect their contribution to soil fertility and crop productivity in these areas. Additional work needs to be done on the spatial variability of soil fertility on homefields and outfields of Msinga especially comparing type I, which showed fertility gradients, and type III farmers. This needs to be done before attempting to put a reference crops and recommendations in terms of fertilisers.

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APPENDICES

Appendix 1: Questionnaire

1. Farm description

Date:

Site with GPS co-ordinates and elevation:
Village name & District:
Farmer name & cell no:
Gross income per farm (Ranges):
Name of Interviewer:

Family members/labour use

Name of Head	Sex/gender	Age range	Marital status	Education	Major source of income
		< 25			
		26 – 40			
		41 – 55			
		>55			

Male and female households' members	
Living and working on the farm	
Living in farm, but works full-time elsewhere	
Living in farm, but works part-time elsewhere	
Income from farming	
Use own labour, hire casual labour or Both	
Permanent labour	
If hiring, for what activities?	

Land use and management

General

Farm size	
Cropped land (%)	
Cash crops (type and proportion)	
Food crops (type and proportion)	
Livestock (types and units)	

Do you rotate crops intercropping/mixed cropping?	
If yes, which field?	
The sequence of crops in rotation?	
Do you prepare and apply Compost?	
Do you apply fertiliser/organic manure or both and in which field?	
How do you manage your crop residue after harvest? Burn/cover/feed to livestock	

Farm Sketch and additional comments:

2. Famer’s perception of soil fertility gradients

1. How do you define fertile soils?

2. How do you define infertile soil?

3. What are the plant indicators of fertile and infertile soils?

4. How long have you lived here?

5. Please rank the most important crops in your fields.

6. Last season harvest (amount) of the different current major crops?

7. Has the amount harvested changed during the last 10 years (How/ why?)

8. Reasons for the differences in yields between fields

Pest or disease	
Use of different varieties	
Management inputs	
Water logging/ erosion/ draught	
Declining soil fertility	
Others (specify)	

9. When do you usually prepare your land?

Before the rains start	
Just as the rains start	
After the rains have started	

10. Does it vary with plots (preparation of land), in which order or why?

11. Additional comments and observations: Plots that show decline in fertility overtime.

Fertility management practices Soil

Which field do you prioritise in terms of fertiliser/manure/compost and why?

Do you apply these fertilisers every year?

Plot	Expected yield	Inorganic fertilisers		Organic fertiliser		Previous and next crop rotations	Crop residue management
		Type	amount	Source	amount		
Home field							
Outfield							