SPATIAL VARIABILITY OF AGGREGATE STABILITY, SIZE DISTRIBUTION, EROSION AND RUNOFF IN SELECTED SOILS IN SOUTH AFRICA

BY

MABASA HLAYISANI ZACHARIA

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SUPERVISOR: PROF IIC WAKINDIKI

CO-SUPERVISOR: DR AD NCIIZAH

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DEDICATION

I dedicate my dissertation to my loving parents, Mabasa M.D and Masingi P.I, other family members, partner, friends and church family who supported me throughout the researching process.

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DECLARATION

I, Hlayisani Zacharia Mabasa, hereby declare that the dissertation for the master's degree at the University of Venda, hereby submitted by me, has not been submitted previously for a degree at or any other university, that it is my own work in design and in execution, and that all reference material contained therein has been duly acknowledged.

Signed:……………………...................Date……………………………

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LIST OF SYMBOLS AND ABBREVIATIONS

ARC	Agricultural Research Council
CT	Computed tomography
CV	Coefficient of variation
dS/m	Deci siemens per meter
E	East
EC	Electrical conductivity
ERL	Eutrophic Red Latosol
ESRI	Environmental Systems Research Institute
Fig	Figure
GIS	Geographic Information System
GPS	Global Position System
ha	Hectare
MWD	Mean Weight Diameter
N(h)	Number of pairs of the locations separated by distance h
NECSA	South African Nuclear Energy Corporation
OC	Organic Carbon
S.D	Standard deviation
SOC	Soil organic carbon
pH	Power of hydrogen
WSA	Water Stable Aggregates
$y(h)$	Semi-variance
$Z(x_i)$	Measured variable at a location i
$Z(x_i+h)$	Measured variable at the spatial location (i+h)

ABSTRACT

Soil erosion and runoff are a major threat to soil productivity since it is associated with the removal of the top layer, depletion of essential plant nutrients, and reduces infiltration of water into the soil. Soil aggregate stability and size distribution are important physical factors in the assessment of soil erosion and runoff. A study was carried out in an approximately 1 ha field in different soils to ascertain the spatial variability of soil erosion, runoff, aggregate stability and size distribution. The spatial variability approach provides insight into the search for soil management strategies to reduce soil erosion and runoff. Twelve soil samples were collected at 0 – 150 mm depth for measurements of soil aggregate stability, size distribution, erosion and runoff at the University of Venda agricultural farm and at the Agricultural Research Council – Vegetable and Ornamental Plants (ARC-VOP) farm. The University of Venda agricultural farm falls under low veld climate and had deep well-drained red soil with high clay content and the soil is classified as Hutton form which is equivalent to Rhodic Ferralsol. ARC-VOP farm falls under humid subtropical climate and is characterised by sandy clay loam soil classified as Clovelly soil form, which is equivalent to Luvisols/Cambisols. Soil aggregate stability and size distribution were measured following the wet sieving method. Macro-aggregate (>0.25 mm) and micro-aggregates (<0.25 mm) were considered in this study. Soil erosion and runoff were measured using a rotating disc rainfall simulator at a rainfall intensity of 45 mm/h. Semi-variogram analysis was used to determine the spatial variability of soil aggregate stability, size distribution, erosion and runoff. A spatial distribution map was produced using ordinary kriging method in ArcMap of ArcGIS 10.5 software. The results showed very weak spatial variability of soil erosion and runoff at both sites. This could have resulted from weak variability of soil infiltration rate, soil crust strength, porosity. Moreover, the weak variation of soil loss could also have resulted from the weak variation of runoff across the measured site in this study. A very weak spatial variability was recorded with 100% spatial ratio for soil aggregate stability at University of Venda agricultural farm while moderate variability with 42.98% spatial ratio was observed at Agricultural Research Council farm. Similarly, microaggregates had very weak variability with 100% spatial dependence at University of Venda agricultural farm whereas Agricultural Research Council farm was characterised with moderate variability with 66.67% spatial dependence. In this study, strong variability was observed on macroaggregates at Agricultural Research Council farm with a spatial dependence of 17.39% whereas weak variability was observed at University of Venda agricultural farm. The effects of the extrinsic factors mainly tillage could be one on the main reason the landscape was characterized with a very weak and moderate spatial variability in this study. However, soil intrinsic factors could have played a role on macroaggregates at Agricultural Research Council farm. Therefore, the spatial analysis showed great importance to be applied in the assessment of soil erosion, runoff, aggregate stability and size distribution.

Key words: Macroaggregates, microaggregates, Wet sieving method, Rainfall simulation.

CHAPTER ONE

1.0 INTRODUCTION

1.1 Background

Spatial variability of soil structure attributes including aggregate stability and size distribution is caused by agricultural management, geologic and pedologic soil forming factors (Annabi et al., 2017). According to Saglam et al. (2011), measurement of soil spatial variability is essential to provide knowledge to the better decision making of nutrients, water, and fertilizer use during agricultural production to sustain agro-ecosystems. Understanding the spatial variability of soil aggregate stability and size distribution is also significant for the evaluation of soil erosion and runoff. However, the knowledge of the spatial variation of aggregate stability and size distribution is limited. Therefore, the prediction of the spatial variation of soil aggregate stability is fundamental in the management of agricultural soils in a sustainable manner (Annabi et al., 2017).

Soil erosion and runoff are major abiotic drivers of soil degradation (Collins et al., 2015). Soil loss through erosion and runoff disrupts nutrients cycling, depletes soil biodiversity, and leads to losses of soil reservoir storage (Collins et al., 2015). Consequently, lands affected soil by erosion and runoff become less productive. According to Le Roux et al. (2007), over 70% of South Africa’s productive land is affected by erosion of different intensities. Stroosnijder (2003) reported that water loss through runoff can be as high as 50% especially on bare soil.

Soil erosion and runoff does not only affect the soil itself but also pose a burden on the economy due to the huge financial requirements for water purification as well as soil reclamation. For instance, the Environmental Report of South Africa indicated that the annual water treatment cost had increased by ZAR 2 billion because of high water turbidity induced by intensive soil erosion in South Africa (Gibson et al., 2006).

Therefore, one approach of evaluating the soil vulnerability to erosion and runoff is by measuring soil structure attributes.

Soil aggregate stability and size distribution are important soil structure attributes to consider in the assessment of soil erosion and runoff (Barthes and Roose, 2002; Collins et al., 2015). These factors are regarded as signals of soil vulnerability and resilience. For example, the stability of aggregates corresponds to the capability of an aggregate not to break up into smaller fragments, which in turn induce less soil particle detachment and the transport through raindrops impact (Algayer et al., 2014). In contrast, Liu et al. (2015) reported that the breakdown of soil aggregates increases the risk of soil erosion and runoff hazards.

Higher aggregate stability decreases soil vulnerability to erosion and runoff because it minimises the mineralization of soil organic carbon (SOC) by reducing the accessibility organic compounds by microorganisms and enzymes (Bronick and Lal, 2005). However, aggregate stability and size distribution are affected by both natural and anthropogenic processes resulting in their variability in the field. Anthropogenic process such as conventional tillage systems is one of the crucial process that affect these important soil physical properties (Tagar et al., 2017). Soil aggregate stability and aggregate size distribution can be spatially variable within the field due to various soil interactions including soil forming factors and soil management practices (Kilic et al., 2012; Mohammadi and Motaghian, 2011). Other factors that cause soil spatial variability include soil organic matter, texture, electrical conductivity and cations (Annabi et al., 2017).

In recent years, several studies on the spatial variability of soil aggregate stability have been performed (Annabi et al., 2017; Barik et al., 2014; Ye et al., 2018). However, there is limited information on the spatial variability of aggregate stability and size distribution in relation to soil erosion and runoff compared to other soil properties such as soil organic carbon content (SOC) (Annabi et al., 2017), soil texture (Langella et al., 2016; Wang and Shi, 2017) and aggregate formation process (Ye et al., 2018). Moreover, recent literature on the spatial variability of aggregate stability ignores the local spatial autocorrelation and the local clusters of similar behaviour in the spatial arrangement (Ye et al., 2018). Therefore, this study investigated if there was a spatial variation of soil erosion, runoff, soil aggregate stability and size distribution following tillage in cultivated fields.

1.1 Problem statement

Aggregate stability and size distribution influence soil erosion and runoff. Nevertheless, the search for remedial soil management measures using this knowledge has eluded researchers for a long time. This is probably because of the methodology used in data collection and analysis. The spatial relationship of soil erosion, runoff and soil aggregate stability and size distribution is less studied and understood.

1.2 Justification

Soils, their properties and processes vary across a landscape. Therefore, studies on spatial variability are likely to mimic a soil behaviour compared to the traditional representative sample approach. Such knowledge could improve soil use and management resulting in improved soil productivity and environmental protection.

1.3 Objectives

1.3.1 To determine the spatial variability of aggregate stability and size distribution in selected soils.

1.3.2 To determine the spatial variability of soil erosion and runoff in selected soils.

1.4 Hypotheses

1.4.1 There is no spatial variability of soil aggregate stability and size distribution in the selected soils.

1.4.2 There is no spatial variability of soil erosion and runoff in the selected soils.

CHAPTER TWO

2.0 LITERATURE REVIEW

2.1 Soil Erosion and Runoff

Soil erosion and runoff are major problems affecting natural ecosystems and the productivity of land resource in South Africa. For example, about 12.6 t/ha/y of soil loss due to erosion and runoff was reported in South Africa by Le Roux et al. (2008). Cultivation as traditional tillage practice is one of the major drivers of soil erosion and runoff because of the disturbance of soil structural stability. About 62% of the South African areas are currently under active farming and this includes commercial and subsistence farming in different slopes (National Land Cover, 2000). Le Roux et al, (2008) predicted water erosion using the Revised Universal Soil Loss Equation at a national scale for South Africa. It was reported that approximately 61 m ha or 50 % of the South African land was had moderate to severe potential erosion risk, while more than 91 m ha or 75 % area of land had very low to low actual erosion risk. Moreover, about 26 m ha or 20 % of the national land had soil loss of 10 t/ ha/y.

In other studies, higher runoff rate of 26.2 mm h^{-1} was observed under non-cultivated soil than in cultivated soil where by 20.5 mm h^{-1} was observed on the bare clayey soil in a semi-arid region in Limpopo Province (Mzezewa and van Rensburg, 2011). It was suggested that these results could be due to the formation of surface crust on the non-cultivated soil. Surface crust is associated with minimised water infiltration, hence increasing surface runoff and erosion. However, there was no significant difference between cultivated and non-cultivated soils after 71 mm h^{-1} rainfall intensity was applied. High rainfall intensity is associated with slaking of aggregates as well as seal formation due to the high kinetic energy of raindrop under cultivated soil resulting in reducing infiltration rate. Moreover, high rainfall intensity of 71 mm h^{-1} gave little time for water percolation into the soil results in runoff and erosion.

Keay-Bright and Boardman (2009) also measured erosion in the field using a grid pattern of erosion pins over a period of 3 years in different sites in the central Karoo of South Africa. They reported that erosion continued at an average rate of 5.6 mm y^{-}

^{1} on interfluves, 2.6 mm yr^{-1} at channels, 4. 7 mm yr^{-1} at foot-slopes and sidewalls was 16.7 mm yr^{-1}. The risk for soil erosion and runoff depends on the management of the soil. Low soil loss of 4 g m^{-2} h^{-1} was observed on the plot treated with 75 – 100 % grass cover compared with 1883 g m^{-2} h^{-1} soil loss on the plot with 0 % grass application rate (Podwojewski et al., 2011). Therefore, the evaluation of soil erosion and runoff is important for an agricultural and environmental ecosystem. For instance, Zere et al, (2005) successfully used runoff data to simulate the long-term crop yield using PutuRun Model in the semi-arid region in Free State Province, South Africa.

2.2 Aggregate Stability and Size Distribution

Soil aggregate stability and size distribution are mainly affected by intrinsic and extrinsic factors. Some of the factors include soil bulk density, organic matter content, soil texture. Significant increase in soil bulk density resulted from compaction was associated with decreased soil macro-aggregates while increasing micro-aggregates after the traffic operation in the study conducted by Mathews et al. (2010). In contrast, macro-aggregates sizes were formed due to the rearrangement of the primary soil particles and dispersed micro-aggregates as reported by Meterechera, (2009a). Soil organic matter content is one of the major cements for soil aggregation (Wei et al., 2014). Moreover, soil aggregate stability was influenced by soil organic matter content by increasing the intra-aggregate cohesion as well as aggregate hydrophobicity (Blanco-Moure et al., 2012). Soil organic matter also bind soil micro-aggregates into macro-aggregates.

Soil aggregates stability was also affected by water movement especially soil erosion. For instance, decreased soil aggregate stability was reported due to accelerated soil erosion which enhanced microbial decomposition and reduced soil organic matter content (Zhang and Horn, 2001). Ye et al. (2019) reported that, soil aggregate stability was strongly and negatively correlated with soil pH because increasing soil pH promotes clay dispersion resulting from the increased repulsion of negatively charged clay particles. Furthermore, clay particles were dominate binding agents for soil aggregates smaller than 2 mm in farmland as reported by Ye et al. (2019). Extrinsic factors that affect soil aggregate stability and size distribution mainly include tillage. Tillage practice especially cultivation leads to the degradation of macro-aggregates into micro-aggregates due to rearrangement of the micro-aggregates and primary soil particles (Barik et al., 2014). On the other hand, cultivation practice destroys the root system and greatly lower the stabilizing effects on root system on soil aggregates (Ye et al., 2018).

2.3 Aggregate Stability and Size Distribution Effects on Soil Erosion and Runoff

Soil aggregate stability and aggregate size distribution have been used as essential physical indicators to predict soil erosion and runoff. Few researchers have investigated the relationship between soil aggregates and soil erosion as well as runoff in South Africa (Materechera, 2009b; van Zijl, 2010; Paterson et al., 2011). A study conducted by Paterson et al. (2011) investigated the influence of palm mats on soil erosion on different soil conditions namely: bare soil, mine tailing and soil covered with palm mats. Soil stable aggregates were measured as one of the soil erosion indicators in all those three soil conditions. Higher soil water stable aggregates and subsequently lower soil erosion were observed on mine tailing soils than on bare soils and soil with palm mats.

Materechera (2009b) studied the effects of amendments application including phosphogypsum, polymer gel, grass mulch, and cattle manure on soil aggregation on soil with surface crusting. The application of amendments significantly improved stable macro-aggregates. The mean weight diameter was 2.23 mm on phosphogypsum, 2.17 mm on polymer gel, 3.31 mm on manure, and 4.23 mm on grass mulch, compared to the control with 1.36 mm. The author concluded that stable macro-aggregates have the positive role in increasing infiltration rate and soil moisture which may, in turn, reduce soil erosion and runoff.

According to Barthes and Roose (2002), runoff and soil loss were negatively correlated with soil macro-aggregates in a 3 year study. However, Nciizah and Wakindiki (2015) reported that soil macro-aggregates are mainly influenced by disruptive forces which may result in soil erosion compared with micro-aggregates. In contrast, Lado et al, (2004) reported that dispersion of micro-aggregate is the primary step in reducing infiltration due to surface seal formation and subsequently soil erosion and runoff generation. Furthermore, micro-aggregates stability was suggested as the better indicator of soil erosion since their breakdown through dispersion results in finer particles which can be easily transported by water (Igwe and Obalum, 2013).

Findings by Shi et al. (2017) indicated that runoff was delayed with a greater aggregate stability of 1.14 mm, whereas earlier runoff was produced with low soil aggregate stability of 0,80 mm. Furthermore, soil aggregate stability of greater than 1.0 mm resulted in low surface runoff rate of 0.17 L min^{-1} and 4.71 gL^{-1} for erosion. In contrast, higher runoff rate of 0.34 L min^{-1} and the greater erosion rate of 7.36 gL^{-1} were reported with a low amount of 0.80 mm of aggregate stability. Moreover, severe gully erosion density of 13, 6 km/km^2 was observed in 2004 on a duplex soil with lower water stable aggregate on the upper layer of the soil profile in Lesotho, South Africa (Van Zijl, 2010).

Many authors have reported that higher and more stable soil aggregates reduce soil erosion and runoff. For instance, a linear positive relationship between aggregate stability and soil erosion as well as runoff was observed in the study conducted by Wang and Shi (2015). Increased runoff from 1.25 to 1.88 L m^{-1} min^{-1} and erosion from 0.015 to 0.028 kg L^{-1} rates were reported with increasing soil aggregate stability from 0.04 to 0.36 mm. These results were related to soil texture whereby increased aggregate stability from 0.04, to 0.36 mm was related with increased fine particles from 19.4 to 38.1. Soils with higher fine particles are more prone to surface seal formation and clogging which in turn reduce infiltration rate, hence increased runoff and erosion. Results from the study carried out by Li et al (2011) agreed that high infiltration rate reduced runoff rate.

2.4 Spatial Variation

Spatial variation of soil mainly results from intrinsic and extrinsic forming factors. Such factors include soil forming factors, soil organic matter, texture, electrical conductivity and cations (Annabi et al., 2017; Kilic et al., 2012; Mohammadi and Motaghian, 2011). According to Ye et al. (2018), soil parent materials, texture contributed to the strong spatial variation of soil properties. In contrast, Wang et al. (2009) reported that the application of fertilizers and cultivation practices are responsible for the moderate and weak spatial variation. Moreover, land use change was reported to influence the spatial variability of soil structure attributes which include soil aggregate stability in the study conducted by Xu (2003).

2.5 Spatial Variability of Aggregate Stability and Size Distribution

The analysis of the spatial variability of soil aggregate stability and aggregate size distribution provides agronomic useful information to manage soil in a sustainable manner. The variation of soil aggregates has been studied by several authors in different areas (Souza et al., 2009; Mohammadi and Motaghian, 2011; Ye et al., 2018). Moderate spatial dependency of the three aggregate size fractions namely: macro, meso, and micro-aggregate measured by mean weight aggregate (MWD) was reported in an area of 92 km^2 on Entisols and Inceptisols (Mohammadi and Motaghian, 2011). The variograms range values were 3091 m for macro, 2371 m for meso and 4201 m for micro aggregates. The variance nugget values were 2.0×10^{-4} for macro, 6.0×10^{-4} for meso and 3.6×10^{-3} for micro aggregates and sills variance of 4.0×10^{-4} for macro, 1.3×10^{-3} for meso and 3.6×10^{-3} for micro aggregates.

Ye et al. (2018) investigated the spatial analysis of soil aggregate stability in a small catchment of the Loess Planteau, in China. The samples were collected in different landscape units of various landforms including terrains, land use types, and vegetation factors. The spatial variability was reported for both aggregate stability as presented by mean weight-diameter (MWD) and size distribution as described by water stable aggregates (WSA) considered as aggregates > 0.25, %. MWD and WSA > 0.25 were significantly lower in farmland than in other land use types and reported higher in shrubland than in woodland. A strong spatial dependence of 9.13 % was reported for MWD at 0 – 10 cm and 19.49 % at 10 – 20 cm soil depth. Similarly, strong spatial dependence of 12.48 % for WSA > 0.25 was observed at 0 – 10 cm and 17.71 % at 10 – 20 cm soil depth. Therefore, strong spatial dependence was reported to be influenced by the contribution of soil intrinsic factors including soil texture, soil parent materials, topography, and vegetation cover.

The spatial variability of soil aggregate stability was also researched at an approximately 800 km^2 scale of an agricultural region in Tunisia using geosatistical analyses (Annabi et al., 2017). The results showed a nugget values ranged from 0.06 to 0.19 whereas the sill values ranged from 0.13 to 0.33. The range values varied from 4000 to 8000 meters. A strong spatial dependence of soil aggregate stability was observed at 0 – 20 cm depth in eutrophic Red Latosol and dystrophic Red Latosol under cultivated sugarcane (Souza et al., 2009). Moreover, a strong spatial dependency of aggregate size fraction greater than 2 mm was also observed on dystrophic Red Latosol whereas moderate spatial dependence was observed on eutrophic Red Latosol.

The variation range value of aggregate stability for eutrophic Red Latosol was 58 m and dystrophic Red Latosol was19 m with nugget values of 0.11 for eutrophic Red Latosol and 0.001 for dystrophic Red Latosol. The reported sill values were 0.46 for eutrophic Red Latosol and 0.79 for dystrophic Red Latosol. For aggregate size fraction greater than 2 mm, a variation range value of 70 for eutrophic Red Latosol and 19 for dystrophic Red Latosol were observed. The strong spatial dependence of aggregate stability and size fraction for dystrophic Red Latosol were correlated with the strong spatial variability of organic matter content within the field scale. Similarly, a moderate spatial dependence of aggregate size fraction was associated with the moderate spatial dependency of soil organic matter content.

2.6 Implications of spatial variability of soil aggregate stability and size distribution on soil erosion and runoff

Knowledge on the spatial variability of soil aggregate stability and aggregate size distribution is important for management practices to harness erosion and runoff. Spatial variability of runoff and erosion in relation to variation in soil aggregates have been measured in different areas. Le Bissonnais et al, (2002) observed the spatial and temporal variation of runoff and erosion derived by the spatial variation of aggregate stability in three different sites (Rennes, Tocplouz, and Kerjos). The spatial variation was quantified using semi-quantitative analysis (geostatistics). The range value for Rennes was approximately 250 m, while Tocplouz and Kerjos were 415 m, 340 m long, respectively. Observed runoff and erosion variance were 192 to 399 L and 736 to 21568 g, respectively (for Rennes), 4 to 88 L and 1 to 735 g (for Tocplouz), and 14 L to 162 L and 8 g to 1053 g (for Kerjos). Higher runoff and erosion rates in Rennes were related to lower spatial variance of aggregate stability ranged from 0.31 to 0.44 mm compared to Tocplouz that ranged from 1.09 to 2.12 mm and Kerjos as ranged from 0.54 to 0.96 mm. Additionally, soil organic matter and clay content were observed as the main factors that influenced the spatial variability of soil aggregate stability in all three sites. As reported, Rennes had lower variance amount of organic matter and clay compared to Tocplouz and Kerjos.

Andreu et al, (2001) studied the influence of the spatial variation of soil aggregates on water erosion on north-facing and south-facing slopes affected by fire in a Mediterranean pine forest from 1993 to 1996. The top 5 cm depth was the soil depth most affected by the temperature of the fire and exhibited clear changes on soil aggregate distribution as well as the temporal variability in both zones. The north-facing slope was observed with substantial recovery of soil aggregates greater than 5 mm in diameter which reached an increase of about 27% mass of the soil aggregates. In contrast, the south-facing slope was observed to have smooth changes of soil aggregate fraction less than 0.1 mm. Higher sediment loss of 52.42 % and erosion concentration of 29.95 % were observed on the south-facing zone than the north-facing zone during the study period. They concluded that higher erosion and runoff were caused by the lesser cohesiveness of soil aggregates on south-facing zone than north-facing zone.

Runoff was also investigated as influenced by other soil properties affected by climate at the spatial and temporal scales (Boix-Fayos et al., 1998). Some of the properties studied include soil aggregates which include water-stable micro-aggregation and macro-aggregation, infiltration rate and soil moisture content. Runoff was concluded to be lower on the north-facing slope and in vegetated patches compared to the south-facing slope and bare patches soils. Due to the fact, north-facing slope had higher soil aggregate stability and consequently improved infiltration rate which in turn had the potential to reduce soil erosion and runoff.

CHAPTER THREE

3.0 MATERIALS AND METHODS

3.1 Study Sites and Soils

The study was carried out at two different sites namely: University of Venda and Agricultural Research Council (ARC) farm at Roodeplaat as shown in Fig. 1. These sites were select due to their differences which include soil types, climatic conditions, soil textural classes, land management and land use practice.

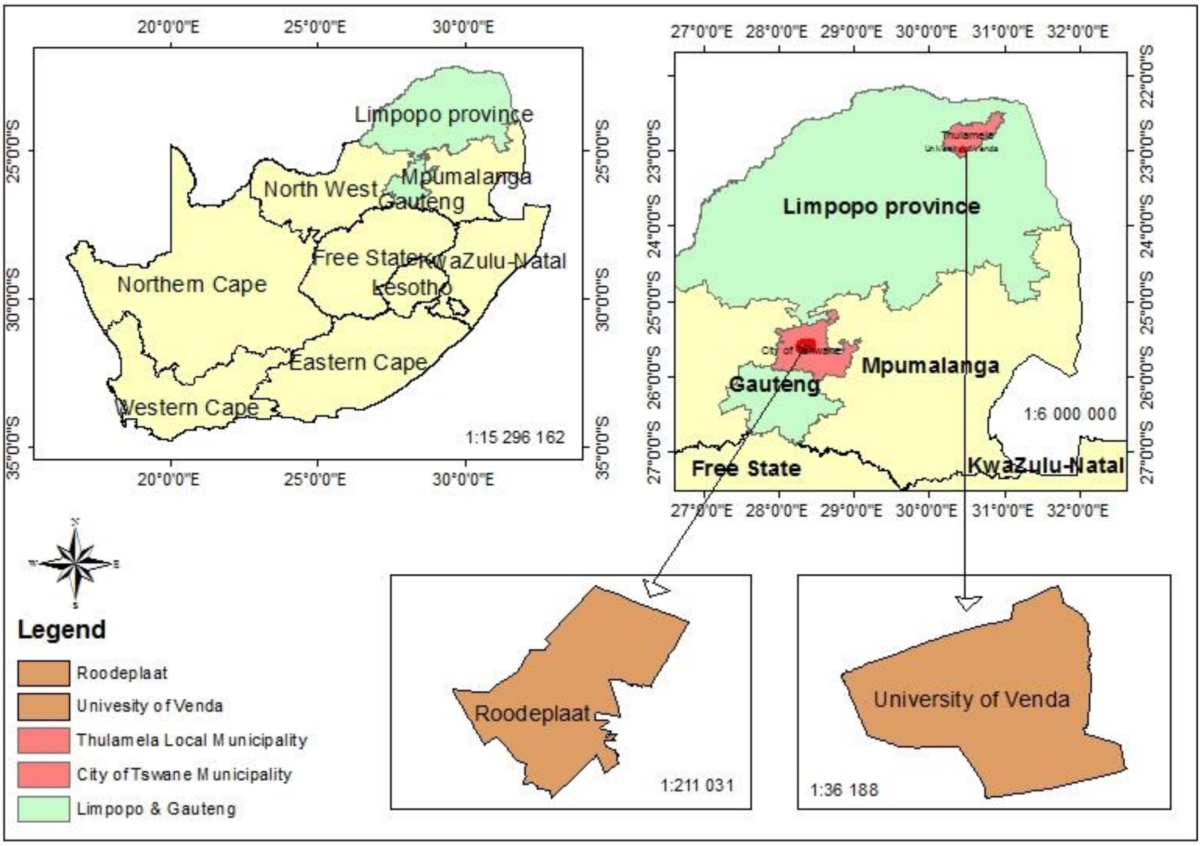


Fig. 1. Study area: University of Venda agricultural farm and Agricultural Research Council farm at Roodeplaat.

University of Venda agricultural farm

The site is situated at 22°58’ S, 30°26’ E and ±596 m above the sea level in Thohoyandou, Limpopo Province of South Africa. The area is located approximately 2 km west of Thohoyandou Town in Vhembe region and falls within the low veld. The area has an approximately 8% gently slope from North to South direction (Mzezewa and van Rensburg, 2011). It receives a highly seasonal rainfall, about 85% of which falls between October and March (Mzezewa and van Rensburg, 2011). The mean rainfall is approximately 780 mm and the daily temperature varies from 25 °C to 40 °C in summer and ±12 °C to 26 °C in winter. The site is characterized by deep well-drained red soil with high clay content (Odhiambo, 2011). The soil is classified as Hutton form (Soil Classification Working Group, 1991), which is equivalent to Rhodic Ferralsol (WRB, 2006). The soil suffers from excessive erosion (Nethengwe, 2007). More details of the area are explained by Mzezewa and van Rensburg (2011). The site was previously covered by natural vegetation and used for animal grazing.

Agricultural Research Council farm

The ARC experimental farm is located at Roodeplaat, Pretoria, Gauteng Province, South Africa. The area is located at 25° 35’ N, 28° 21’ E and 1168 m above the sea level. The region falls under humid subtropical climate and experiences a summer rainfall, with an average of about 650 mm per annum. It also receives an average daily air temperature which ranges from an approximately 8 – 34 °C in summer and from 4 – 23 °C in winter (Beletse et al., 2013). The soil is classified as Clovelly form (Soil Classification Working Group, 1991). The site is characterised by sandy clay loam soil and classified as Clovelly soil form (Soil Classification Working Group, 1991) which is equivalent to Luvisols / Cambisols (FAO, 2016). The site was previously used to grow sweet potatoes. NPK fertilizer was used to support crop growth in the field. Grazon herbicide was used to control pesticides.

3.2 Study Layout

The study layout map for site 1 is shown in Fig. 2 and for site 2 in Fig. 3. Approximately 1 ha field was cultivated with a mouldboard plough and followed by harrowing in both sites. Thereafter, the field was divided into 20 × 20 m grids. Similar sampling units were used by Shukla et al. (2007). In each grid cell, a centre point was marked with a wooden peg at a distance of 10 m from the edge of the grid cell and was referred as the centre sampling point. About 12 sampling points were georeferenced to determine the spatial variability of aggregate stability, size distribution, erosion and runoff. Georeferenced sampling points were done using a global position system (Garmin GPSMAP 60 cx ModelPS).

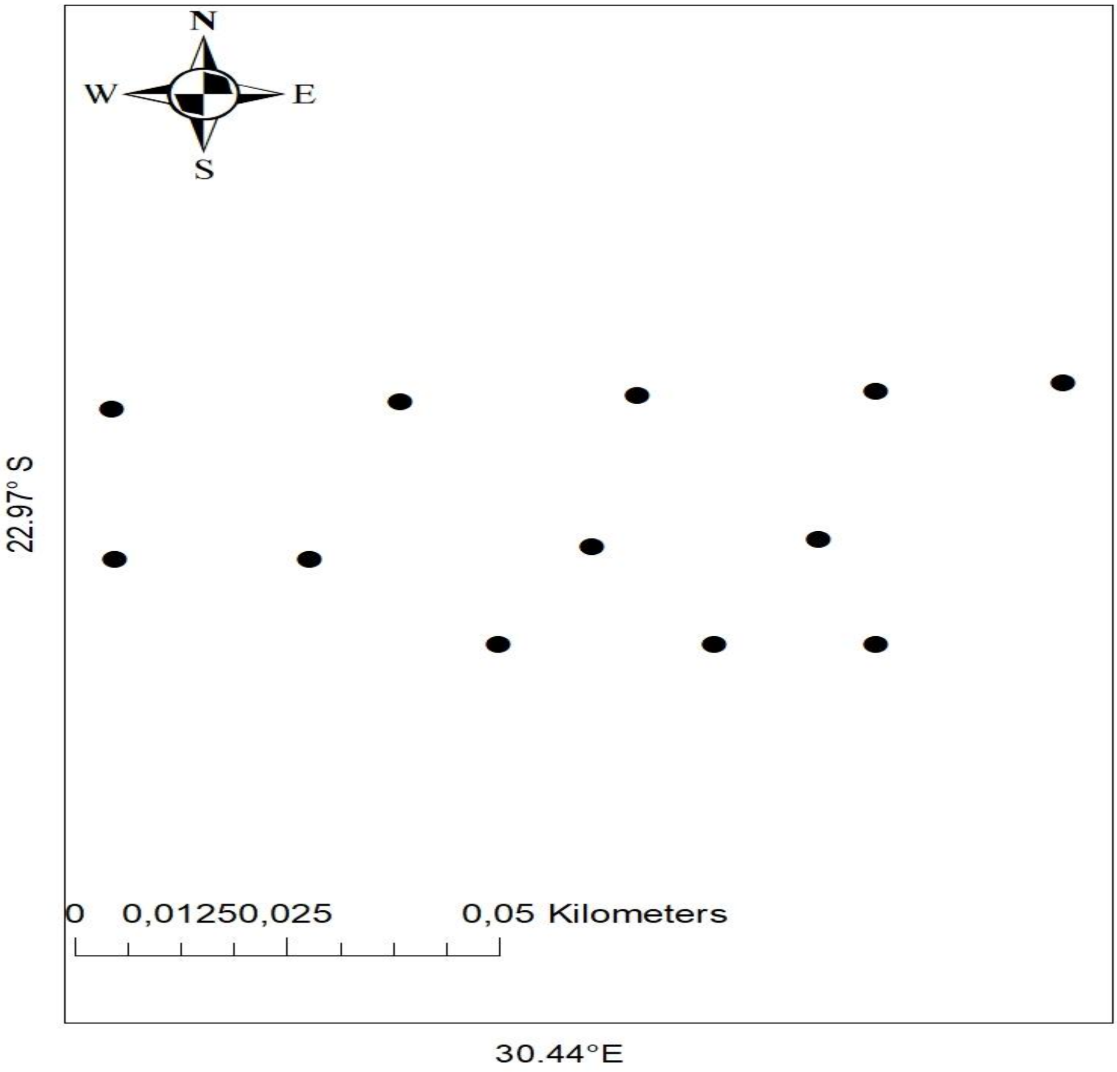


Fig. 2: Study layout map for University of Venda agricultural farm.

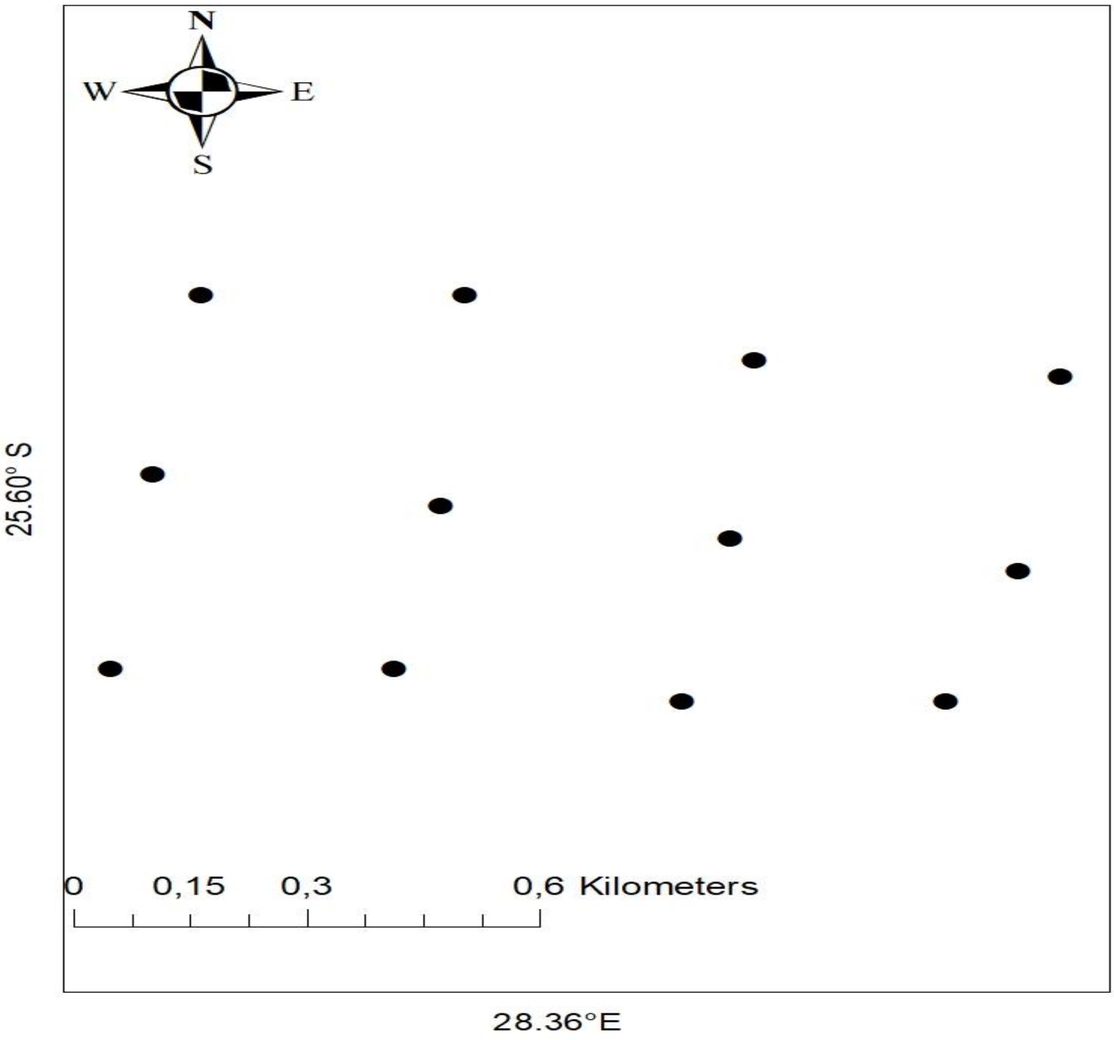


Fig. 3: Study layout map for ARC-VOP farm.

3.3 Soil Sampling

Soil samples were collected in each grid cell from 0 – 150 mm depth. The same sampling depth was used by Shukla et al. (2007). For soil aggregate stability and size distribution measurement, samples were collected using a spade at the centre of each grid cells and placed in rigid boxes. Rigid boxes were used to avoid breakdown of aggregates during transportation to the laboratory. About 20 kg soil sample was collected using a spade adjacent to the centre sampling point in each grid cell for soil erosion and runoff measurements. Thereafter, soil samples were placed in a bucket.

A soil auger was used to collect soil samples adjacent to the centre sampling point for selected physiochemical parameters such as soil organic carbon (SOC), soil pH, electrical conductivity (EC), and soil particle size, then placed in sealed plastic bags. A soil core sampler was used to collect soil samples for bulk density measurements. All sampled soils were transported to the laboratory for measurements. Sample for soil bulk density were oven dried at 105 ^{0}C while other samples were air dried for a week and sieved through a 2 mm sieve aperture. Sampling was done in April for University of Venda agricultural farm whereas for ARC-VOPI farm was done in August 2018

3.4 Aggregate Stability and size distribution Measurements

Soil aggregate stability and size distribution were measured in three replicates following the wet sieving procedure described by Eijkelkamp Agrisearch Equipment (Art no: 08.13). The wet sieving instrument consists of a sieve holder with 8 sieves of 0.25 mm. It has two holes (build-in stop) on the shaft with one on the top position of the other with distinct functions. The top hole allows water to leak after sieving while the bottom hole is responsible for allowing sieving into the filled cans.

A 4.0 g sample of air-dried 2 mm aggregates were weighed and transferred onto a 0.25 mm sieve. The aggregates were pre-moistened then left for approximately 10 minutes before submerging them into the water-filled cans. The reason to pre-moisten aggregates was to prevent slaking when the sieve was submersed into the water filled can. Thereafter, the sieves were placed in the sieve holder. Below the sieves, weighed and numbered cans were placed. The cans were filled with sufficient distilled water to cover the soil aggregate during sieving. Thereafter, the sieve holder was placed in the second hole on the instrument shaft. Sieves were moved up and down in the distilled water by switching on the motor for 3 minutes. After three minutes the motor automatically stopped then the sieve holder was uplifted and placed in the top hole on the instrument shaft to allow water to leak from the sieves. When water stopped leaking, the cans were replaced with another set of numbered cans and then sufficiently filled with dispersing solution of 2 g L^{-1} sodium hexametaphosphate for soils with pH > 7 or 2 g L^{-1} of NaOH for soils with pH < 7.

The sieve holder was then placed again in the second hole on the instrument shaft. Sieves were again moved up and down in the dispersing solution by switching on the motor into the continue position until sand particles remain on the sieve. Thereafter, cans were dried in an oven at 110 °C for 24 h to obtain a constant weight. The mass obtained from the cans filled with distilled water was considered as micro-aggregates and classified as size distribution less than 0.25 mm sieve aperture. Mass obtained from the dispersion solution was regarded as macro-aggregates and classified as size distribution greater than 0.25 mm sieve aperture. Thereafter, an index for aggregate stability was given as the mass of soil obtained in the dispersing solution cans divided by the sum of the masses obtained in the dispersing solution cans plus distilled water cans.

3.5 Runoff, Erosion and Infiltration Measurements

Soil erosion, runoff and infiltration were measured in three replicates using a rainfall simulator. Rainfall simulation was carried out in the laboratory using a rotating disc rainfall simulator (Morin et al., 1967). The simulator used has five soil holding trays of 600 × 300 mm, which carry up to 5 kg of soil. It has a portable nozzle-type mounted at the top to produce rainfall. The trays were perforated to allow collection of runoff, erosion and infiltrated water. Five kg soil, air dried and sieved through a sieve of 2 mm aperture was packed on the trays. Before application of the rainfall, soils were saturated using tap water at 0.7 dS/m to allow all soils to receive a similar treatment. Deionized water was used for rainfall simulation.

Rainfall was simulated at 45 mm/h intensity on soil placed at 8% slope. A slope of 8 % was used to mimic the natural slope of the study areas. The same slope was used by Mzezewa and Rensburg (2011). Rainfall was applied until runoff steady state was achieved. Soil loss, runoff and infiltration volume were collected during rainfall simulation.

3.6 Other Soil Properties

Soil organic carbon (SOC) was determined in potassium dichromate oxidation following Walkley and Black procedure described by Nelson and Sommers (1996).

Soil pH and electrical conductivity (EC) were measured in water using as described by Okalebo et al. (2000). Soil particle size was determined using the hydrometer method (Bouyoucos, 1962). Soil bulk density was measured following the core method proposed by Lal and Shukla, (2004). Soil crust strength was measured using a flat point hand-held penetrometer (Geotest Instrument Corp) into the 5 mm depth of the soil. Soil porosity was calculated as the total number of pore voxels divided by the total number of volume voxels after scanned by Nikon XTH 225L micro-focus Computed Tomography (CT) X-ray unit (Nikon Metrology, Leuven, Belgium) at the MIXRAD laboratory at the South African Nuclear Energy Corporation (Necsa), Pelindaba.

3.7 Data analysis

The descriptive statistics, which include minimum, maximum, mean, standard deviation (S.D) and coefficient of variation (CV) were calculated. Coefficient variability was used to relate the variability to the mean of soil properties. A CV < 15 % was recommended as the weak, 15 % < CV < 35 % as moderate and CV > 35 % as the strong variable. The spatial variability of soil aggregate stability, size distribution, soil erosion and runoff were determined using ordinary Kriging method in ArcMap of ArcGIS 9.3.1 (Warrick et al., 1986). The semi-variogram was made up of three basic factors which are nugget effect, the sill, and the range. The nugget effect was described as a spatial component of variation occurring at distance smaller than the sampling interval. It is also attributed to the measurement error. The sill represented the value of the total variance while the range was representing the distance at which beyond that the values of the aggregate stability, aggregate size distribution, runoff and erosion were considered as not correlated.

Using this analysis, the spatial variability results were interpreted as the degree of spatial dependence classes namely; strong, moderate and weak. When the spatial dependence class is < 25 %, the variability was considered as strong, whereas moderate and weak spatial dependence levels were considered with percentage values of 25 – 75 % and >75 %, respectively. These spatial dependency classes were calculated as the ratio of nugget to the total variance described as sill then multiplied by 100 to get the percentage.

The geographic information system (GIS) software Mapcalc (Red hen system, inc) was used to determine the spatial autocorrelation of soil measured parameters. Analysed geostatistical data was exported to Arc GIS [ArcView 9.3.1 software (ESRI)] to create maps. Semi-variogram was used to compute the extent of dissimilarity between measured points as the function of a distance by following the equation below:

$$\gamma(h) = \frac{1}{2N(h)} \sum_{i=1}^{N(h)} [Z(x_i + h) - Z(x_i)]^2 \qquad [1]$$

Where;

y(h) = semi-variance,

N(h) = number of pairs of the locations separated by distance h,

Z(x_i) = measured variable at a location *i*

Z(x_i+h) = measured variable at the spatial location (*i*+h) (Isaaks and Srivastava 1989).

CHAPTER FOUR

4.0 RESULTS AND DISCUSSION

4.1 Selected soil properties

4.1.1 University of Venda agricultural farm

University of Venda agricultural farm had 52.3% of sand, 11.8% of silt and 35.9% for clay particles in site 1 (Table 1). Sand and clay had the weak variability with CV values of 11.74 and 15.04%, respectively. A strong spatial variability was observed on the silt fraction, which had a CV value of 72.8%. A lower bulk density of 1.08 g/cm^{-3} was observed in University of Venda Agricultural farm as compared to the higher estimated bulk density of the soils with 50% pore space (i.e. 1,33 g/cm^{-3}). Soil bulk density lower than that of 50% pore space simple represents less compaction of the soil which accelerate soil permeability including water infiltration rate. Similarly, as for sand and clay, bulk density had a weak variability with the CV value of 14.81 %. The soil pH at University of Venda Agricultural farm was slightly acidic with pH value of 5.9. In addition, soil pH had weak variability with a CV value of 3.56%. Similarly, University of Venda Agricultural farm had a weak variability of SOC with a CV value of 12.86% and a mean value of 1.4% (Table 1). Almost all the measured parameters at the University of Venda Agricultural farm had weak variability within the field except for silt particles. This could be attributed to the extrinsic factors such as cultivation since the site is used for research purposes. Cultivation promotes uniformity within the field since it mixes soils from one point to another.

Table 1: Descriptive statistics of the selected soil properties for University of Venda Agricultural farm.

Parameter	Minimum	Maximum	Mean	S.D	CV (%)
Sand (%)	36	58	52.3	6.14	11.74
Silt (%)	2	27	11.8	8.59	72.80
Clay (%)	21	40	35.9	5.40	15.04
Bulk density (g)	0.9	1.22	1.08	0.16	14.81
pH (H_20)	5.6	6.3	5.9	0.21	3.56
OC (%)	0.1	1.7	1.4	0.18	12.86

OC – Organic carbon; S.D – Standard deviation; CV – Coefficient of variation.

This site had a higher negative correlation between soil aggregate stability and microaggregates (r^2 = – 0.98) (Table 2). In contrast, soil aggregate stability had positive relationship with macroaggregates with 0.77 (Table 2). Infiltration rate and soil loss has negative correlation (r^2 = – 0.80) (Table 2). Similarly, negative correlation of infiltration rate and runoff was observed (Table 2). Soil loss and runoff had higher positive correlation (r^2 = 0.98) as shown in Table 2. This support that as runoff increases, soil loss increases too. Soil crust strength had more than 50% positive correlation with soil loss and runoff at the university of Venda farm (Table 2).

Table 2: Correlation of measured soil properties for University of Venda farm.

	Clay	BD	OC	AS	Mi-A	Ma-A	IR	SL	R	CS	P	Me-P	Ma-P
Clay	1												
BD	-0,07	1											
OC	-0,05	0,08	1										
AS	-0,43	-0,04	0,06	1									
Mi-A	0,48	-0,03	-0,01	-0,98	1								
Ma-A	-0,32	-0,24	0,20	0,77	-0,65	1							
IR	-0,04	0,029	0,21	-0,23	0,28	0,16	1						
SL	0,02	-0,02	-0,09	0,20	-0,24	-0,11	-0,80	1					
R	0,06	-0,03	-0,15	0,15	-0,19	-0,13	-0,81	0,98	1				
CS	0,01	-0,09	-0,14	0,26	-0,33	-0,18	-0,85	0,66	0,68	1			
P	0,05	-0,01	-0,01	0,13	-0,12	0,17	0,04	-0,31	-0,32	-0,24	1		
Me-P	0,02	-0,03	0,17	-0,30	0,31	-0,19	0,18	0,12	0,143	-0,06	-0,81	1	
Ma-P	0,05	-0,01	-0,02	0,14	-0,13	0,17	0,03	-0,30	-0,31	-0,23	0,99	-0,83	1

BD – Bulk density; OC – Organic carbon; AS – Aggregate stability; Mi-A – Microaggregates; Ma-A – Macroaggregates; IR – Infiltration rate; SL – Soil loss; R – Runoff; CS – crust strength; P – Porosity; Me-P – Mesoporosity; Ma-P - Macroporosity

4.1.2 Agricultural Research Council farm

The site had 38% of sand, 39% of silt and 23% of clay particles (Table 3). A weak variability of sand, silt and clay was observed with the CV values of 7.45, 10.59 and 8.45%, respectively. Soil bulk density of 1.41 g/cm^{-3} had a weak variability within the filed with the CV value of 9.22% (Table 3). Generally, a bulk density of 1.33 g/cm^{-3} is the bulk density expected in soils with 50% pore spaces in mineral soils. Therefore, Agricultural Research Council farm had compacted soils since the bulk density was higher compared to the expected mineral soils with 50% pore space. Slightly acidic soil pH of 6.9 was observed at Agricultural Research Council farm and the variability of soil pH was weak with the CV value of 1.59% (Table 3). In opposite, soil organic carbon content had strong variability with a CV value of 39.60% (Table 3).

All measured soil properties had weak variability within the field at Agricultural research council farm. Agricultural research council farm is also used as farmland for research purposes, therefore, cultivation could have led to weak variability of soil properties. Moreover, the use of heavy machines during cultivation increases soil compaction due to heavy weight released on soil, hence higher bulk density was observed. Similarly, bulk density was influenced by traffic operations in the study conducted by Barik et al. (2014). Cultivation also causes turning over of soil organic matter into the sublayer which affect the accumulation of soil organic carbon content on the upper layer, hence, organic carbon content was low at Agricultural research council farm.

Table 3: Descriptive statistics of the selected soil properties for Agricultural Research Council farm.

Parameter	Minimum	Maximum	Mean	S.D	CV (%)
Sand (%)	34	42	37.7	2.81	7.45
Silt (%)	32	44	39	4.13	10.59
Clay (%)	20	28	23.3	1.97	8.45
Bulk density (g)	1.19	1.62	1.41	0.13	9.22
pH (H_20)	6.7	7.1	6.9	0.11	1.59
OC (%)	1.1	1.57	1.01	0.40	39.60

OC – Organic carbon; S.D – Standard deviation; CV – Coefficient of variation.

Agricultural Research Council farm also had a higher negative correlation between soil aggregate stability and microaggregates (r^2 = – 0.94) (Table 4). Aggregate stability and soil bulk density had negative correlation of – 0.71 (Table 4). Runoff and Soil loss had higher positive correlation with a value of 0.88 as shown in Table 4. Soil crust strength had positive correlation with soil loss (r^2 = 0.87) and runoff with a correlation of 0.75 (Table 4).

Table 4: Correlation of the measured properties for Agricultural Research Council farm.

	Clay	BD	OC	AS	Mi-A	Ma-A	IR	SL	R	CS	P	Me-P	Ma-P
Clay	1												
BD	0,01	1											
OC	0,22	0,15	1										
AS	-0,24	-0,71	-0,23	1									
Mi-A	0,18	0,30	0,71	-0,94	1								
Ma-A	-0,17	-0,61	-0,01	0,27	0,03	1							
IR	0,08	0,13	0,07	-0,12	-0,07	-0,16	1						
SL	0,06	0,01	-0,16	0,05	-0,08	0,05	-0,06	1					
R	-0,06	-0,03	-0,03	0,08	0,02	0,08	-0,01	0,88	1				
CS	0,10	-0,08	-0,04	0,20	-0,06	0,20	0,02	0,87	0,75	1			
P	-0,09	-0,14	0,05	0,37	0,08	0,40	-0,14	0,37	0,33	0,38	1		
Me-P	0,34	0,20	-0,01	-0,46	-0,08	-0,48	0,37	-0,34	-0,3	-0,3	-0,8	1	
Ma-P	-0,10	-0,14	0,05	0,3	0,08	0,40	-0,1	0,37	0,3	0,3	0,9	-0,8	1

BD – Bulk density; OC – Organic carbon; AS – Aggregate stability; Mi-A – Microaggregates; Ma-A – Macroaggregates; IR – Infiltration rate; SL – Soil loss; R – Runoff; CS – crust strength; P – Porosity; Me-P – Mesoporosity; Ma-P - Macroporosity

4.2 Spatial variability of soil loss and runoff and other properties

4.2.1 University of Venda agricultural farm

Spatial analysis of soil loss and runoff at 45 mm h^{-1} rainfall intensity were investigated using the degree of spatial dependence as nugget (Co) / sill (Co + C) % and are presented in Table 5 while semi-variograms are shown in Fig. 4. Exponential and Gaussian models were proved to be the best fit models to describe the spatial variability of soil properties (Table 5). Weak spatial dependence was observed on soil loss and runoff as well as other measured soil properties including infiltration, soil crust strength, porosity, mesoporosity and macroporosity. Soil loss was observed with a spatial ratio of 100% while runoff was observed with 88% of the spatial ratio.

Fig. 5 shows the spatial distribution patterns of soil loss, erosion and other measured soil properties including infiltration, soil crust strength, and soil porosity. Their spatial distributions were generated based on the fitted semi-variogram models. Soil loss and runoff exhibited a similar spatial distribution patterns where by low to high values were observed from the east to west of the measured field as shown in Fig. 5 A and B. In contrast, low to high concentration of spatial variability patterns was observed from west to east on soil infiltration rate (Fig. 5C). Among other measured soil properties, soil crust strength exhibited higher spatial variability as shown in Fig. 5D compared to infiltration rate, and soil porosity. No clear variability was observed on soil porosity and macroporosity whereas mesoporosity showed some weak variability within the field. In general, all the presented maps in Fig. 5 for University of Venda Agricultural farm, show a weak spatial variability trends of the measured soil parameters within the field.

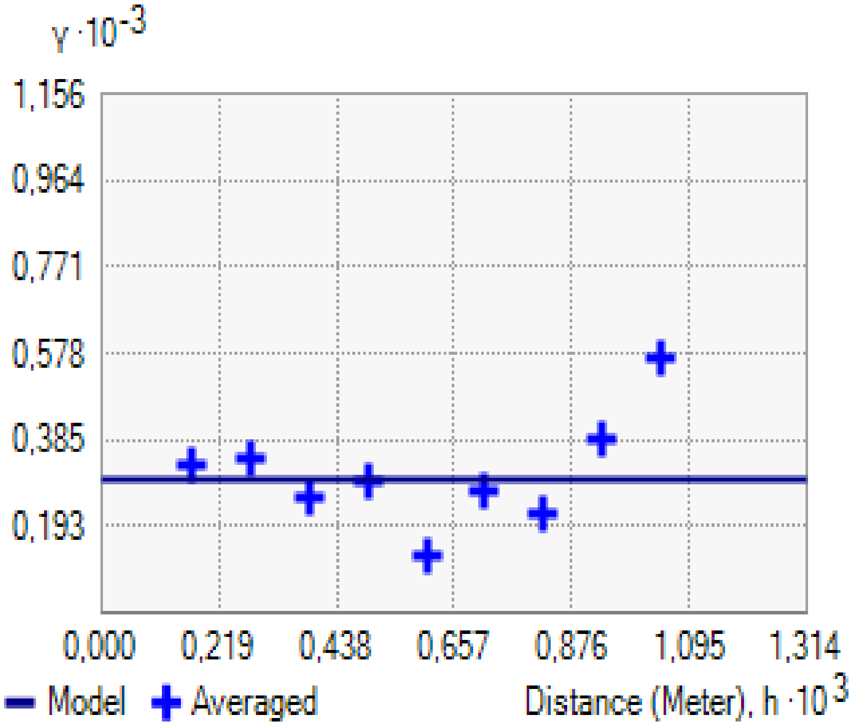
The weak spatial variation of soil loss and runoff could have resulted from weak variability of soil infiltration rate. Soil infiltration rate was strongly negative correlated with soil loss and runoff. Jin et al. (2008) reported that decrease in infiltration promotes higher runoff which may also leads to higher soil loss. Moreover, the weak variation of soil loss could also be resulted from the weak variation of runoff across the measured site in this study (Table 5). This can also be supported by the higher correlation of soil loss and runoff ($r^2 = 0.98$) as shown in Table 2. The weak variation of soil crust strength at this site is also one of the main factor that might cause the weak variation of soil loss and runoff (Table 5) since crust strength influence runoff and erosion. Soil surface crust was reported as the major factor in runoff generation (Philippe et al., 2001). Furthermore, the weak variation of soil loss and runoff can also be due to the weak variation of soil porosity, mesoporosity and macroporosity because these factors are known to drive water dynamics within the soil. Similarly, the University of Venda Agricultural farm had a weak variation of soil aggregate stability, micro and macro-aggregates. Aggregate stability and size distribution are primary factors to control soil erosion and runoff. For instance, high concentration of macro aggregates is associated with high infiltration rate which reduce erosion and runoff. Runoff and soil loss were negatively correlated with soil macro-aggregates in a 3 year study reported by Barthes and Roose (2002).

Table 5: Semi variance models and the degree of spatial dependence of the selected soil properties for University of Venda Agricultural farm.

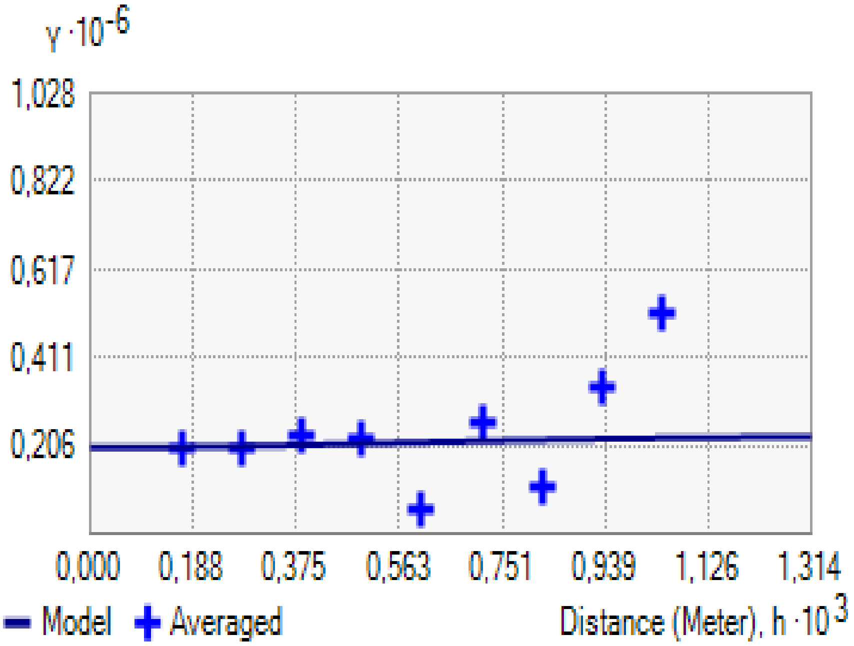
Parameter	Model	Nugget	Sill	Range	Spatial ratio	Spatial class
Soil loss (kg/ha)	Exponential	297.5	297.5	1.31E-03	100	Weak
Runoff (m^3/ha)	Gaussian	0.2	0.2	1.31E-03	88	Weak
Infiltration (mm h^{-1})	Gaussian	58.3	67.1	1.31E-03	87	Weak
Soil crust strength (kg/cm^2)	Exponential	0.70	0.70	1.31E-03	100	Weak
Porosity (%)	Exponential	20.42	20.42	1.31E-03	100	Weak
Mesoporosity (%)	Exponential	0.02	0.02	1.31E-03	100	Weak
Macroporosity (%)	Exponential	21.63	21.63	1.31E-03	100	Weak

4.2.1.1 Semi-variograms of soil loss, runoff and other soil properties

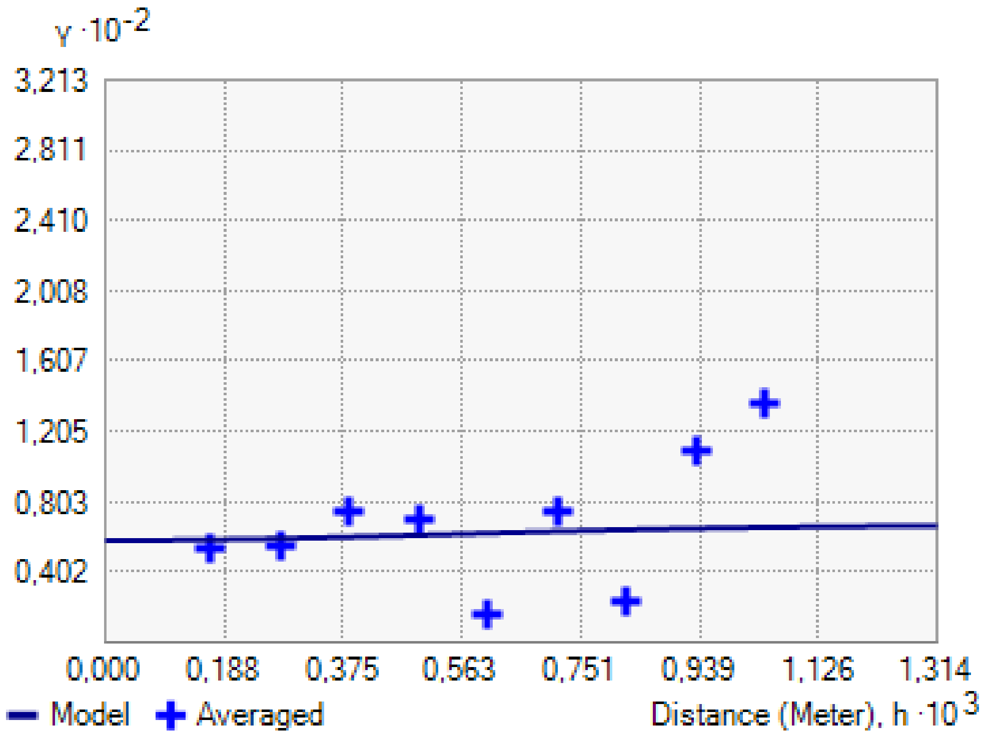
Semi-variograms for soil loss, runoff and other measured properties at 45 mm h^{-1} rainfall intensity for University of Venda Agricultural farm are presented in Fig. 4.



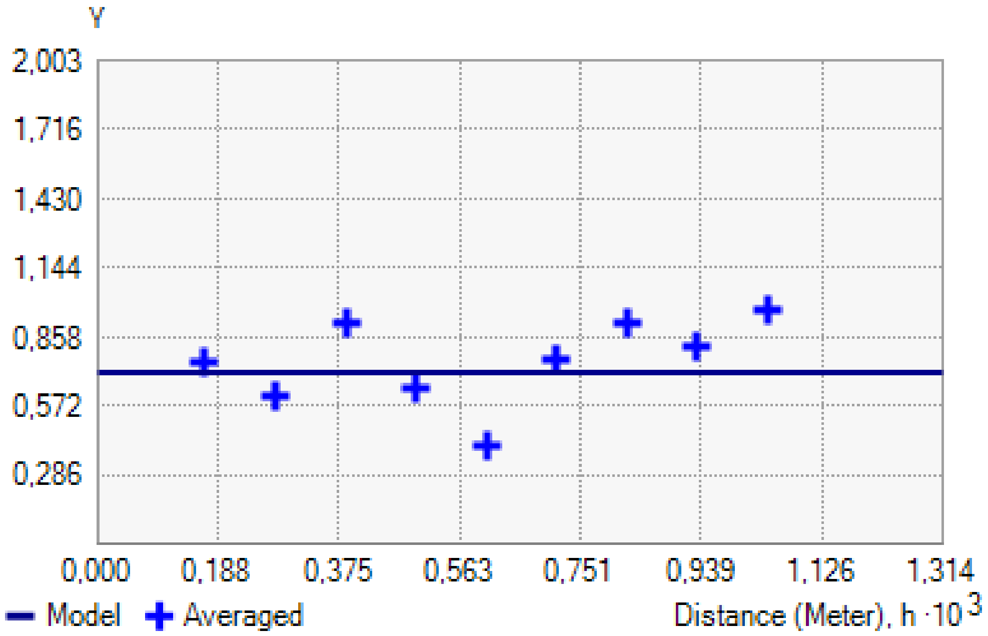
A



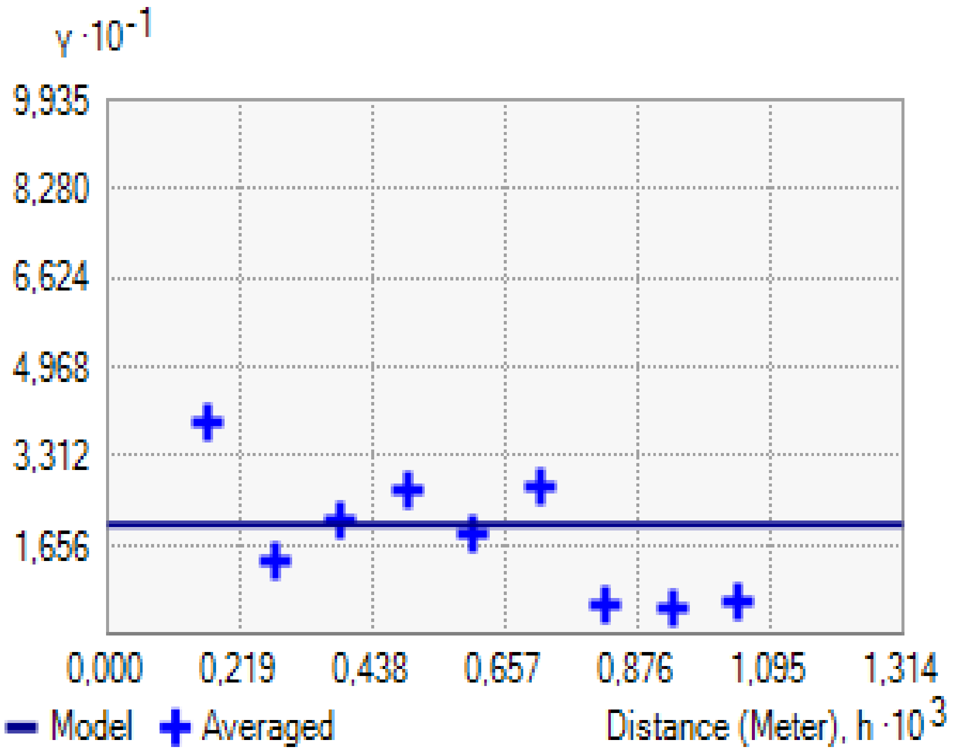
B


γ ·10-2
3,213
2,811
2,410
2,008
1,607
1,205
0,803
0,402
0,000
0,188
0,375
0,563
0,751
0,939
1,126
1,314
Model
Averaged
Distance (Meter), h ·10 3

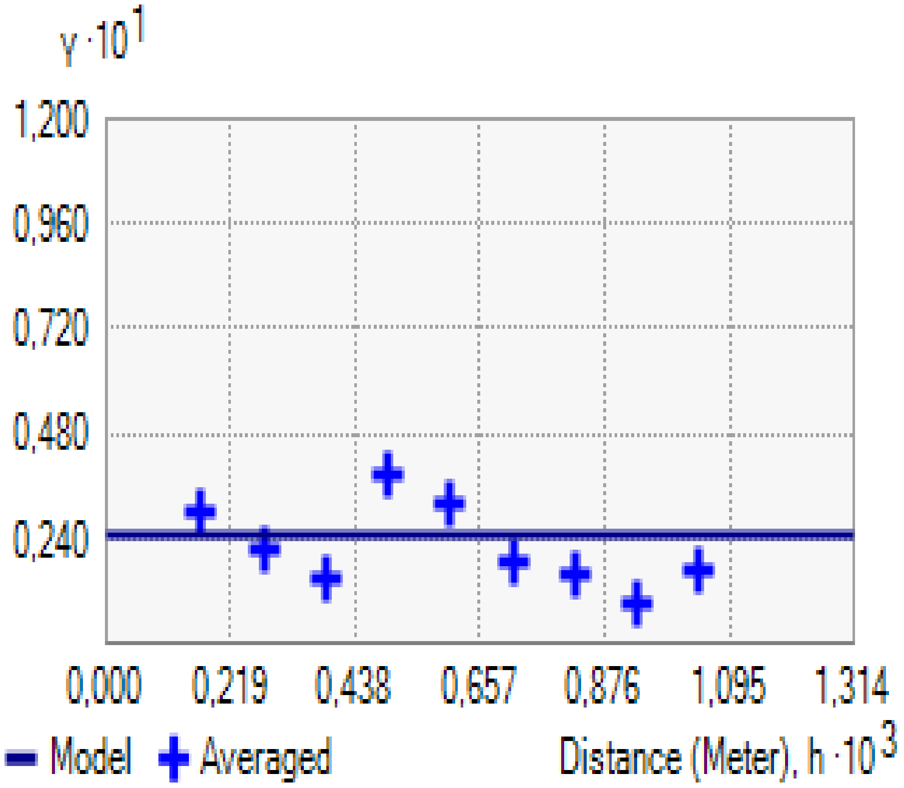
C


γ
2,003
1,716
1,430
1,144
0,858
0,572
0,286
0,000
0,188
0,375
0,563
0,751
0,939
1,126
1,314
Model
Averaged
Distance (Meter), h ·10 3

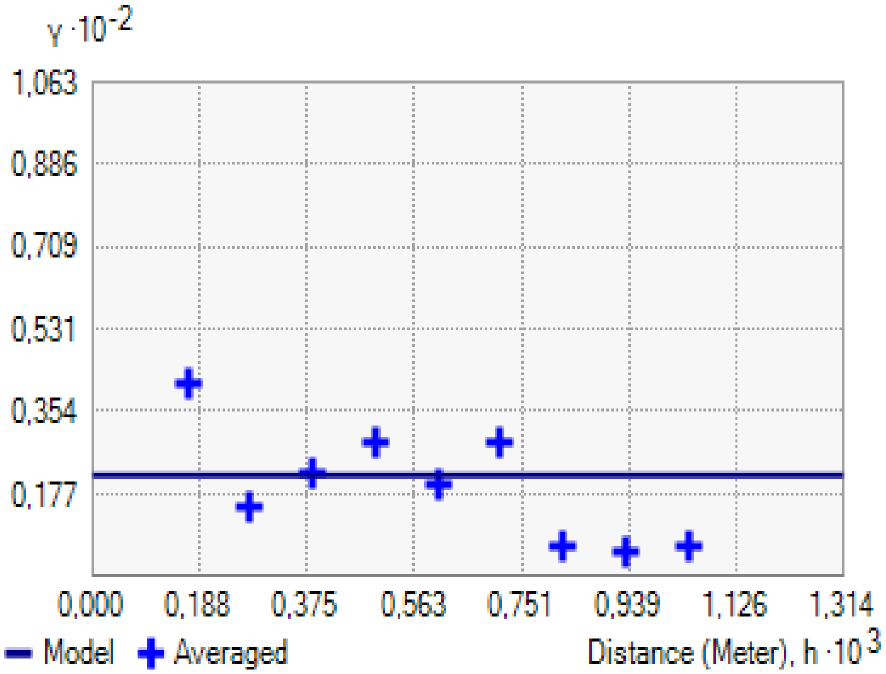
D


γ ·10-1
9,935
8,280
6,624
4,968
3,312
1,656
0,000
0,219
0,438
0,657
0,876
1,095
1,314
Model
Averaged
Distance (Meter), h ·10 3

E


γ ·10 1
1,200
0,960
0,720
0,480
0,240
0,000
0,219
0,438
0,657
0,876
1,095
1,314
Model
Averaged
Distance (Meter), h ·10 3

F



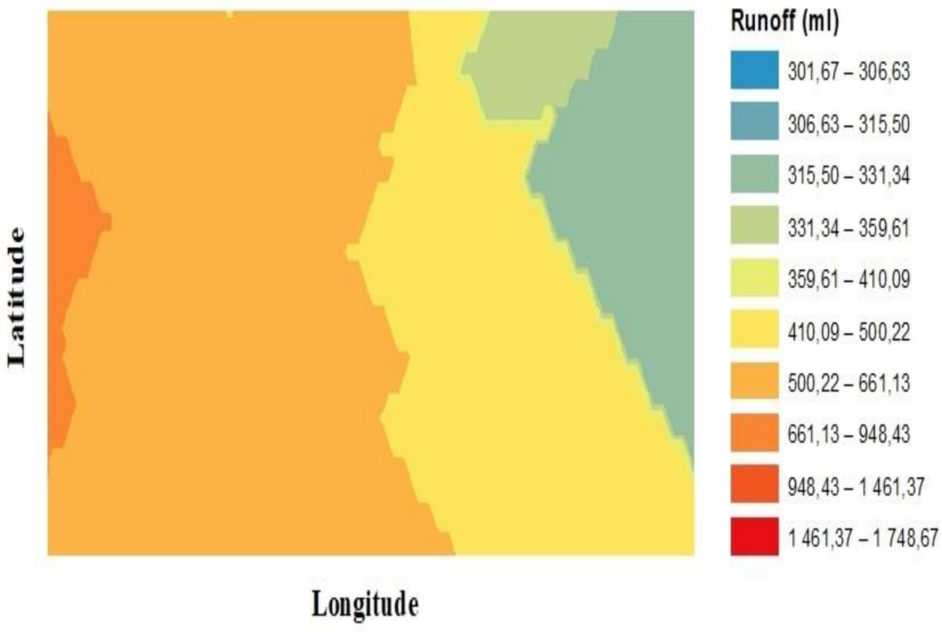
G

Fig. 4: Semi-variograms for selected measured soil properties at 45 mm h^{-1} rainfall intensity for University of Venda Agricultural farm. A – Soil loss; B – Runoff; C – Infiltration; D – Soil crust strength; E – Porosity; F – Mesoporosity; G – Macroporosity.

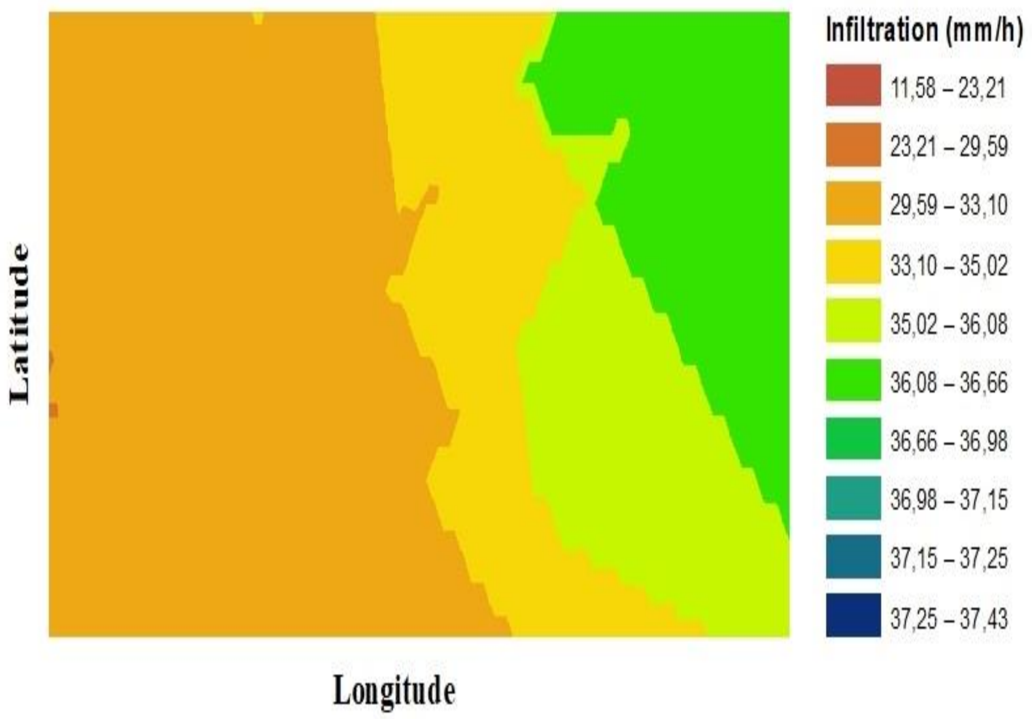
4.2.1.2 Spatial variability maps of soil loss, runoff and other soil properties

The spatial variability maps of the measured soil properties for University of Venda Agricultural farm at 45 mm h^{-1} are presented in Fig. 5.

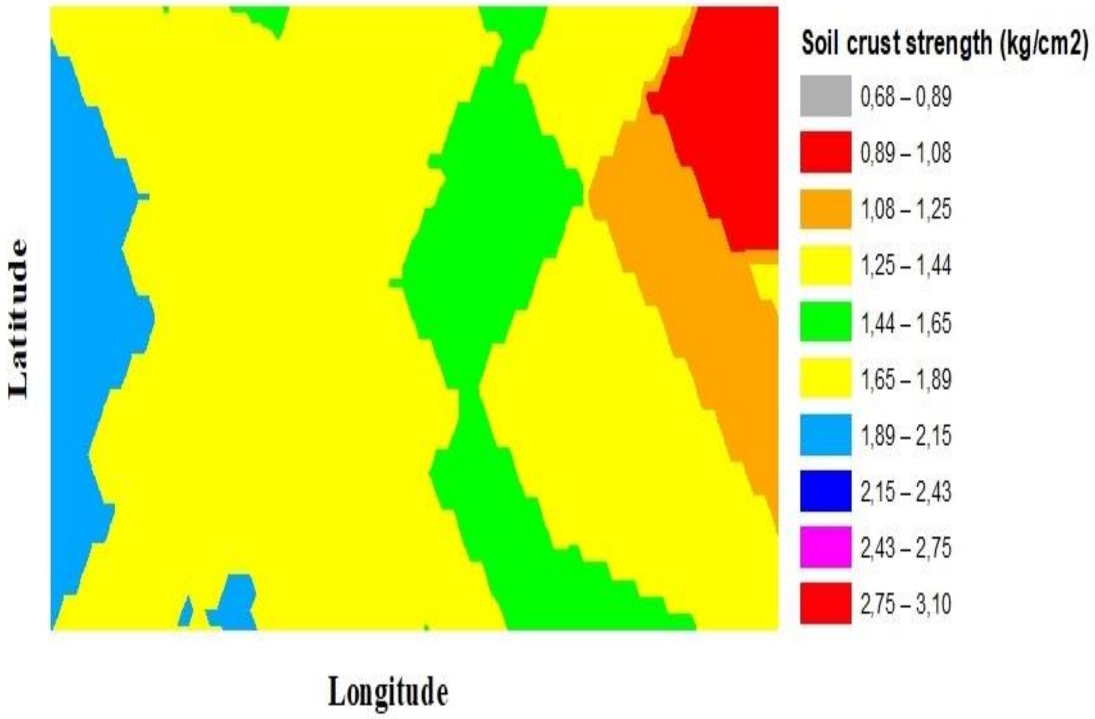
A



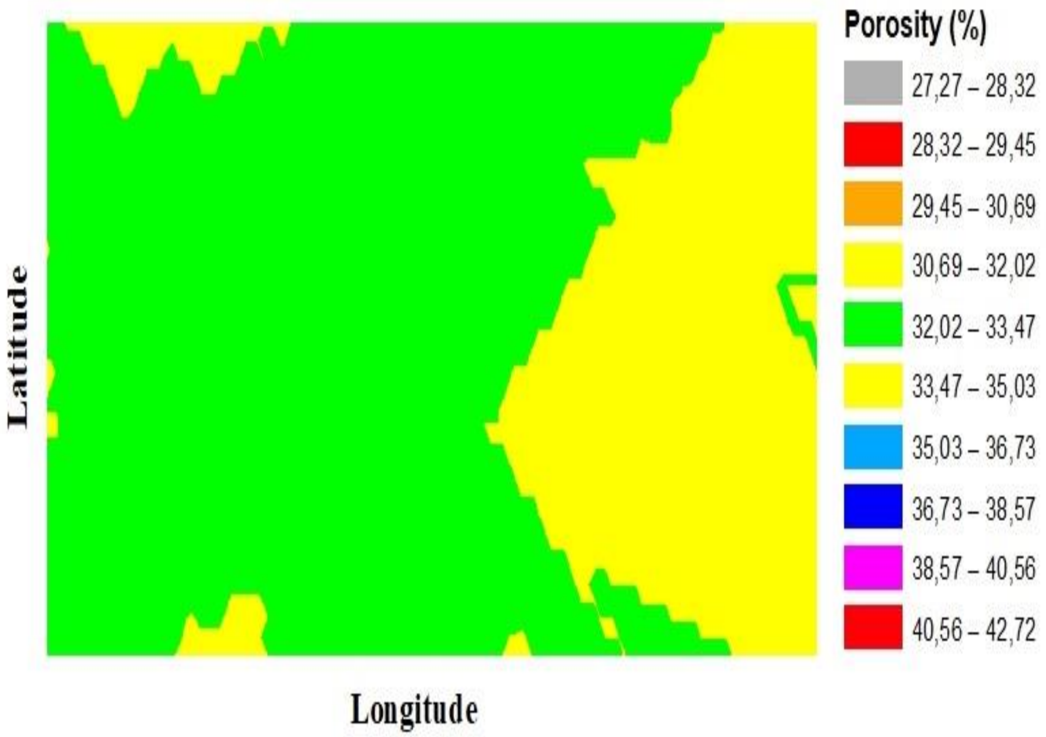
B


Infiltration (mm/h)
11,58 – 23,21
23,21 – 29,59
29,59 – 33,10
33,10 – 35,02
35,02 – 36,08
36,08 – 36,66
36,66 – 36,98
36,98 – 37,15
37,15 – 37,25
37,25 – 37,43
Latitude
Longitude

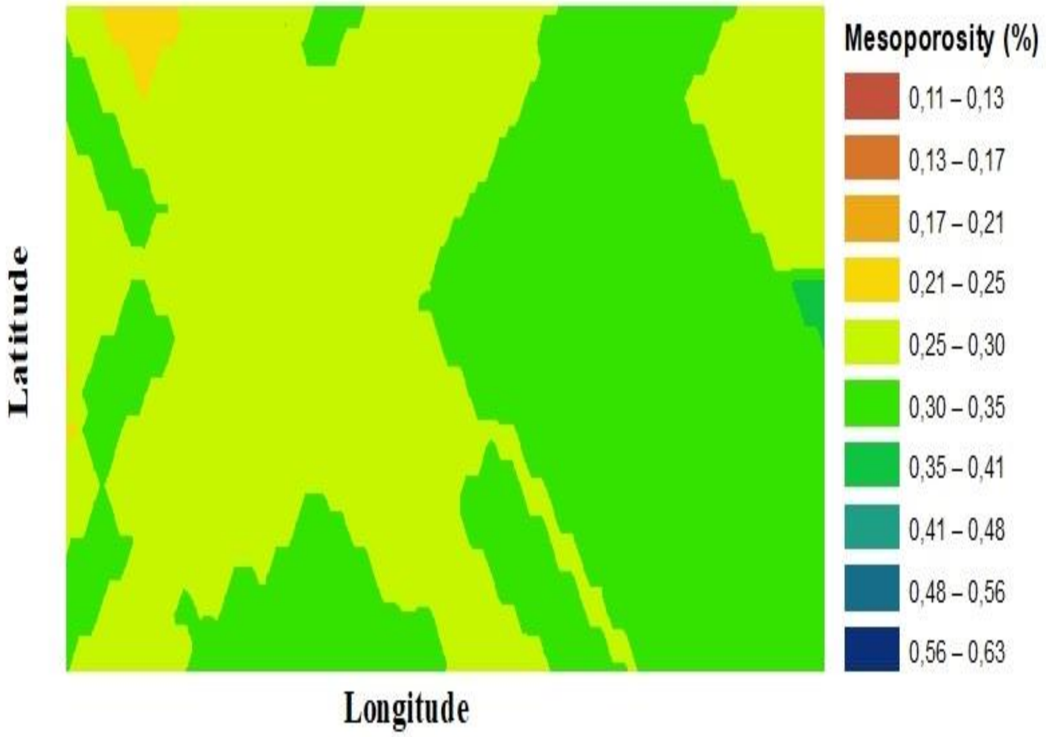
C


Soil crust strength (kg/cm2)
0,68 – 0,89
0,89 – 1,08
1,08 – 1,25
1,25 – 1,44
1,44 – 1,65
1,65 – 1,89
1,89 – 2,15
2,15 – 2,43
2,43 – 2,75
2,75 – 3,10
Latitude
Longitude

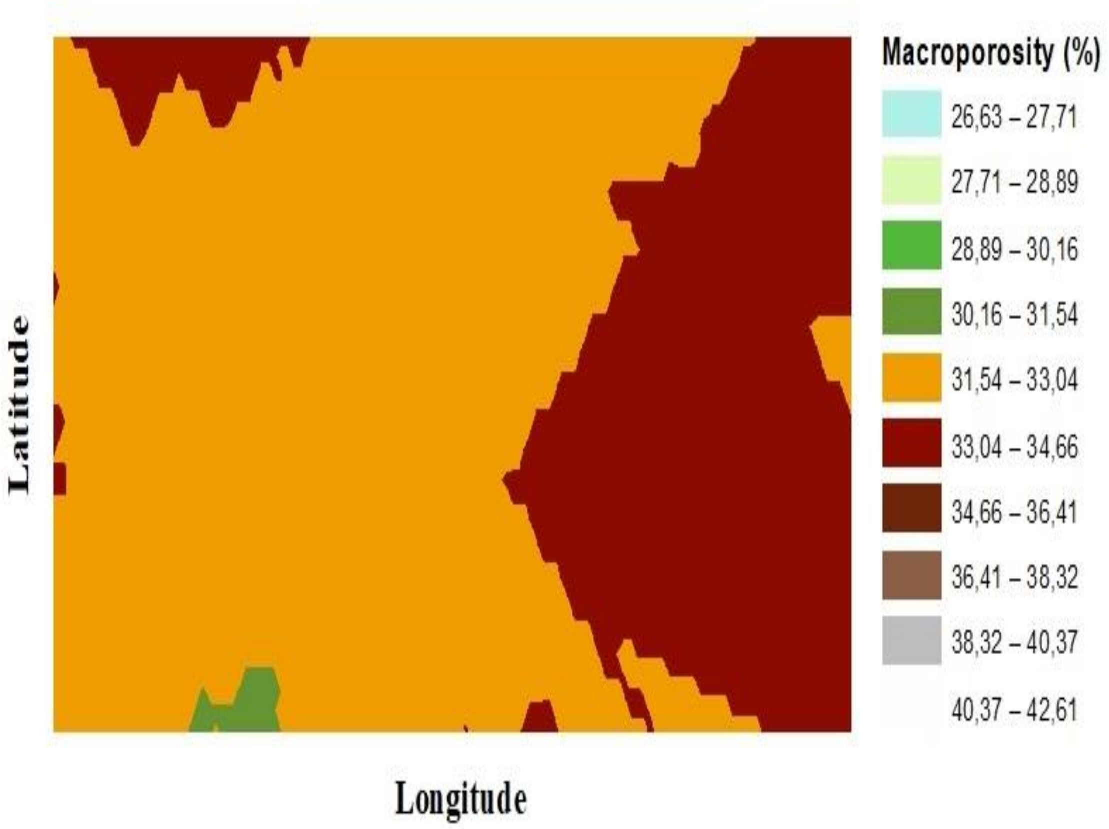
D


Porosity (%)
27,27 – 28,32
28,32 – 29,45
29,45 – 30,69
30,69 – 32,02
32,02 – 33,47
33,47 – 35,03
35,03 – 36,73
36,73 – 38,57
38,57 – 40,56
40,56 – 42,72
Latitude
Longitude

E


Mesoporosity (%)
0,11 – 0,13
0,13 – 0,17
0,17 – 0,21
0,21 – 0,25
0,25 – 0,30
0,30 – 0,35
0,35 – 0,41
0,41 – 0,48
0,48 – 0,56
0,56 – 0,63
Latitude
Longitude

F



G

Fig. 5: Spatial variability maps for selected soil properties at mm h^{-1} rainfall intensity for University of Venda Agricultural farm. A – Soil loss; B – Runoff; C – Infiltration; D – Soil crust strength; E – Porosity; F – Mesoporosity; G – Macroporosity.

4.2.2 Agricultural Research Council farm

The spatial variability of soil loss and runoff at 45 mm h^{-1} rainfall intensity presented as degree of spatial dependence are shown in Table 6 whereas their spatial variograms are shown in Fig. 6. Soil loss and runoff had weak spatial dependency at Agricultural Research Council farm with a spatial ratio of 100% (Table 6). Weak spatial dependency was also observed on other measured soil properties which include infiltration, soil crust strength, porosity and macroporosity (Table 6). In contrast, mesoporosity had strong spatial dependency with a spatial ratio of 20%.

The spatial distribution maps for measured parameters at Agricultural Research Council farm are presented in Fig. 7. Very weak spatial distribution patterns were observed on soil loss, runoff and other measured soil properties including infiltration rate, soil crust strength, porosity and macroporosity (Fig. 7). In opposite, soil mesoporosity had strong spatial distribution patterns with high concentration values at southeast and southwest (Fig. 7F).

Similarly, weak spatial variability of soil loss and runoff found at this site could be attributed to the weak variation of infiltration rate. The weak variation of runoff could also be the possible reason for the weak variability of soil loss as shown in Table 6. Soil loss exhibited a high positive correlation with runoff (r^2 = 0.88) (Table 4). This positive correlation means that when spatial variability of runoff becomes weak the soil loss also becomes weak. Moreover, weak spatial variation could be attributed to soil crust strength, which showed a weak variation. Soil crust strength also exhibited a positive correlation with soil loss (r^2 = 0.87) and runoff (r^2 = 0.75) as shown in Table 4. The weak variation of soil porosity and macroporosity could have resulted into weak variation of soil loss and runoff at this study site (Table 6). Furthermore, the study site was previously used for farming purposes using traditional cultivation with the application of fertilizers. Therefore, the weak spatial variation of soil loss and runoff could be attributed to human impacts including cultivation and land management practices. Wang et al. (2009) reported that extrinsic factors such as fertilization and cultivation practices are responsible for the moderate weak (50 – 75%) and very weak

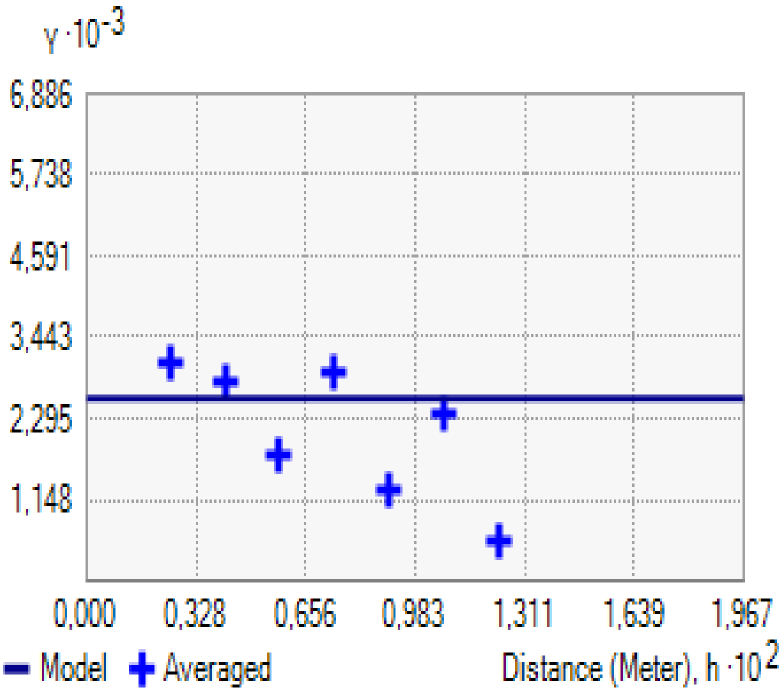
(>75%) spatial dependence. Moreover, continuous cultivation affects soil bulk density and destroys different soil pores. This could be also the possible reason for weak variation of soil porosity and macroporosity which might have resulted into weak soil loss and runoff (Table 6).

Table 6: Semi variance models and the degree of spatial dependence of the measured soil properties for Agricultural Research Council farm.

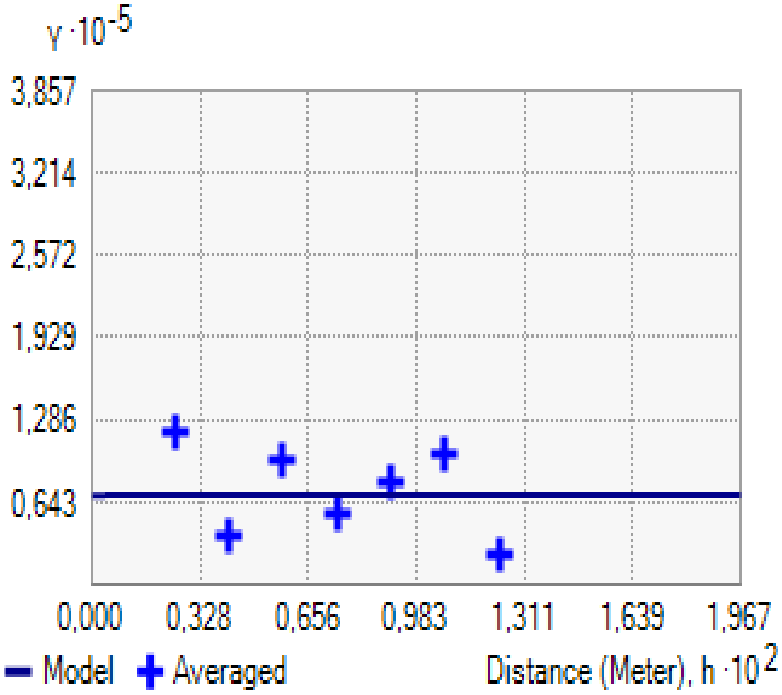
Parameter	Models	Nugget	Sill	Range	Spatial ratio (%)	Spatial class
Soil loss (kg/ha)	Exponential	2.6	2.6	0,02	100	W
Runoff (ml)	Exponential	0.07	0.07	0,02	100	W
Infiltration (mm h^{-1})	Exponential	13,21	13,21	0,02	100	W
Soil crust strength (kg/cm^2)	Exponential	1,15	1,15	0,02	100	W
Porosity (%)	Exponential	32	32	0,02	100	W
Mesoporosity (%)	Exponential	0,01	0,05	0,02	20	S
Macroporosity (%)	Exponential	34	34	0,02	100	W

4.2.2.1 Semi-variograms of measured soil properties

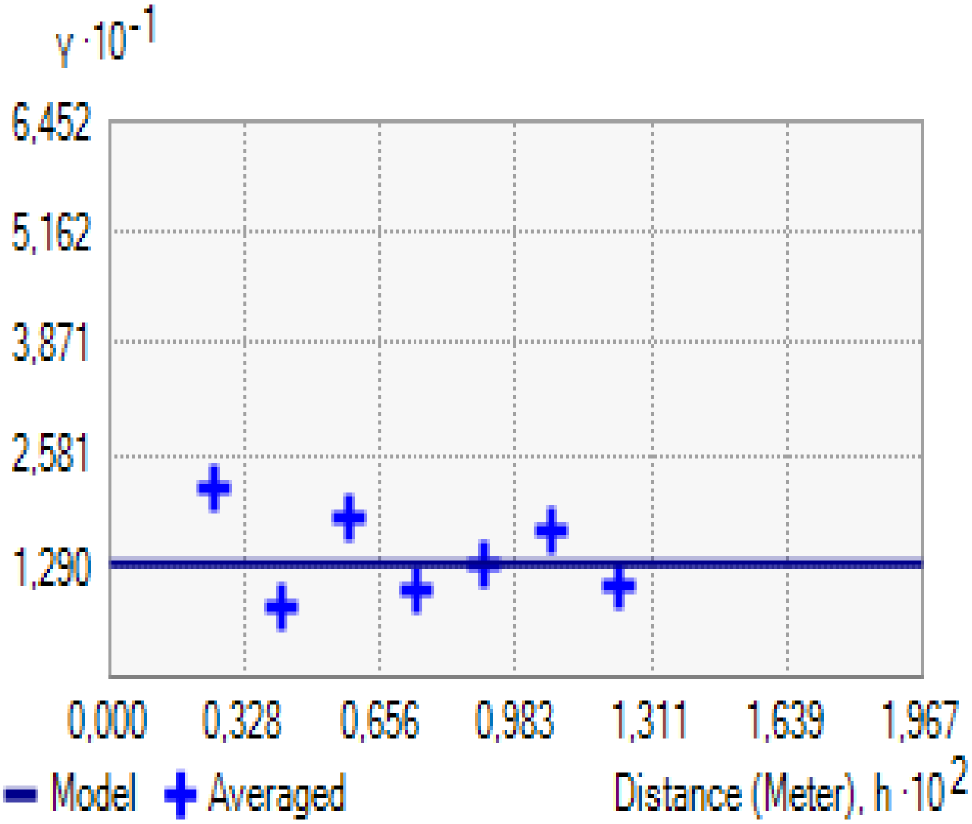
Semi-variograms for measured soil properties at mm h^{-1} rainfall intensity for Agricultural Research Council farm are presented in Fig. 6.



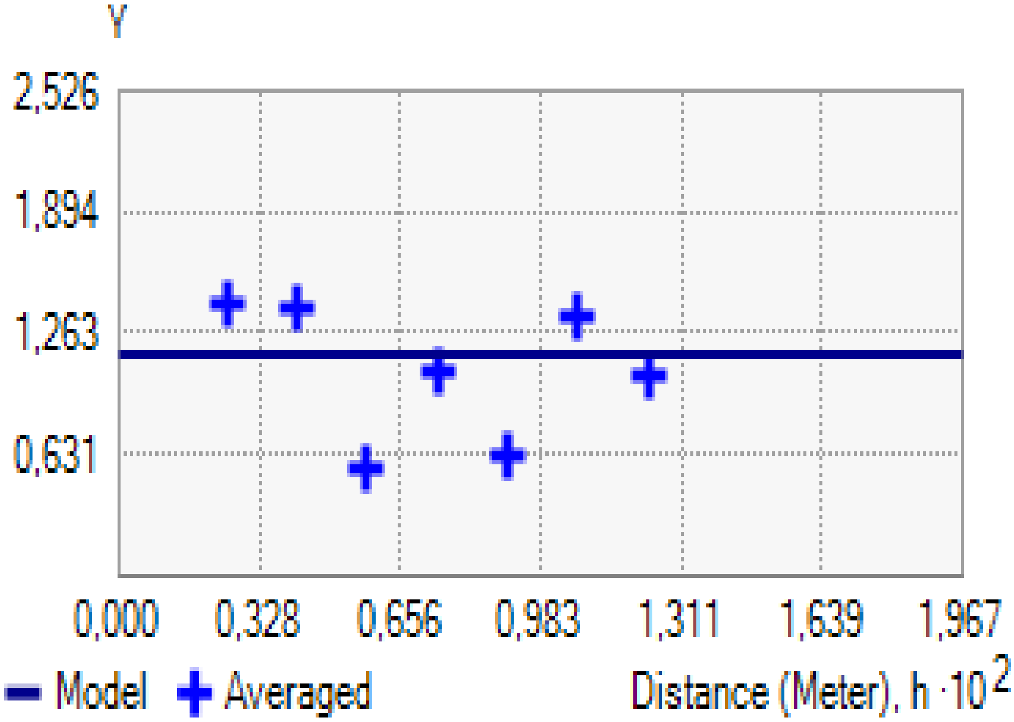
A



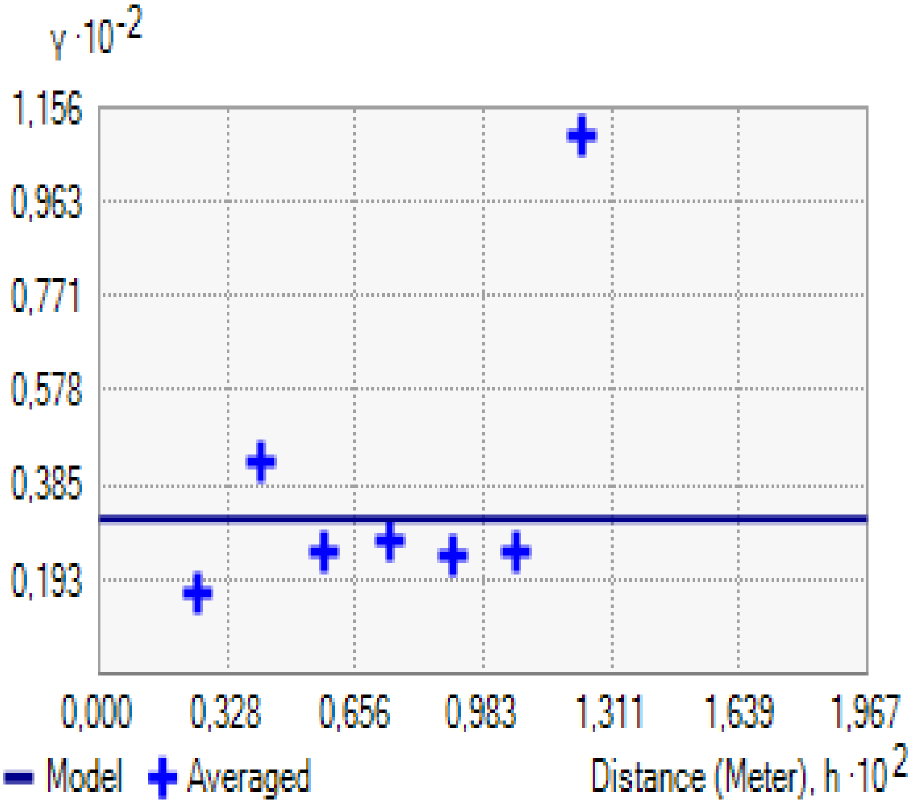
B


$\gamma \cdot 10^{-1}$
6,452
5,162
3,871
2,581
1,290
0,000
0,328
0,656
0,983
1,311
1,639
1,967
Model
Averaged
Distance (Meter), h $\cdot 10^{2}$

C

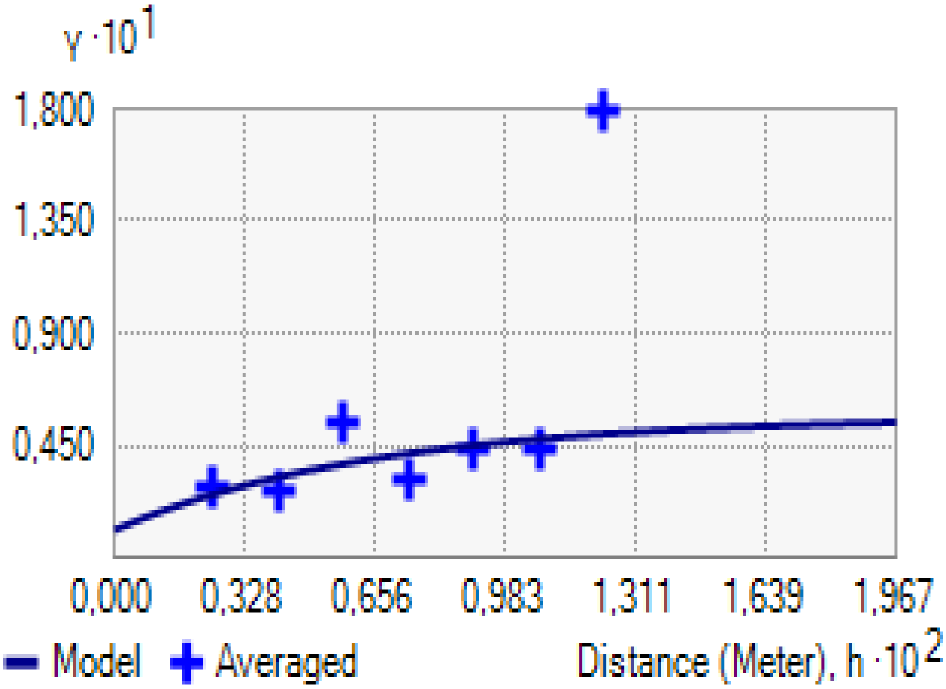

γ
2,526
1,894
1,263
0,631
0,000
0,328
0,656
0,983
1,311
1,639
1,967
Model
Averaged
Distance (Meter), h $\cdot 10^{2}$

D



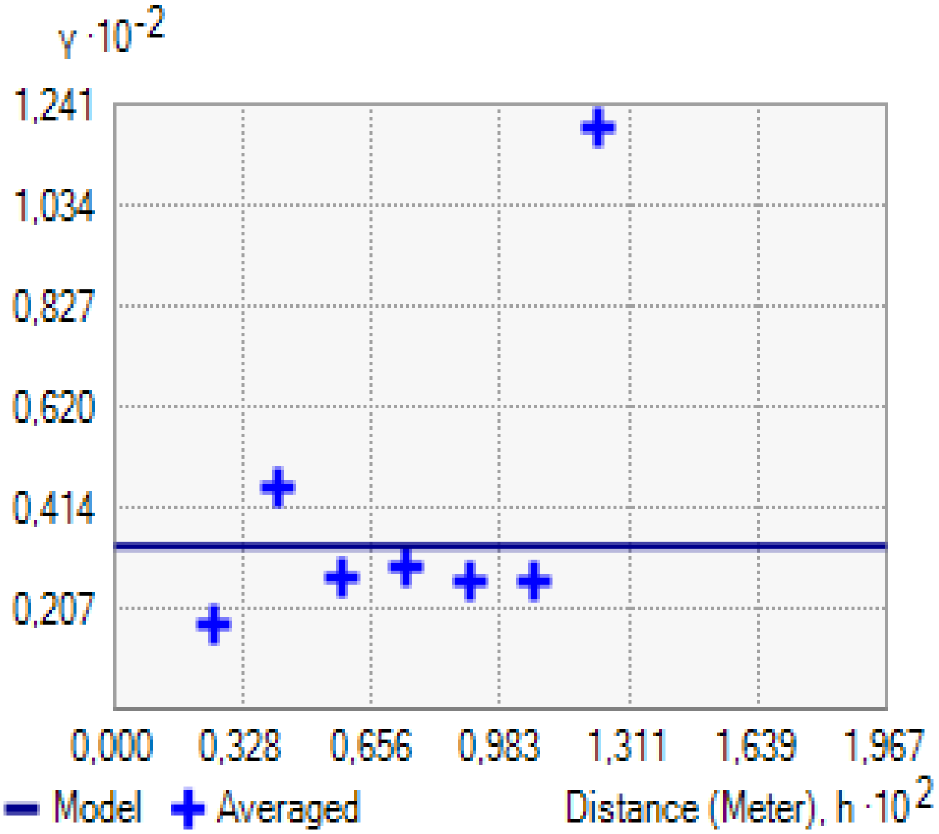
γ ·10-2
1,156
0,963
0,771
0,578
0,385
0,193
0,000
0,328
0,656
0,983
1,311
1,639
1,967
Model
Averaged
Distance (Meter), h ·10 2

E



γ ·10 1
1,800
1,350
0,900
0,450
0,000
0,328
0,656
0,983
1,311
1,639
1,967
Model
Averaged
Distance (Meter), h ·10 2

F

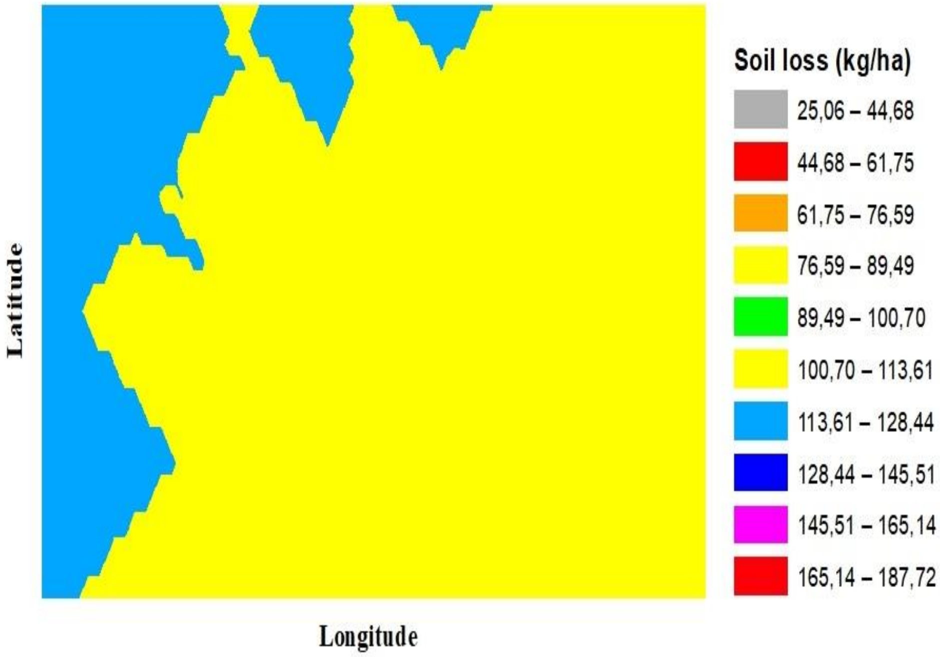


G

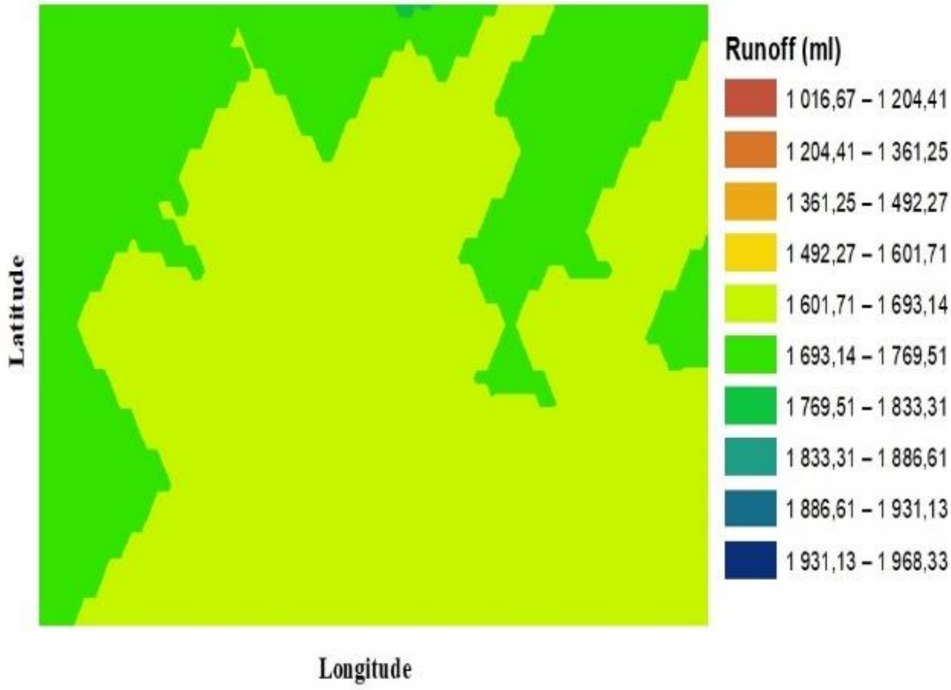
Fig. 6: Semi-variograms for selected measured soil properties at mm h^{-1} rainfall intensity for Agricultural Research Council farm. A – Soil loss; B – Runoff; C – Infiltration; D – Soil crust strength; E – Porosity; F – Mesoporosity; G – Macroporosity.

4.2.2.2 Spatial variability maps for measured soil properties

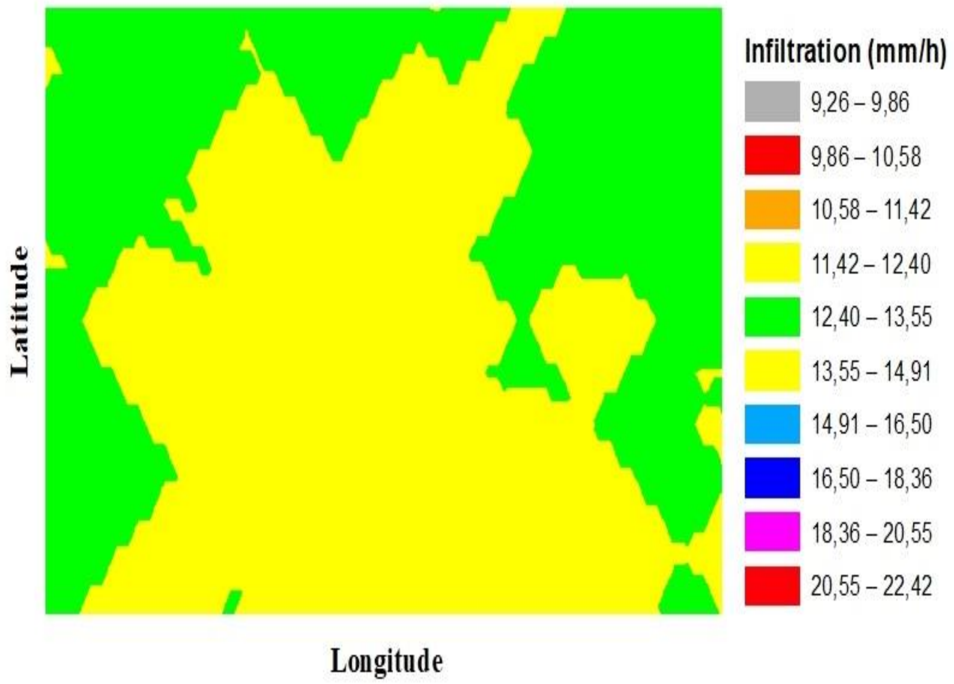
The spatial variability maps of the measured soil properties at 45 mm h^{-1} rainfall intensity for Agricultural Research Council farm are presented in Fig. 7.



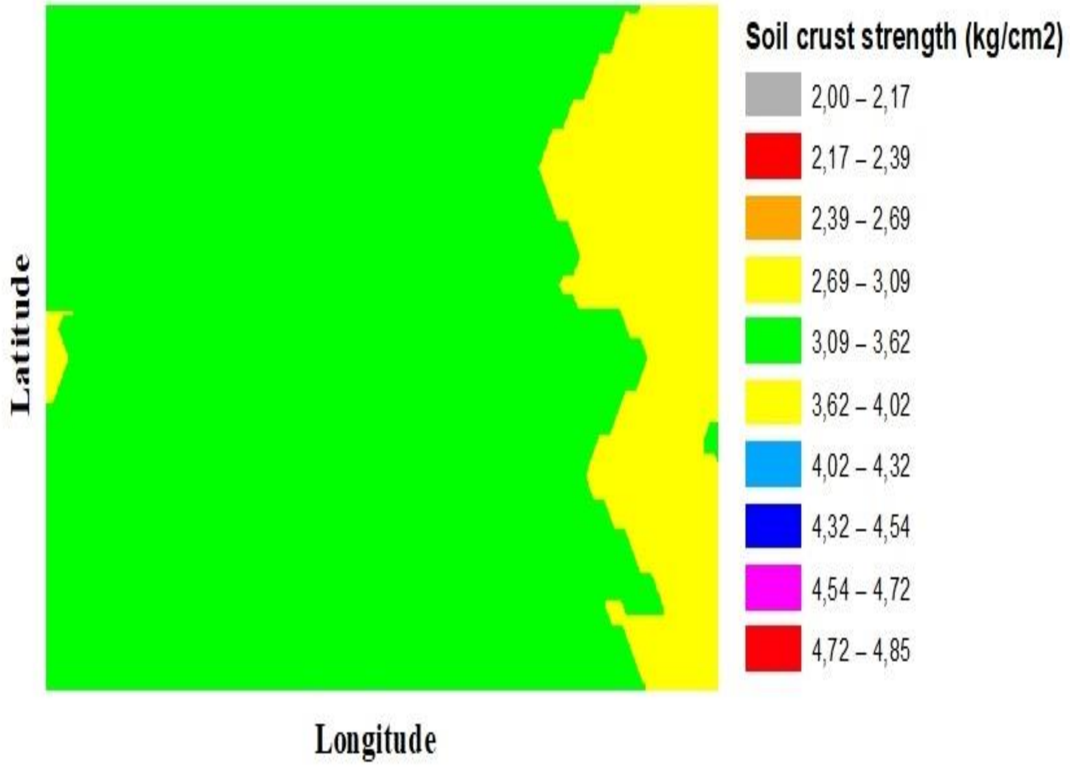
A



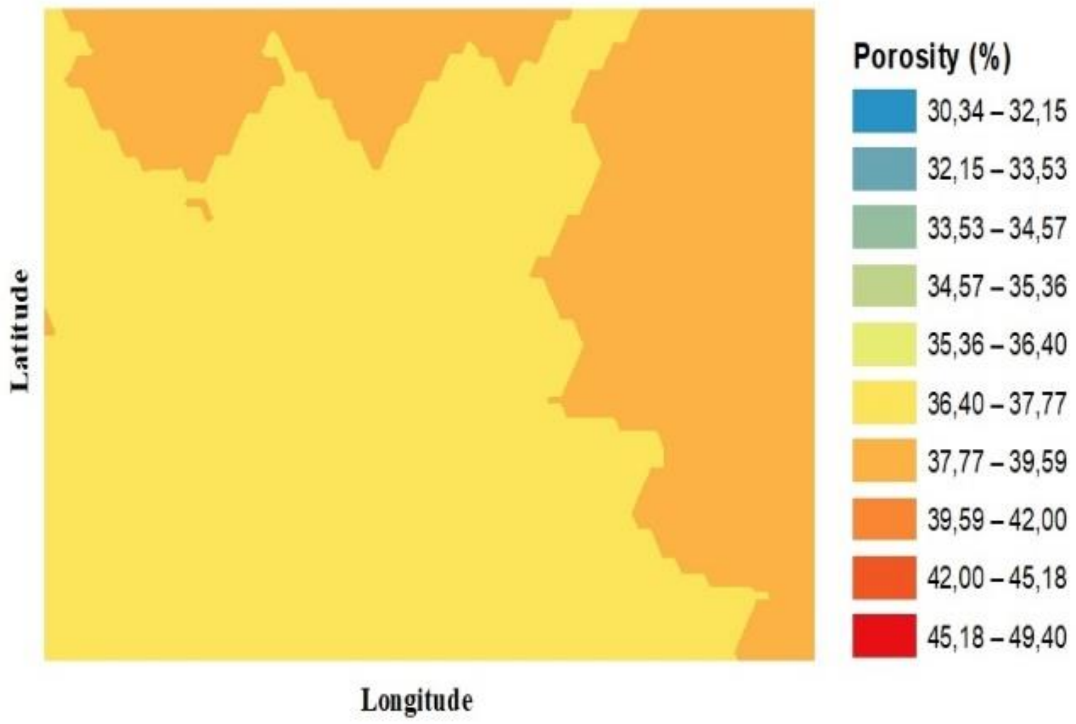
B


Infiltration (mm/h)
9,26 – 9,86
9,86 – 10,58
10,58 – 11,42
11,42 – 12,40
12,40 – 13,55
13,55 – 14,91
14,91 – 16,50
16,50 – 18,36
18,36 – 20,55
20,55 – 22,42
Latitude
Longitude

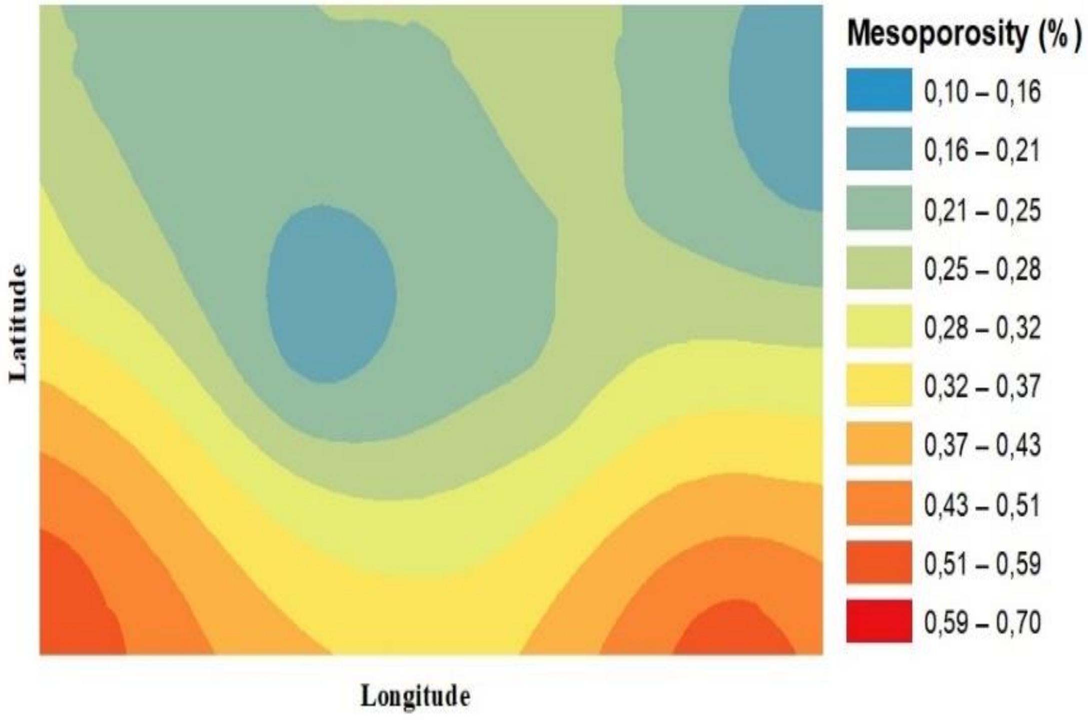
C


Soil crust strength (kg/cm2)
2,00 – 2,17
2,17 – 2,39
2,39 – 2,69
2,69 – 3,09
3,09 – 3,62
3,62 – 4,02
4,02 – 4,32
4,32 – 4,54
4,54 – 4,72
4,72 – 4,85
Latitude
Longitude

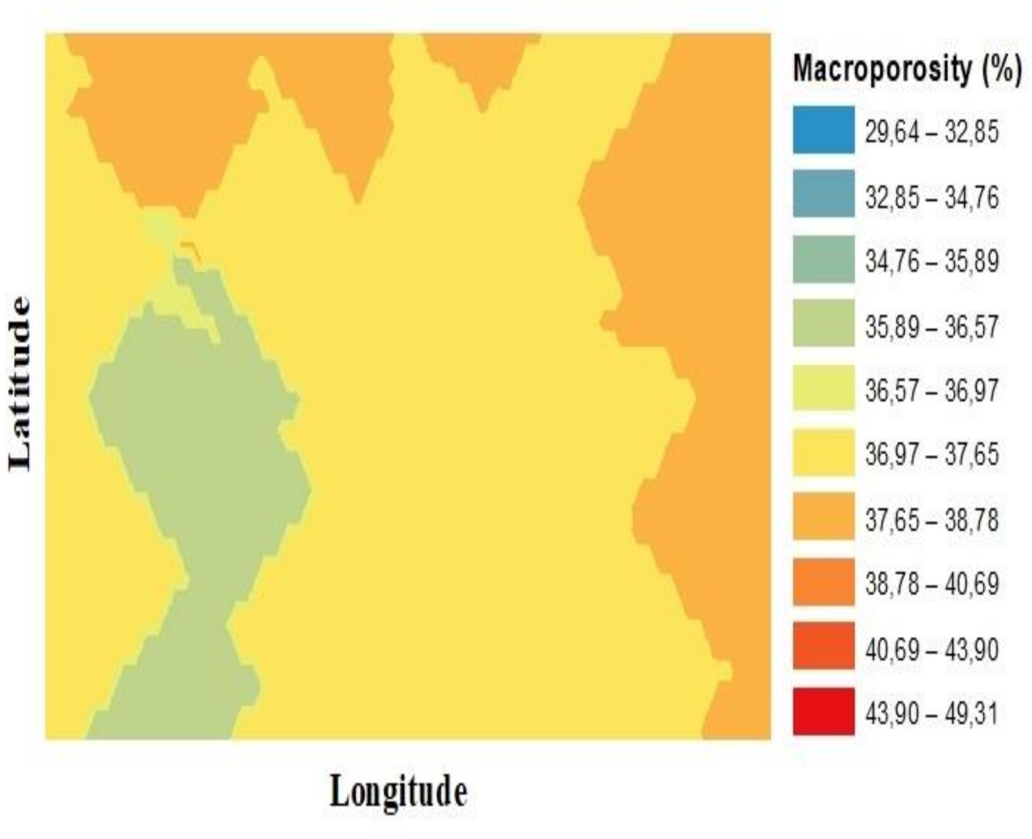
D


Porosity (%)
30,34 – 32,15
32,15 – 33,53
33,53 – 34,57
34,57 – 35,36
35,36 – 36,40
36,40 – 37,77
37,77 – 39,59
39,59 – 42,00
42,00 – 45,18
45,18 – 49,40
Latitude
Longitude

E


Mesoporosity (%)
0,10 – 0,16
0,16 – 0,21
0,21 – 0,25
0,25 – 0,28
0,28 – 0,32
0,32 – 0,37
0,37 – 0,43
0,43 – 0,51
0,51 – 0,59
0,59 – 0,70
Latitude
Longitude

F



G

Fig. 7: Spatial variability maps for soil loss, runoff and selected soil properties at 45 mm h^{-1} rainfall intensity for Agricultural Research Council farm. A – Soil loss; B – Runoff; C – Infiltration; D – Soil crust strength; E – Porosity; F – Mesoporosity; G – Macroporosity.

4.3 Soil aggregate stability and aggregate size distribution

4.3.1 University of Venda Agricultural farm

Semi-variance models and spatial dependence of soil aggregate stability and aggregate size distribution are presented in Table 7 while their semi-variograms are shown in Fig. 8. Exponential model was proved to be the best fit model in University of Venda Agricultural farm. Weak spatial dependency was observed on soil aggregate stability, microaggregates and macroaggregates in University of Venda Agricultural farm. Similar findings were reported by Barik et el. (2014) whereby weak spatial dependence was observed after traffic operation at 0-10 and 10-20 cm depth with spatial ratio of 91 and 92%, respectively. In contrast, strong spatial dependence of MWD and WSA (> 2 mm) was reported by Ye et al. (2018). The spatial distribution maps for soil aggregate stability, microaggregates and macro aggregates for University of Venda Agricultural farm are presented in Fig. 9. Aggregate stability, micro and macro aggregates had very weak spatial distribution patterns as shown in Fig. 9.

Weak spatial variation of soil aggregate stability could be attributed to the weak variation of macroaggregates as shown in Table 7. Macroaggregate is known to influence aggregate stability. For instance, higher aggregate stability was reported with more stable aggregates after the amendments and mulch application (Materechera, 2009b). Soil aggregate stability was positively correlated with macroaggregates (r^2 = 0.77) at this site. Weak variation of microaggregates could be another factor that caused weak variation of soil aggregate stability as shown in Table 7. Furthermore, macroaggregates could have contributed to the weak variation of soil aggregate stability and macro aggregates as well (Table 7).

Microaggregates was negatively correlated with aggregate stability (r^2 = - 0.98) (Table 2). Additionally, weak spatial variability of soil aggregate stability, micro and macro aggregates might be due to the weak variability of clay particles with a CV value of 15% and soil organic carbon content with a CV of 12.86%. Clay and soil organic matter are primarily soil properties that influence the stability of soil aggregates. Clay content was significantly related with the soil aggregate stability in the study conducted by Annabi et al. (2017).

Moreover, low soil organic carbon content ranging from 0.2 – 2% was reported with no effect on soil aggregate stability (Annabi et al., 2017). These results are different from those reported by Ye et al. (2018), who stated that strong spatial variation is mainly determined by soil intrinsic factors including soil parent material and soil texture. Moreover, Xu (2003) concluded that spatial variation of soil aggregate stability resulted from the land use change. Cultivation could be one of the other factors that caused weak variation of soil aggregate stability, microaggregates and macroaggregates since the site was cultivated before taking soil samples. Wang et al. (2009) supported that cultivation leads to weak variation of soil properties. This is because, cultivation disrupt soil aggregate formation due to the turning over of soil and breaks down soil structural stability. For instance, higher soil aggregate stability was reported in areas with lack of disruption of soil aggregates induces by ploughing activities in dryland and pasture (Mohammadi and Motaghian, 2011).

4.3.2 Agricultural Research Council farm

The spatial variability dependence and semi-variance models for soil aggregate stability, micro and macro aggregates are presented in Table 7 while their semi-variograms are shown in Fig. 8. Gaussian model was the best fit model in Agricultural Research Council farm (Table 7). Moderate spatial dependence was observed on aggregate stability with 42,98% and microaggregates with 66,67%. In contrast, a strong spatial dependency was observed on macroaggregates with 17,39% spatial ratio in Agricultural Research Council farm. In this study, low range values were experienced in both sites. According to Phafedu and Kutu (2016), low range value indicates a great amount of variability within the field.

Krigged maps for soil aggregate stability, microaggregates and macro aggregates for Agricultural Research Council farm are also presented in Fig. 9. Agricultural Research

Council farm was observed with moderate spatial distribution trends on soil aggregate stability and microaggregates. Aggregate stability was observed with higher concentration at northwest while low concentration appeared from the southwest of the measured field (Fig. 9 A2). Low to high concentration of microaggregetes was observed from south to the north of the field as shown in Fig. 9 B2. A strong spatial distribution patterns was observed on soil macroaggregates where by high concentration was at the southeast whereas low concentration was at northwest towards the west part of the field (Fig. 9 C2).

Moderate spatial variation of soil aggregate stability could be attributed to the moderate variation of microaggregates as shown in Table 7. Soil aggregate stability was highly negative correlated with microaggregates with a correlation value of -0.97 (Table 4). Strong variation of soil macroaggregates could be due to the intrinsic soil forming factors such as soil parent materials as well as geologic factors. According to Ye et al. (2018), strong spatial dependence is mainly resulted from soil intrinsic factors such as soil parent material and soil texture. However, soil texture particularly clay content was not a leading factor on soil aggregate stability, micro and macro aggregates because of its weak variation with a CV of 8.45% (Table 3). This could be due to the dissolved and decomposition of soil organic matter in the area since the site was previously used for farming purposes using traditional tillage system. In contrary, soil compaction at this site could have caused rearrangement of primary soil particles and dispersed microaggregates to form macroaggregates (Materechera, 2009a)

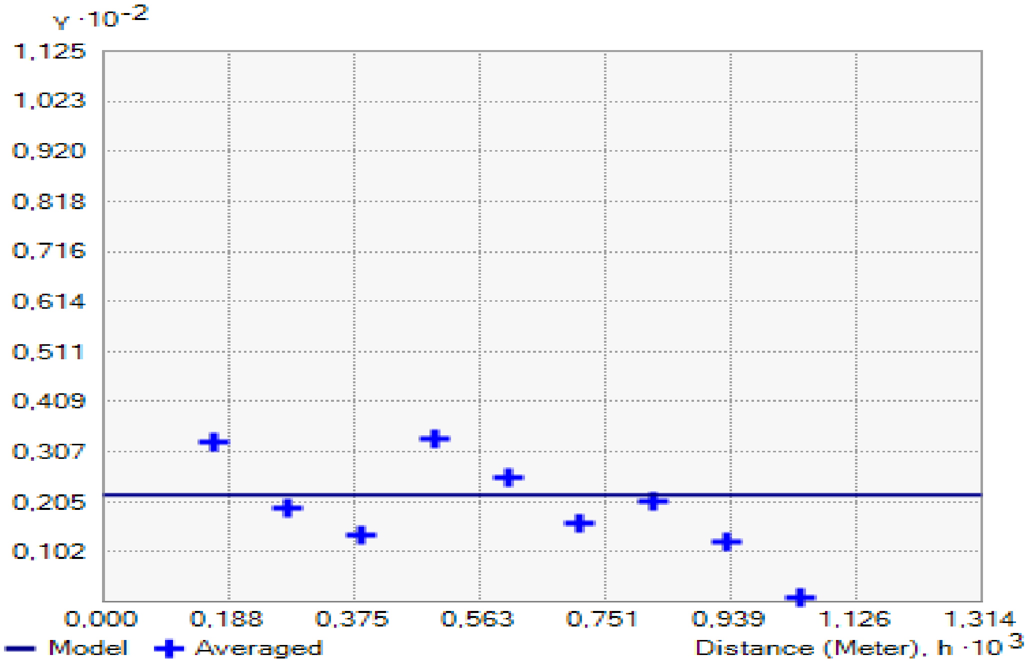
Table 7: Semivariance models and the degree of spatial dependency of aggregate stability and size distribution for University of Venda Agricultural farm and Agricultural Research Council farm.

Parameters	Site	Models	Nugget	Sill	Range	Spatial ratio (%)	Spatial class
Aggregate stability (%)	1	Exponential	21,90	21,90	1,31E-03	100	W
	2	Gaussian	19,27	44,84	0,01	42,98	M
Microaggregates (<250 um)	1	Exponential	0,03	0,03	1,31E-03	100	W
	2	Gaussian	0,02	0,03	0,01	66,67	M
Macroaggregates (>250 um)	1	Exponential	0,03	0,03	1,31E-03	100	W
	2	Gaussian	0,04	0,23	0,01	17,39	S

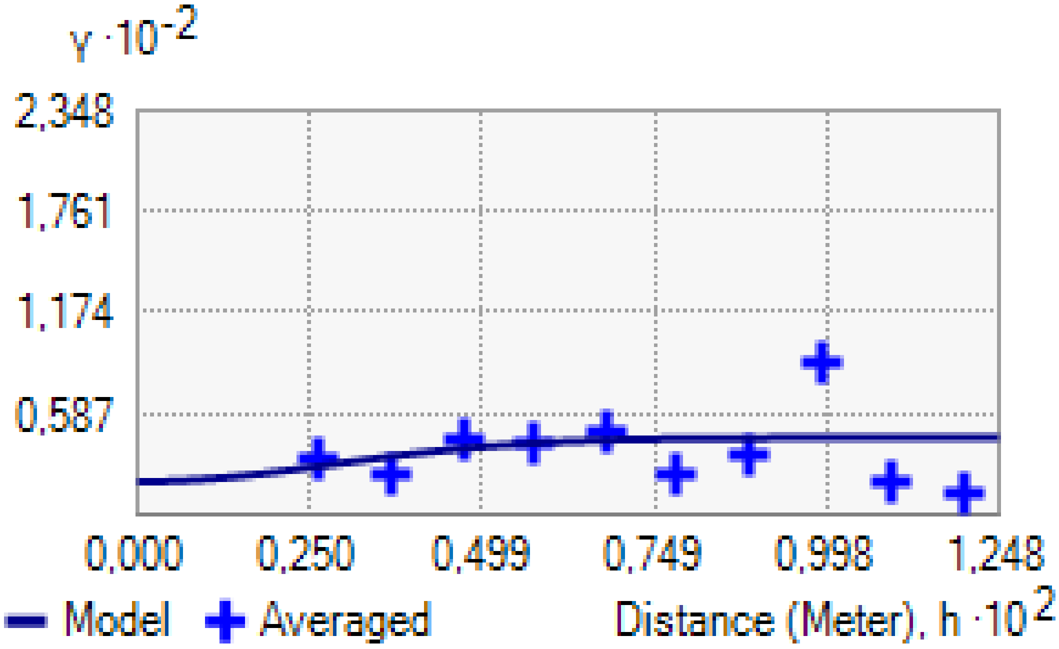
1 – University of Venda agricultural farm; 2 – Agricultural Research Council farm; W – Weak; M – Moderate; S - Strong

4.3.3 Semi-variograms for soil aggregate stability and size distribution

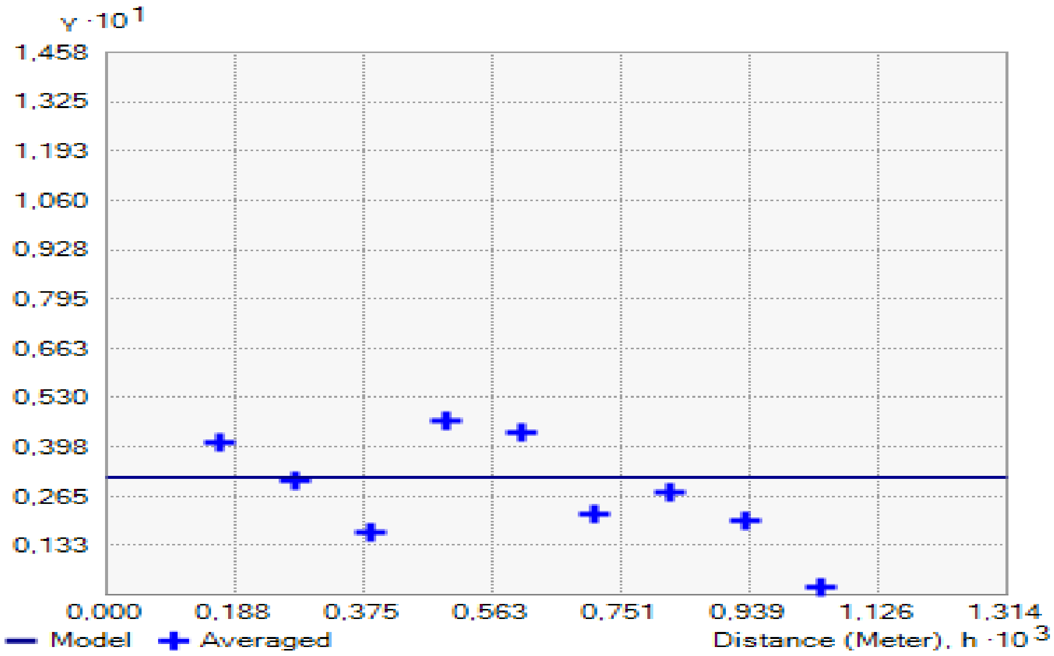
The semi-variograms for soil aggregate stability and size distribution for University of Venda Agricultural farm and Agricultural Research Council farm are presented in Fig. 8.



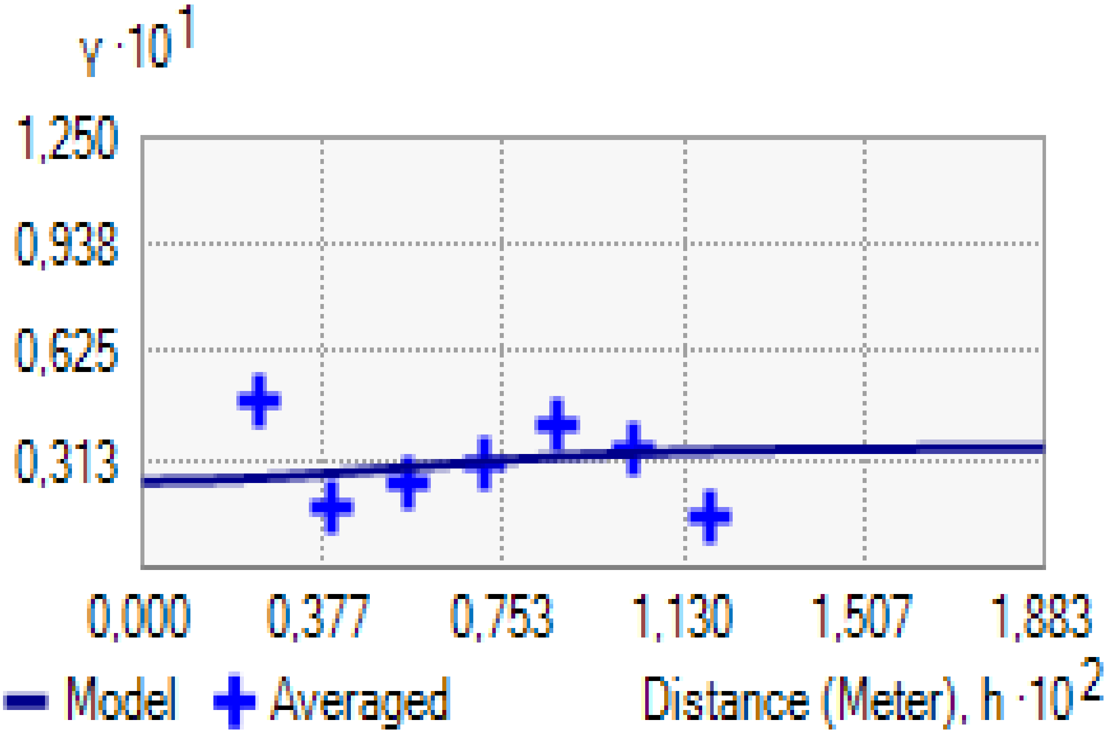
A1



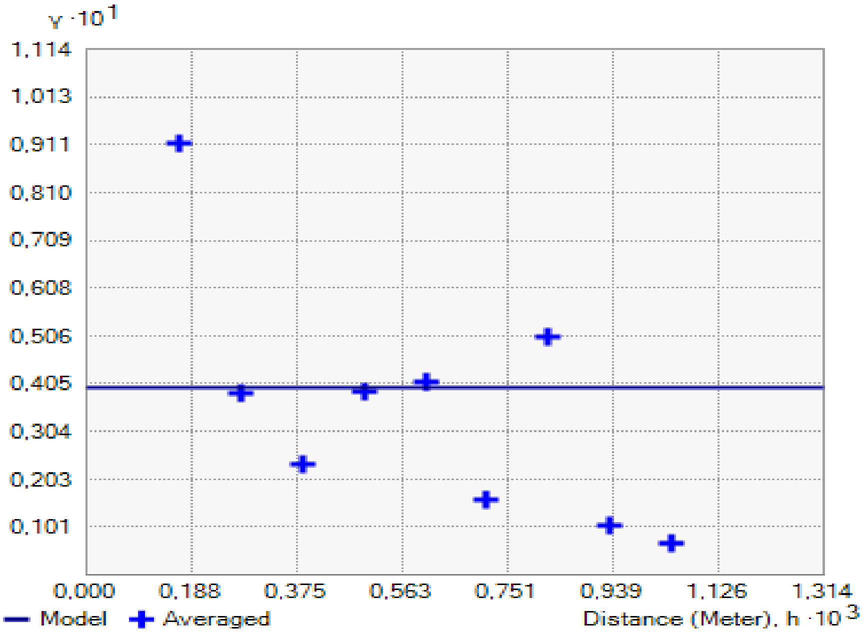
A2


γ ·10 1
1,458
1,325
1,193
1,060
0,928
0,795
0,663
0,530
0,398
0,265
0,133
0,000
0,188
0,375
0,563
0,751
0,939
1,126
1,314
Model
Averaged
Distance (Meter), h ·10 3

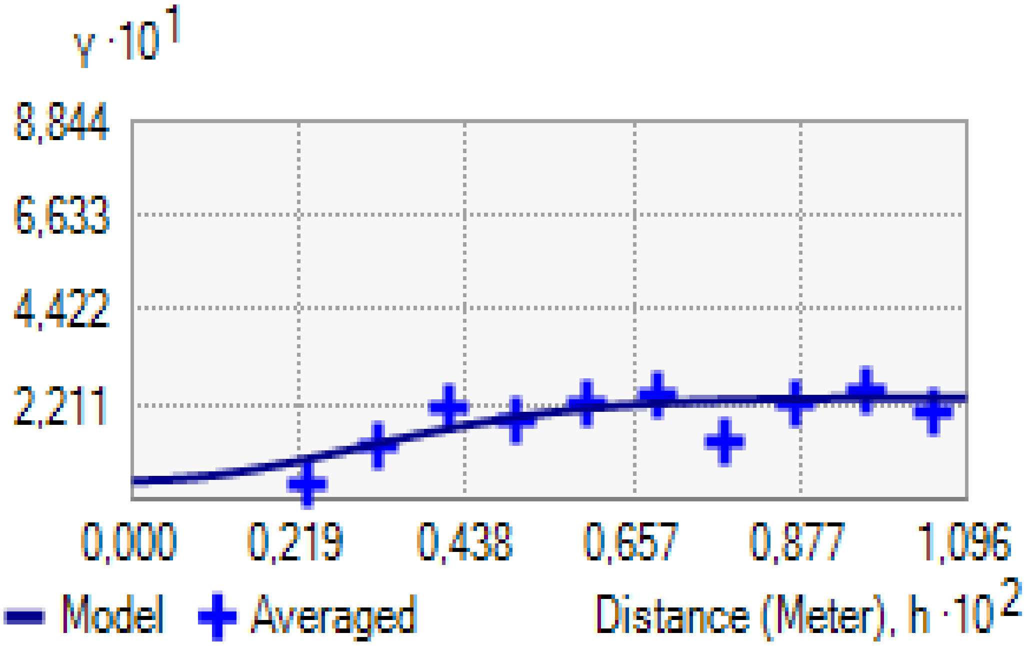
B1


γ ·10 1
1,250
0,938
0,625
0,313
0,000
0,377
0,753
1,130
1,507
1,883
Model
Averaged
Distance (Meter), h ·10 2

B2



C1

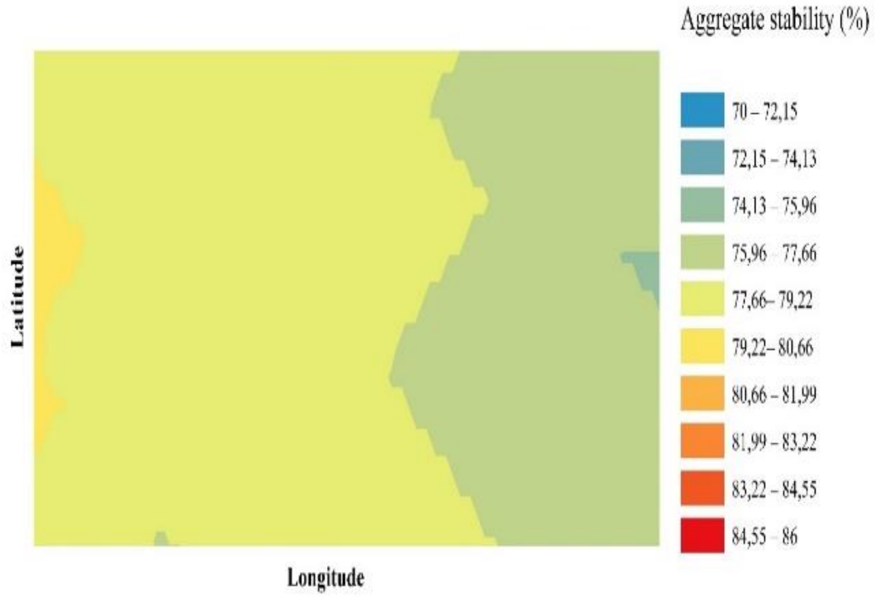


C2

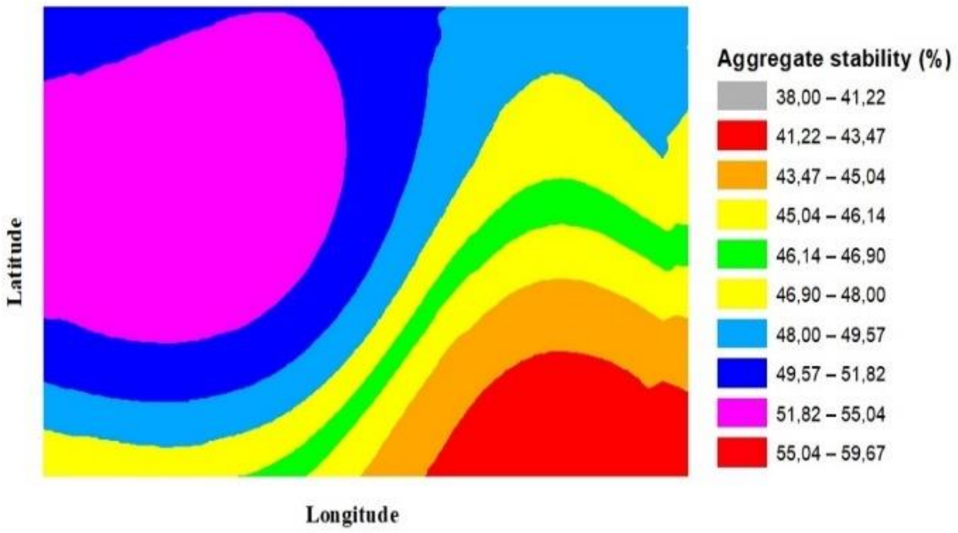
Fig. 8: Semi-variograms for soil aggregate stability and size distribution for University of Venda agricultural farm and Agricultural Research Council farm. A1 and A2 – Soil aggregate stability for University of Venda agricultural farm and Agricultural Research Council farm; B1 and B2 – microaggregates for University of Venda agricultural farm and Agricultural Research Council farm; C1 and C2 – macroaggregates for University of Venda agricultural farm and Agricultural Research Council farm.

4.3.4 Spatial variability maps for soil aggregate stability and size distribution

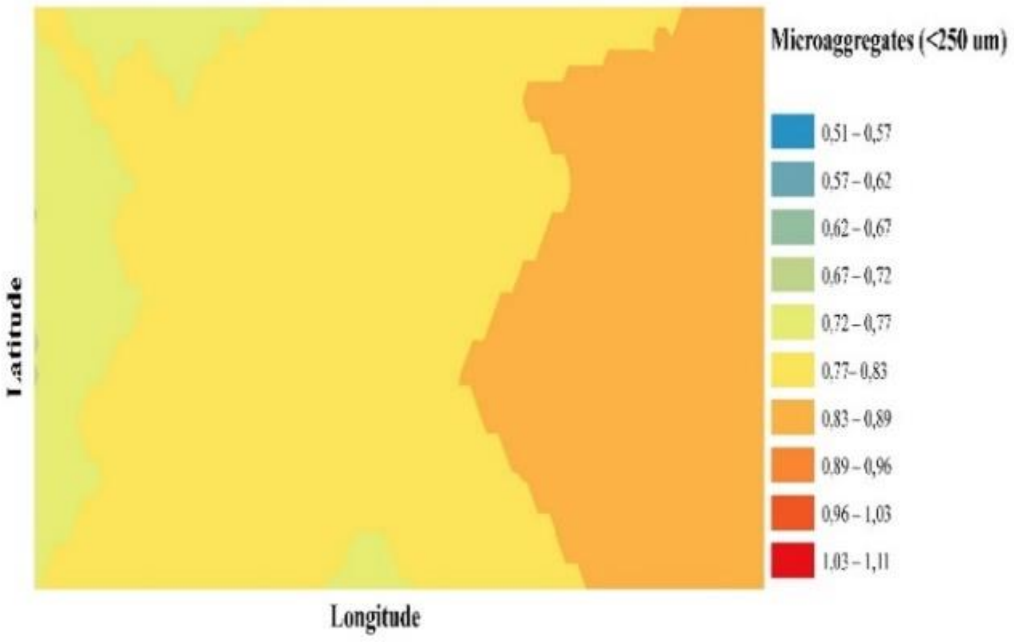
The spatial variability maps for soil aggregate stability and size distribution for University of Venda Agricultural farm and Agricultural Research Council farm are presented in Fig. 9.



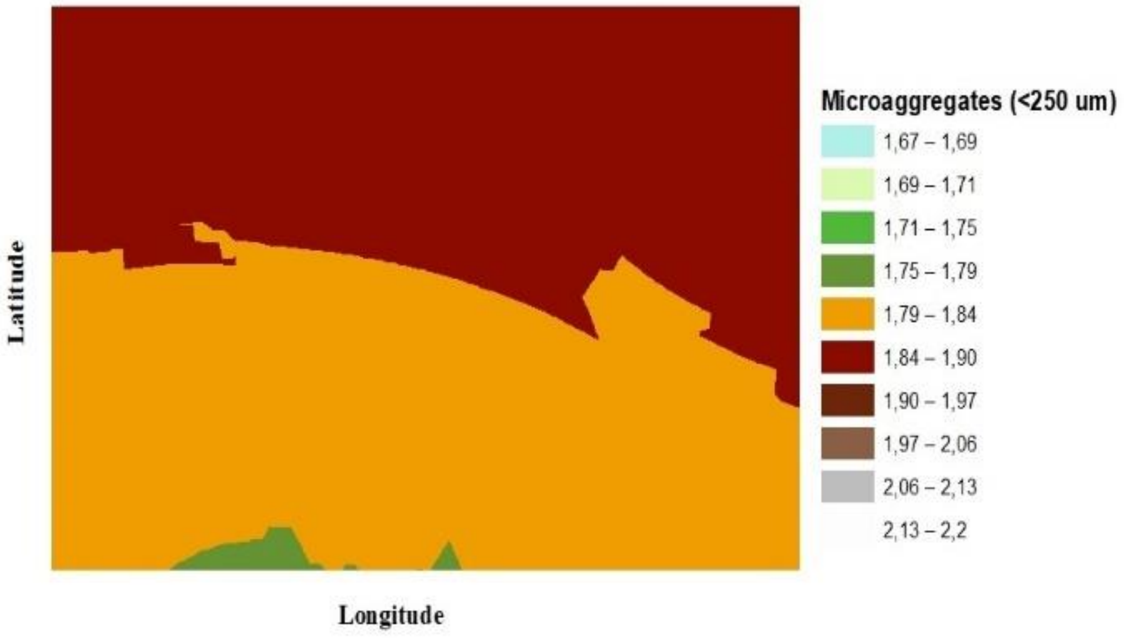
A1



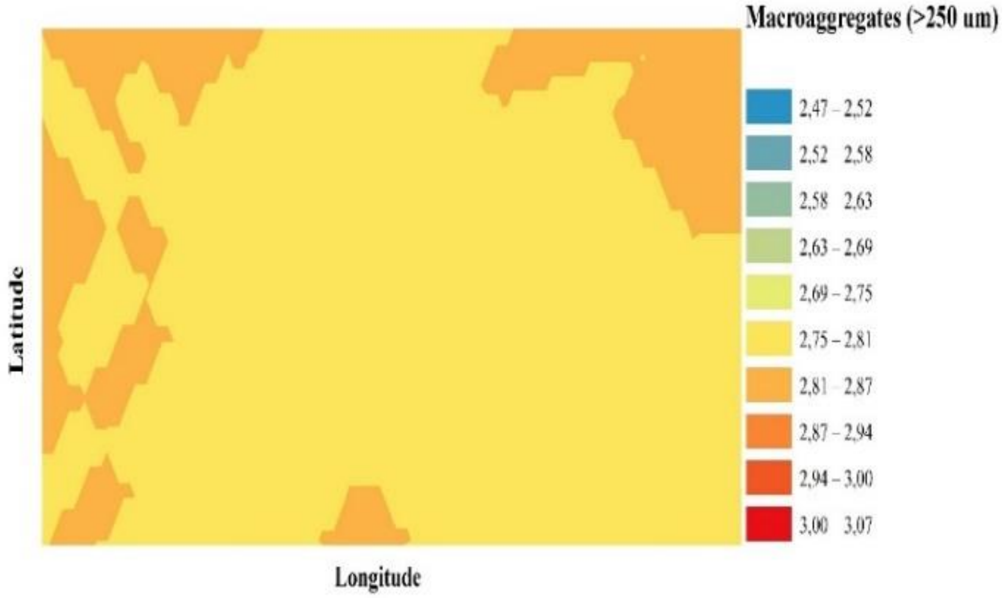
A2


Microaggregates (<250 um)
0,51 – 0,57
0,57 – 0,62
0,62 – 0,67
0,67 – 0,72
0,72 – 0,77
0,77– 0,83
0,83 – 0,89
0,89 – 0,96
0,96 – 1,03
1,03 – 1,11
Latitude
Longitude

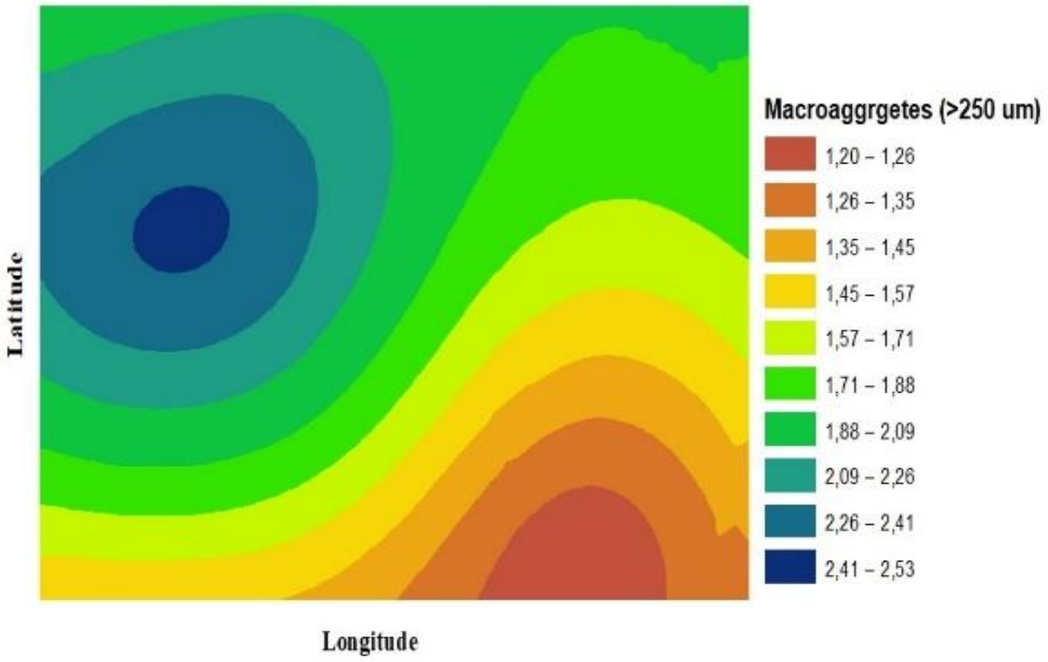
B1


Microaggregates (<250 um)
1,67 – 1,69
1,69 – 1,71
1,71 – 1,75
1,75 – 1,79
1,79 – 1,84
1,84 – 1,90
1,90 – 1,97
1,97 – 2,06
2,06 – 2,13
2,13 – 2,2
Latitude
Longitude

B2



C1



C2

Fig. 9: Spatial variability maps for soil aggregate stability and size distribution for University of Venda Agricultural farm and Agricultural Research Council farm. A1 and A2 – Soil aggregate stability for University of Venda Agricultural farm and Agricultural Research Council farm; B1 and B2 – microaggregates for site 1 and 2; C1 and C2 – macroaggregates for University of Venda Agricultural farm and Agricultural Research Council farm.

CHAPTER FIVE

5.0 Conclusion and Recommendations

The spatial variability of soil erosion, runoff, aggregates stability and size distribution, were evaluated in an approximately 1 ha field in two selected fields. Soil erosion and runoff had weak spatial variability in University of Venda Agricultural farm and Agricultural Research Council farm of the measured fields. Soil erosion and runoff exhibited close similarity of spatial distribution patterns where by low to high concentration appeared from the east to west of the landscape. Measured soil aggregate stability had weak spatial variability at University of Venda Agricultural farm whereas moderate spatial variability was observed at Agricultural Research Council farm. Similarly, weak spatial variability at University of Venda Agricultural farm and moderate variability at Agricultural Research Council farm were observed on soil microaggregates. Moreover, weak variability was observed on macroaggregates at University of Venda Agricultural farm while Agricultural Research Council farm had strong spatial distribution of soil macroaggregates. In this study, soil extrinsic and intrinsic factors especially had influenced soil erosion, runoff, aggregate stability, microaggregates and macroaggregates in both sites. Therefore, considering the complexity of the environmental and intrinsic factors, more studies are needed to investigate effects of factors such mineralogy on the spatial variability of soil erosion, runoff, aggregate stability and size distribution. Mineralogy has profound effects of soil behaviour particularly stability and erosion.

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