Effects of Slope and Land Management on Soil Hydraulic and Thermal Properties

By

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CHAPTER ONE

Introduction

Soils are the backbone of society serving as a medium for plant growth, ecosystem for macro- and microorganisms, transport for water and nutrients, and a flood-plain regulator (Dabney et al., 2001). As such, soils quietly hold tremendous weight in the world. Many civilizations of the past exploited their soils to a point of no return such as the Ancient Greeks where the effects of poor land management can still be seen today. Once fertile lands, the flatlands and hills of southern Greece to this day lack natural vegetation. Although, soil degradation and erosion is not the only factor contributing to the demise of a society, it does leave them increasingly vulnerable to hostile neighbors, internal sociopolitical disruption, and harsh winters or droughts due to low production soils (Montgomery, 2007). By not understanding the fragile and dynamic nature of soils, many societies will face the same issues as the Ancient Greeks. To compensate for this issue farming will need to increasingly take place on hilly lands with less productive soils. In this case, it is important to study the effects of slope and land management in regard to soil health.

The most influential threat to productivity and sustainability of soils is cultivation of plants and animals (agriculture). Agriculture poses the most critical threat to soils because it can lead to internal and external threats to the environment. Agriculture poses an internal threat to quality and quantity of productive soil because it makes soils more susceptible to erosion, run-off, and leaching. Therefore after, agriculture poses potential external threats to the surrounding environment including polluting ground water and toxifying natural wildlife habitats. The ramifications of agriculture in regard to sustainability threaten the carrying capacity of the world.

This study is focused in the AgroSciences, and more specifically spatial variability in soil physical, hydraulic, and thermal properties across a slope on agricultural land. Much of Middle Tennessee consists of rolling hills, where less productive soil exists. As less productive soils are available due to poor land management techniques and global climate change, the use of catenas in agriculture will become increasingly important. Studies in this area are important because they lend insight on how soil properties vary across a relatively short distance because of the influence of agriculture and slope. This information can help a land manager cope with issues such as global climate change.

An investigation of soil hydraulic and thermal properties was conducted on majority (87%) Typic Paleudalfs, with some Rhodic Paleudalfs soils classified by the USDA from the MTSU Farm Laboratory located in Murfreesboro, TN. This study features discussions of bulk density, saturated hydraulic conductivity, soil water retention, pore size distribution, heat capacity, heat conductivity, thermal diffusivity, spatial variability, range of spatial variability, and fractal characteristics. Furthermore, this study investigates three adjacent agricultural fields on a catena with various land managements: continuous cattle grazing field, rotational cattle grazing field, and corn/soybean rotation field. Triplicate samples were taken up to a depth of 18cm at five slope positions: summit, shoulder, back, foot, and toe slopes (Brady and Weil, 2008). Chapters 4 and 5 cover the baseline information about the nature of the soil’s thermal and hydraulic properties and spatial variability on a slope. Secondly, the fields are re-sampled in order to investigate the interaction effect between slope and land management. Importantly, the ladder sheds light on potential problems that may arise from the interaction between land management techniques and slope.

Land management is important to consider in conjunction with slope because it is an understudied area in the field of soil science. It is also important because less arable land is available than ever yet more food is needed to feed growing populations, so the use of catena in agriculture will become increasingly important to understand. The negative effects of land management can be amplified if the land being cultivated is sloped. For example, if no land management techniques are being utilized (e.g., cover crops) the effects of water and wind erosion can increase greatly on a catena (Haruna et al., 2018b; Vaezi et al., 2017).

This study is sorted into chapters culminating in an Undergraduate Honor's Thesis at Middle Tennessee State University. The objectives of this study are 1) to measure the soil hydraulic properties along five slope positions, 2) measure the soil thermal properties along five slope positions, 3) calculate the soil spatial variability and fractal dimensions of soil hydraulic properties along five slope positions, 4) calculate soil spatial variability and fractal dimensions of soil thermal properties along five slope positions. Chapters 3 and 4 have been submitted for peer review and are included in this thesis. Due to time constraints, the proposed chapters 5 and 6 were not included in this thesis at the time of the defense. However, they were finalized and also submitted for peer-review. A total of four scientific papers were generated from this undergraduate thesis.

CHAPTER TWO

Literature Review

The current exponential increase in human population places significant demand on natural resources, especially soils. Broadly speaking, soils provide several ecological benefits that include serving as a medium for plant growth, habitat for several macro- and micro- organism, flood and climate regulation (Dabney et al., 2001). The ability of the soil to provide these benefits is dependent on anthropogenic (e.g. cropping systems, livestock management, crop rotation, etc.) and pedogenetic (parent materials, biota, topography/landscape, etc.) factors and processes (Lacasse and Nadim, 1996). Thus, soils are not homogenous, and they tend to vary spatially and temporally as a result of the aforementioned factors (Haruna and Nkongolo, 2013). Spatial variability studies are important in predicting the influence of soil natural and anthropogenic factors on soil productivity and in characterizing specific ecosystem functions of soils (Kosmas et al., 2000). Spatial variability information leads to better management practices aimed at maintaining and improving the sustainability of crop production systems (Ozgoz, 2009). The following subsections provide a synopsis of current literature on the influence of various land management practices on soil physical and hydraulic properties.

Soil Physical, Hydraulic, and Thermal Properties

Soil physical and hydraulic properties are important factors to consider in agriculture because they can improve agricultural productivity and environmental sustainability. These properties influence plant and livestock management that can promote or inhibit agricultural productivity. Furthermore, these properties can influence the availability of water and nutrients for plants and livestock. Soil physical and hydraulic properties considered in this study are bulk density, pore size distribution, soil water retention, and saturated hydraulic conductivity.

Soil Bulk Density

Bulk density is a key physical property to investigate as it measures the overall compaction of the soil. In general, as the soil depth increases so does bulk density (Nemes et. al., 2010). Bulk density is an important soil property because of its effect on other soil hydraulic and thermal properties. For example, infiltration capacity and total porosity are derived from soil bulk density (Liu et. al., 2001).

Despite its importance, there is no universal optimum soil bulk density value, as demonstrated by Reichert et. al. (2009). In other words, soil that is compact for one type may be defined as loose for another type of soil. Soil compaction can seriously threaten agricultural productivity and environmental sustainability, thus understanding bulk density is important and different for every agricultural field.

Bulk density can be affected by a multitude of factors including the direction and gradient of a slope and grazing practices. Bulk density has been reported to exhibit less variation on South-North slopes than East-West. Furthermore, it has been reported that bulk density increases with an increase in gradient (Wang et al., 2020). As for grazing practices, the hooves of grazing animals can compact the soil, increase bulk density, reduce volumetric water content, total porosity, saturated hydraulic conductivity (K_{sat}), and water retention (Brady and Weil, 2008). Furthermore, Haruna et al. (2017) and Zaibon et al.

(2019) reported a reduction in volumetric water content, total porosity, and K_{sat}, while volumetric heat capacity increases with an increase in bulk density in a corn/soybean cropping system.

Pore Size Distribution

The size of soil pores can be characterized by their effective diameters. There are three broad sizes including macropores (> 1,000 µm), mesopores (60-1,000 µm), and micropores (10-60 µm) (Anderson et al. 1990). However, Zaibon et al. (2016) characterized soil pore sizes into macropores (> 1,000 µm), coarse mesopores (60 – 1,000 µm), fine mesopores (10 – 60 µm) and micropore (< 10 µm). Pore size distribution plays an important role in soil water retention, saturated hydraulic conductivity (K_{sat}), soil bulk density, and water infiltration. Generally, most pore sizes are directly proportional to K_{sat}, cumulative infiltration, infiltration rate, and water retained at several pressures and inversely proportional to soil bulk density (Brady and Weil, 2008).

Soil Water Retention

Soil water retention is a hydraulic property that is in large part determined by soil water content and soil water potential. Soil water retention refers to the ability of the soil to retain soil water under specific pressure represented by the soil water characteristic curve (Assouline et al., 1998). Soil water denotes a small portion of the available water in the hydraulic cycle but has a massive influence on agriculture as a whole. Soil water, among other things, is vital for plant growth, microbial activity, nutrient transport, and pedo-genesis (Western et al. 2003). Temporal and spatial variability of soil water has been described as a controlling influence within many ecosystems and especially agriculture (Haruna and Nkongolo, 2013).

Soil texture and structure are the most influential physical properties effecting soil water retention (Nimmo, 1997). When values are high, structure is said to be more influential than texture, while low values are more strongly influenced by texture. Other soil physical and hydraulic properties that influence soil water retention are bulk density, particle sizes, and organic carbon content (Williams et al., 1983).

Saturated Hydraulic Conductivity

Saturated hydraulic conductivity is another hydraulic property that is strongly determined by soil texture and structure. It is important because it controls surface runoff, leaching, and migration of pollutants to ground water (Gimenez et al., 1997). Because of these potentially negative effects of K_{sat}, it is important to consider for agricultural fields because of the increased use of inputs (i.e., pesticides) on these lands.

Slope has not been found to be statistically significant in determining K_{sat}. However, slope plays a major role in pedogenic soil formation. Therefore, it can be said that slope plays a major role in conjunction with K_{sat} when considering ecological effects including degradation (runoff, leaching, erosion, etc.) of agricultural land (Sobieriaj et al., 2002).

Soil Thermal Properties

Soil temperature and thermal properties are influenced by the amount of solar radiation hitting the soil surface. Other contributing factors to soil temperature and thermal properties include water content, texture, structure, and organic matter content. Soil temperature and thermal properties also change with depth and time of day (de Vries, 1975). Vegetation plays a huge role in the regulation of soil temperature and thermal properties. As many agricultural practices shift to more conservative tillage practices (including no-till), the influence of vegetation becomes ever more important for understanding soil thermal properties (Haruna et al., 2017), especially in regard to global climate change.

Heat transfer within soils is a dynamic process. Changes in soil temperature happen consistently without end. In general, heat is transferred through soils from hotter to cooler areas much like diffusion of water from high concentrations to low. Moreover, heat transfer is maintained by heat capacity and conductivity of different soil layers and constituents (Bristow, 2002).

Topography also has a role in soil temperature and thermal properties. Topography considers vegetation, elevation, weather, and slope. While topography plays a role in soil thermal properties, its effect is less than that of the aforementioned factors (Kumhálová et al., 2011).

Spatial Variability

Classical measurements of variability include measures of central tendency and the spread of sample values around a mean. However, since measures of central tendency do not provide information about spatial correlation between soil samples at a given location, it is rather limited in its ability to describe the variability of a sampled population (Mulla and McBratney, 2002).

Spatial variability of physical properties can occur over a range of distances, thus improved accuracy is needed to attribute physical properties to spatial variability. Spatial variability is improved through spatial correlation by implementing methods of spatial modeling (variography), spatial interpolation (krigging), and fractal characterization (Issaks and Srivastava, 1989; Cressie, 1991). This approach has been used by several authors to report spatial and fractal variability in soil physical, chemical and biological properties (Robinson and Metternicht, 2006; Fu et al., 2010; Haruna and Nkongolo, 2013; Bogunovic et al., 2014; Haruna and Nkongolo, 2014; Yang et al., 2016; Bogunovic et al., 2017).

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CHAPTER THREE

SPATIAL AND FRACTAL CHARACTERIZATION OF SOIL HYDRAULIC PROPERTIES ALONG A CATENA

Core Ideas

- Soil hydraulic properties will influence crop productivity at each slope position
- Range of spatial variability was different for hydraulic properties along a catena
- Saturated hydraulic conductivity was highest at the toe slope compared with other positions
- Spatial autocorrelation of hydraulic properties depends on intrinsic soil properties
- As the soil dries, most soil hydraulic properties tend to be less self-similar

Abbreviations: A_0, range of spatial variability; DSD, degree of spatial dependence; F_D, fractal dimensions; K_{sat}, saturated hydraulic conductivity; SOC, soil organic carbon; SWMP, soil water matric potentials

Abstract

Soil hydraulic properties influence water and nutrient availability, as well as environmental sustainability, and these properties vary across several landscape positions. This study investigated the spatial variability and fractal characterization of soil hydraulic properties across five slope positions: summit, shoulder, back, foot, and toe slopes. Triplicate soil samples (0-18 cm) were collected from each slope position from a pasture field planted to tall fescue (*Festuca arundinacea syn. schendonorus arundinaceus*). Soil bulk density (ρb), saturated hydraulic conductivity (K_{sat}), water retention at 0, -33, and -1500 kPa soil water matric potentials, soil organic carbon (SOC), and various pore sizes (macropores [>1,000 µm], mesopores [10-1,000 µm], and micropores [<10 µm]) were analyzed. Results show that SOC was 26% higher, while ρb was 10% lower at the toe slope compared with the summit. Similarly, K_{sat} values were 3, 9, 16, and 2% greater at the toe slope compared with the summit, shoulder, back, and foot slopes, respectively. Semivariogram analysis showed that the gaussian isotropic model provided be best fit ($R^2 > 0.99$) for hydraulic properties across all slope positions. The range of spatial variability of soil hydraulic properties was between 5.60 and 123.00 m at all slope positions. The fractal dimensions of soil hydraulic properties across all slope positions ranged from 0.784 – 1.966. Soil hydraulic properties were more similar at the foot and toe slopes which might favor improved crop productivity at these slope positions.

Introduction

Variability in soil properties can result from pedogenic processes and factors, even within homogenous soil layers (Lacasse and Nadim, 1996) and this can play a major role on crop productivity. Spatial variability studies are important in predicting the influence of soil natural and anthropogenic factors on soil productivity and in characterizing specific ecosystem functions of soils (Kosmas et al., 2000). Spatial variability information leads to better management practices aimed at maintaining and improving the sustainability of crop production systems (Ozgoz, 2009).

Pedonegic factors like parent materials, climate, biota, topography, and time influences the inherent characteristics of soils (Brady and Weil, 2008). These characteristics are subject to major or slight variability with a change in any one or all of the pedogenic factors. Soil property variations on the order level of classification often, but not always, occur over relatively large distances (Mulla and McBratney, 2002). However, soil properties can also vary significantly within fields and across short distances. These in-field variations are often caused by small changes in topography that influences the transport and storage of water across and within the soil profile (Mulla and McBratney, 2002).

Classical measurements of variability include measures of statistical moments and the spread of sample values around a mean. For a normal distribution, about 95% of the population will have a mean value plus or minus 2 standard deviations. However, since measures of statistical moments do not provide information about spatial correlation between soil samples at a given location, it is limited in its ability to describe the variability of a sampled population (Mulla and McBratney, 2002). Due to spatial autocorrelation

(Oliver, 1987), it is important to study the structure of a population using approaches developed in Geostatistics (Isaaks and Srivastava, 1989; Cressie, 1991). These approaches involve spatial modeling (variography) and spatial interpolation (kriging). This approach has been used by several authors to report spatial variability in soil physical, chemical, and biological properties (e.g. Robinson and Metternicht, 2006; Fu et al., 2010; Haruna and Nkongolo, 2013; Bogunovic et al., 2014; Haruna and Nkongolo, 2014; Yang et al., 2016; Bogunovic et al., 2017).

Fractals result from different sources and have been observed in nature. Fractal dimension (F_D) is a statistical index of complexity that compares how the details in a pattern changes over the scale at which it is measured (Kenneth, 2003). Thus, F_D can indicate if, at the smallest possible scale, variabilities in investigated soil properties can be determined through length, area, or volume measurements. Most phenomena with long-range variations would have a F_D tending toward 1 as the observation variance would change with lag. Variabilities in such properties will be better defined by length. Fractals can also fluctuate between 2 and 3, with the former representing an area and the latter representing a volume measurement (Burrough, 1981). As such, fractals are important tools in understanding detailed and sensitive variabilities in soils. Fractals have been used previously to characterize soil parameters (e.g. Burrough, 1981; Perfect and Kay, 1995; Eghball et al., 1997). However, fractals have not been used to describe soil hydraulic properties across a slope.

The variability of soil hydraulic properties in the field is important for environmental and agronomic purposes. In a study on the spatial variability of soil physical properties in the Loess Plateau, Wang and Shao (2011) reported that total porosity, capillary porosity and bulk density (*ρb*) had low variability, whereas, saturated hydraulic conductivity (K_{sat}) had high variability. These researchers reported that the variability in K_{sat} resulted from drastic changes in particle size distribution due to human-induced soil erosion. Further, Zhao et al. (2007) reported a noticeable spatial variability in soil physical properties that could be described by spherical and exponential isotropic models. Mzuku et al. (2005) reported similar findings. An important step toward improving crop and environmental sustainability is by understanding spatial variability of soil physical properties and this can be beneficial for precision agriculture (Haruna and Nkongolo, 2013).

Currently, there are very few studies on the variability and no study on fractal characterization of soil hydraulic properties along a catena. This information is important since it can influence the agronomic suitability of various landscape positions and can be beneficial in guiding management decisions. The objectives of the current study are to a) evaluate the spatial variability of soil hydraulic properties across several slope positions, and b) access the fractal characterization of these hydraulic properties across several slope positions. Due to differences in soil textural and mineralogical characteristics and erodibility along a catena, it is hypothesized that soil hydraulic properties will vary across the landscape.

Materials and Methods

Study Location 3.1

The experiment was conducted at the Middle Tennessee State University Farm in Murfreesboro, TN (35.891103N, -86.267280W; average elevation – 191 m above sea level), with a total area of 177 ha. The majority (87%) of soil in the study area is classified

(USDA) as a Typic Paleudalfs, with some Rhodic Paleudalfs. Five south-facing slope positions were identified on three different fields (Table 1). Each field measured 181m x 60m. Tall fescue (*Festuca arundinacea syn. schendonorus arundinaceus*) was planted on all fields and cut for hay production to be fed to dairy (Jersey [*Bos Taurus*], Holstein Friesian [*Bos taurus taurus*], and brown Swiss [*Bos Taurus*]) and beef (Angus [*Bos taurus*]) cattle. The climate of the study area is Humid Subtropical. The mean 30-year annual temperature is 14.6ºC, with the months of January (-3.7ºC) and August (32.3ºC) being the coldest and warmest months, respectively. The mean precipitation over the last three decades was 1357 mm, with the months of May (139 mm) and October (85 mm) recording the highest and lowest precipitation, respectively.

Table 3. 1: Selected soil properties at the various landscape positions at the study site.

Slope positions	Slope percent	Slope shape	Sand (%)	Silt (%)	Clay (%)
Summit	2	Linear	55.00	24.44	20.56
Shoulder slope	9	Convex	55.56	28.89	15.56
Back slope	14	Linear	53.33	29.44	17.22
Foot slope	5	Concave	58.33	25.56	16.11
Toe slope	2	Linear	55.00	23.89	21.11

Soil Sampling and Measurements 3.2

The study area was divided into a regular grid with each box within the grid approximately 12m x 12m. Triplicate soil samples (0-18 cm) were collected in a cylindrical soil core (volume = 147.5 cm^3) from each grid in each of the three adjacent fields using an uhland soil sampler (Uhland, 1950) during June 2019. The soil samples were trimmed, covered at both ends with a plastic cap and transported to the laboratory. They were refrigerated at 4 ºC until analysis.

After soil cores were removed from the refrigerator, the plastic caps were gently removed. The bottom of each soil core was secured using a cheesecloth and rubber bands. They were placed in a tub and saturated with tap water from the bottom up for about 24 hr by gently raising the water level. The electrical conductivity of the water was 0.3 dS m^{-1} at 20°C. The constant head method was used to evaluate K_{sat} (Reynolds and Elrick, 2002). If any soils had K_{sat} values less than 0.1 cm hr^{-1}, the falling head method was used. Using the same soil samples after K_{sat} measurement, the soil samples were weighed, placed on pressure plates, and equilibrated to -33 and -1500 kPa of pressure (Dane and Hopmans, 2002). After equilibration, the soil samples were weighed and volumetric water content (θ) was determined for each pressure. Pore size distributions were calculated from the soil water retention data using the capillary rise equation to estimate effective soil pore classes (Jury et al., 1991). Three classes of pore sizes were used: macropores (> 1000 μm effective diameter), mesopores (10 – 1000 μm effective diameter) and micropores (< 10 μm effective diameter) (Anderson et al., 1990).

After K_{sat}, θ, and pore sizes were measured, the soil was oven-dried at 105°C and ρb was measured using the core method (Grossman and Reinsch, 2002). The soil was then ground and passed through a 2 mm sieve. Twenty grams of the ≤2 mm aggregates were used for soil particle size analysis using the sedimentation method (Gee and Or, 2002). Another 50 g of the ≤2 mm aggregate was used for SOC determination using combustion analysis (loss on ignition at 360 ^{0}C) (Schulte and Hopkins, 1996).

Statistical and Geospatial Analysis 3.3

Statistical analysis was conducted with respect to moments at each slope position in SAS ver. 9.4 (SAS institute, 2013). Normality was tested using Anderson-Darling statistics at $p \leq 0.05$. Normality test showed that SOC, ρb, and K_{sat} were slightly skewed. In order to improve gaussian distribution, these data were log-transformed. The log-transformed data were normally distributed (Table 2). Therefore, geostatistical analysis was conducted using log-transformed data for SOC, ρb, and K_{sat} and original data for pore size distribution and water retention data. Semivariogram analysis was conducted using GS+ (Gamma Design Software, Plainwell, Michigan) ver. 9. Generally, a semivariogram is defined by the following equation (Ayoubi et al., 2007):

$$\Upsilon(h) = \frac{1}{2m(h)} \sum_{i=1}^{m(h)} [z(x_i + h) - z(x_i)]^2 \quad (1)$$

where $\Upsilon(h)$ is the experimental value of the semivariogram at a distance interval h, $m(h)$ is the sample value pairs within the distance interval h, and $z(x_i+h)$ and $z(x_i)$ are sample values at two points separated by distance h. Experimental semivariograms were evaluated by fitting them to theoretical models. Four isotropic models were encountered during the current study; linear, spherical, exponential, and Gaussian. Each of these models are defined in terms of nugget variance (C_0), sill (sum of structural variance, C_1, and nugget variance, C_0), and correlation range (A_0). Each of the four models are briefly defined below (McBratney and Webster, 1986)

Linear isotropic model

$$\Upsilon(h) = C_0 + \left[h\left(\frac{C_1}{A_0}\right)\right], \quad (2)$$

Spherical isotropic model

$$\Upsilon(h) = \begin{cases} C_0 + C_1[1.5\left({h}/{A_0}\right) - 0.5\left({h}/{A_0}\right)^3] & h \leq A_0 \\ C_0 + C_1 & h > A_o \end{cases} \quad (3)$$

Exponential isotropic model

$$\Upsilon(h) = C_0 + C_1\left[1 - \exp\left(\frac{-h}{A_0}\right)\right] \quad (4)$$

Gaussian isotropic model

$$\Upsilon(h) = C_0 + C_1\left[1 - \exp\left(\frac{-h^2}{A_0^2}\right)\right] \quad (5)$$

The degree of spatial dependence (DSD) of variable was calculated using the ratio of the nugget effect to the nugget/sill. A ratio <25% represents a strong dependence, 25-75% shows a moderate dependence, and >75% shows a weak dependence (Cambardella et al., 1994).

Results and Discussions

Descriptive Statistics 3.4

Table 3.2 shows the descriptive statistics of soil physical and hydraulic properties. Since SOC, ρb, and K_{sat} values were not normally distributed, they were log-transformed. The log-transformed data followed a gaussian distribution. The log-transformed SOC, ρb, and K_{sat} values were then used for geospatial analysis. Results show that SOC values was highest at the toe slope compared with other parts of the landscape. In fact, SOC was 26, 48, 71, and 18% higher at the toe slope compared with the summit, shoulder, back and foot slope positions, respectively (Table 3.2). This was attributed to more deposition of residues by gravity, and by the action of water and/or wind at the toe slope (Burke et al., 1999; Longbottom et al., 2014) and less microbial activity due to the anaerobic conditions prevalent at the toe slope (Garcia-Pausas et al., 2007). The lowest SOC occurred on the shoulder and back slopes, probably due to the slope steepness, higher erodibility at these positions, and greater microbial breakdown from a more favorable soil condition (Huang et al., 2015; Xu et al., 2015). Conversely, Garcia-Pausas et al. (2007) reported the lowest SOC at the summit due to temperature limitation of net primary productivity. One reason for this contrast could be the slope aspect. In the current study, the south-facing slopes are perpendicular to the sunlight, while the slopes in the study by Garcia-Pausas et al. (2007) were not.

Soil *ρb* values was highest at the back slope compared to other landscape positions. Precisely, *ρb* was 5, 2, 6, and 14% higher on the back slope compared with the summit, shoulder, foot and toe slopes, respectively (Table 3.2). This was in concert with SOC results and could be due to the susceptibility of the backslope to runoff, less moisture (which accelerates the breakdown of SOC), and less biopores. Due to the deposition of SOC usually noticed at the foot and toe slopes, *ρb* was lowest at these slope positions. Oztas et al. (2003) reported similar findings. In contrast, Khan et al. (2013) reported lower *ρb* at the summit compared to other landscape position due to soil textural differences. It was reported that the summit had significantly higher sand content and lower clay content compared to other landscape positions (Khan et al., 2013). This contrast could also have resulted from differences in SOC content. The current study had 175, 50, and 39% higher SOC at the summit, back, and foot slopes, respectively, as compared to the study conducted by Khan et al. (2013).

Table 3. 2: **Descriptive statistics of soil physical and hydraulic properties at the study site**

		SOC	ρb	Macropores	Mesopores	Micropores	Total Pores	K_{Sat}	0 kPa	-33 kPa	-1500 kPa
		g kg^{-1}	g cm^{-3}	(>1000 µm)	(10-1000 µm)	(<10 µm)		(mm/hr)	(m^3/m^3)	(m^3/m^3)	(m^3/m^3)
Summit											
Mean	Original	18.734	1.236	0.027	0.165	0.014	0.207	118.856	0.376	0.184	0.135
	Log-transformed	1.252	0.091					2.008			
Median	Original	18.023	1.248	0.016	0.136	0.013	0.195	124.750	0.372	0.188	0.150
	Log-transformed	1.256	0.096					2.096			
Std. Dev	Original	5.800	0.089	0.021	0.112	0.004	0.121	55.884	0.102	0.107	0.085
	Log-transformed	0.135	0.032					0.261			
CV	Original	0.310	0.072	0.767	0.679	0.287	0.588	0.470	0.270	0.583	0.632
	Log-transformed	0.108	0.348					0.130			
Shoulder Slope											
Mean	Original	15.891	1.269	0.096	0.143	0.015	0.254	108.109	0.368	0.128	0.103
	Log-transformed	1.187	0.102					1.903			
Median	Original	14.826	1.288	0.053	0.131	0.011	0.231	114.055	0.332	0.127	0.109
	Log-transformed	1.171	0.110					2.057			
Std. Dev	Original	4.102	0.094	0.093	0.043	0.008	0.091	61.172	0.108	0.072	0.065
	Log-transformed	0.111	0.032					0.403			
CV	Original	0.258	0.074	0.962	0.300	0.550	0.358	0.566	0.295	0.558	0.628
	Log-transformed	0.093	0.317					0.212			
Back Slope											
Mean	Original	13.760	1.300	0.031	0.138	0.019	0.188	93.721	0.314	0.145	0.092
	Log-transformed	1.117	0.113					1.780			
Median	Original	12.791	1.334	0.031	0.154	0.022	0.188	101.460	0.329	0.132	0.071
	Log-transformed	1.107	0.125					2.006			
Std. Dev	Original	4.570	0.083	0.021	0.047	0.011	0.049	62.299	0.102	0.074	0.073
	Log-transformed	0.136	0.028					0.489			
CV	Original	0.332	0.064	0.661	0.341	0.555	0.263	0.665	0.323	0.507	0.789
	Log-transformed	0.122	0.248					0.275			
Foot Slope											
Mean	Original	19.897	1.229	0.039	0.184	0.017	0.241	122.931	0.393	0.169	0.129

		Log-transformed	1.277	0.088					2.023			
	Median	Original	18.023	1.235	0.041	0.183	0.017	0.238	130.040	0.402	0.162	0.114
		Log-transformed	1.256	0.092					2.114			
	Std. Dev	Original	6.350	0.100	0.017	0.020	0.003	0.031	57.809	0.055	0.043	0.047
		Log-transformed	0.135	0.035					0.262			
	CV	Original	0.319	0.082	0.444	0.107	0.152	0.127	0.470	0.140	0.255	0.366
		Log-transformed	0.106	0.399					0.130			
Toe Slope												
	Mean	Original	23.579	1.137	0.038	0.176	0.014	0.228	134.268	0.440	0.226	0.198
		Log-transformed	1.353	0.055					2.070			
	Median	Original	21.512	1.125	0.037	0.183	0.014	0.236	155.980	0.497	0.237	0.210
		Log-transformed	1.333	0.051					2.193			
	Std. Dev	Original	7.095	0.084	0.011	0.060	0.006	0.063	59.345	0.140	0.104	0.100
		Log-transformed	0.129	0.032					0.242			
	CV	Original	0.301	0.074	0.298	0.341	0.456	0.275	0.442	0.319	0.458	0.505
		Log-transformed	0.095	0.582					0.117			

Table 3.2: SOC: soil organic carbon; *ρb*: soil bulk density; K_{sat}: saturated hydraulic conductivity; Std. Dev: standard deviation; CV: coefficient of variation

Pore size distribution results showed that soil macropore values was 256, 210, 146, and 153% higher at the shoulder slope compared with the summit, back, foot and toe slopes, respectively. Mesopore values were 12, 29, 33, and 5% higher at the foot slope compared with the summit, shoulder, back, and toe slopes, respectively. Micropore values were 36, 27, 12 and 36% higher at the back slope compared with the summit, shoulder, foot and toe slopes, respectively. Total pore values were 39, 13, 53, and 20% higher at the toe slope compared with the summit, shoulder, back, and foot slopes, respectively. This agreed with SOC and ρb results. Soil organic carbon has been reported to improve soil aggregation (Chen et al., 2017; Novelli et al., 2017; Ojeda et al., 2018), and increase soil porosity (Rawls et al., 2004; Dexter et al., 2008; Haruna et al., 2017). Thus, the higher total pore values at the toe slope in the current study is attributed to higher SOC values at the toe slope position. This can lead to improved water infiltration at this slope position (Haruna et al., 2018a). Khormali et al. (2009) reported similar findings.

Saturated hydraulic conductivity values were 3, 9, 16, and 2% greater at the toe slope compared with the summit, shoulder, back, and foot slopes, respectively. The K_{sat} of the soil is influenced by SOC, ρb, and total pore spaces (Haruna et al., 2018b). Higher SOC and total pores, as well as lower ρb values is presumed to be responsible for higher K_{sat} at the toe slopes (Singh et al., 2020; Centeno et al., 2020). Furthermore, increased deposition and saturation at the toe slope (Garcia-Pausas et al., 2007) suggests that the soils may remain saturated for a long enough time to allow macropore flow under gravitational potential.

Soil water retention results show that, at 0, -33, and -1500 kPa soil water matric potential (SWMP), θ was highest at the toe slope position compared with other positions

(Table 3.2). This mirrored the results observed for *ρb.* This corresponds to the fact that changes in θ often result from higher porosity (Ahuja et al., 1998). Similar to the results of the current study, Cameron (1978) found that the slope of the water retention curve decreased with an increase in soil bulk density. The lowest slope for the water retention data in the current study occurred at the back slope, which also had the highest *ρb*. Furthermore, the differences in water retention among various slope positions were higher at lower SWMP, suggesting that, compared to the summit, shoulder, and back slopes, the foot and toe slope positions are better able to retain soil moisture longer.

Spatial Variability of Soil Physical and Hydraulic Properties 3.5

Figs. 3.1-3 show the spatial variability of soil physical and hydraulic properties across all 5 slope positions. Soil physical and hydraulic properties were spatially distributed across all slope positions. To fully understand the nature of the variability, semivariogram analysis was conducted for each soil property at each slope position. Table 3.3 shows spatial variability of soil physical and hydraulic properties across 5 slope positions. Semivariogram model fit was determined from the coefficient of determination (R^2) values. At all slope positions, the linear isotropic model provided the best fit for SOC (R^2 = 0.67, backslope) while the gaussian isotropic model provided the best fit for *ρb* (R^2 = 0.99, backslope). The best model fit for the various pore sizes, total pores, and K_{sat} across all slope positions was the gaussian isotropic model (R^2= 0.77-0.94). At 0 and -33 kPa SWMP, the gaussian isotropic model also provided the best model fit across all slope positions (R^2 =0.77-0.79), while at -1500 kPa SWMP, the best model fit across all slope positions was the linear isotropic (R^2=0.74) (Table 3). Other models that provided various levels of fit for soil physical and hydraulic properties include the spherical and exponential isotropic models.

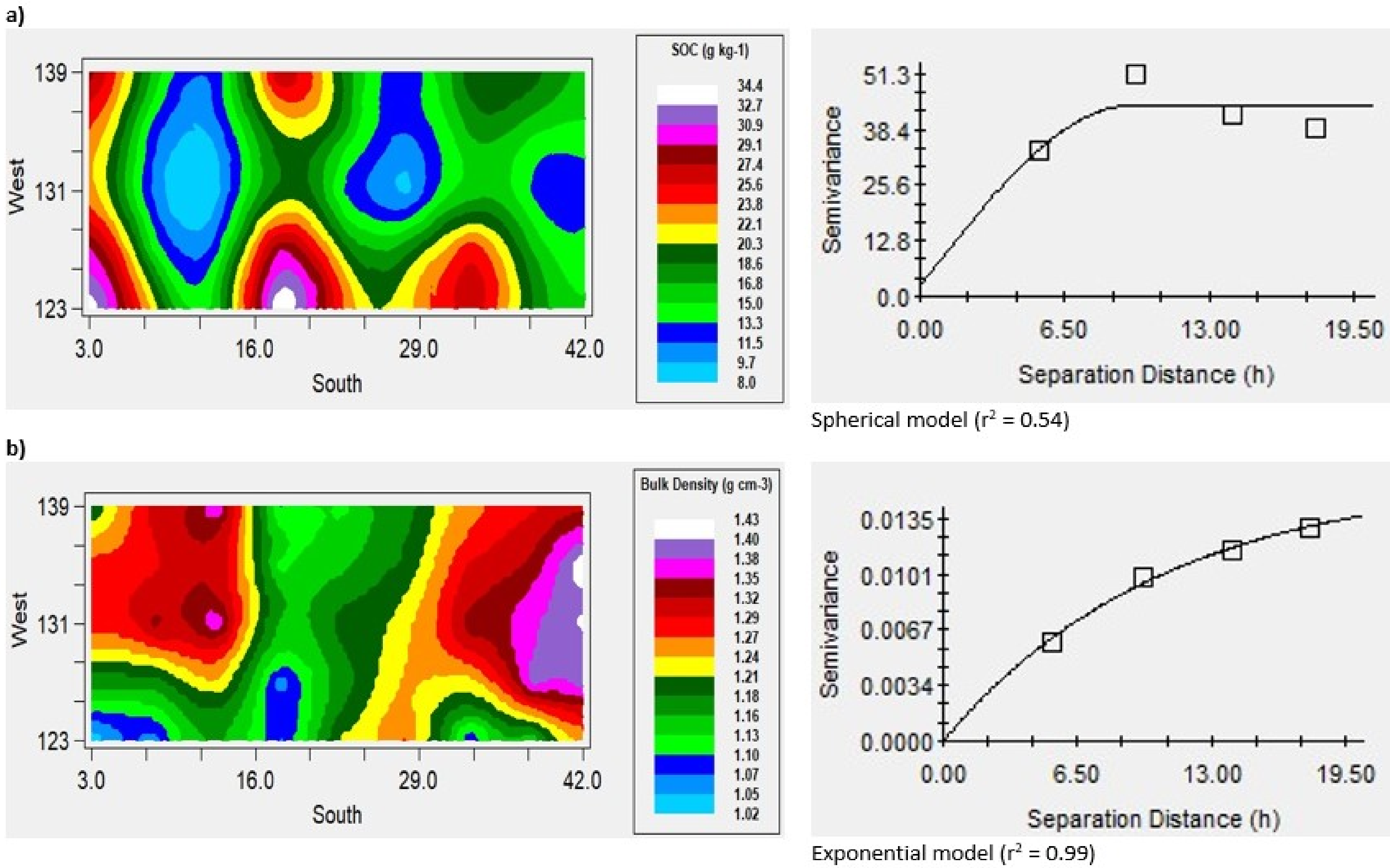

Figure 3. 1: **Spatial variability and model representation of a) soil organic matter (SOC), and b) bulk density across all five slope positions.**

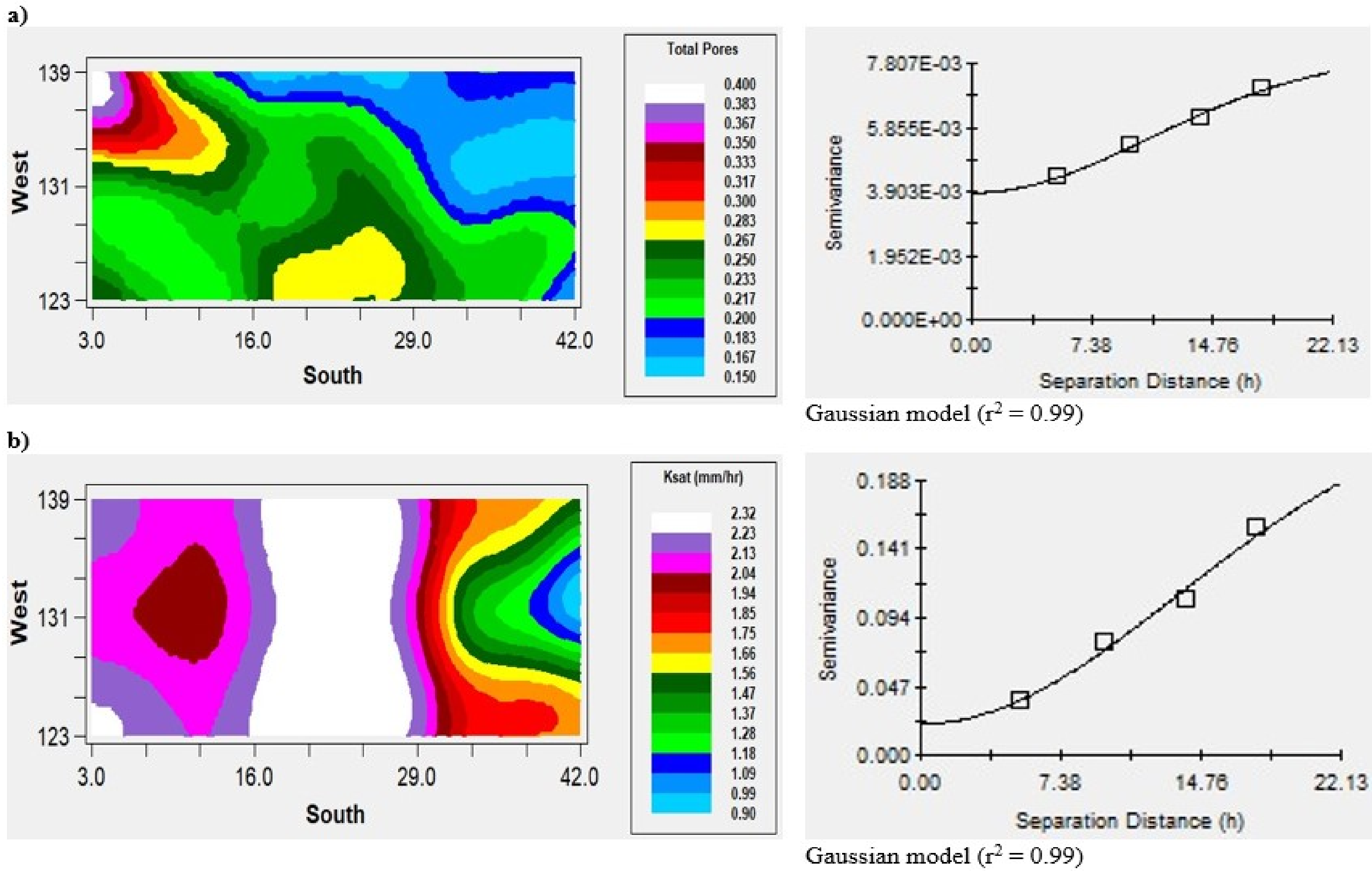

Figure 3. 2: **Spatial variability and model representation of a) total pores, and b) saturated hydraulic conductivity (K_{sat}), across all five slope positions.**

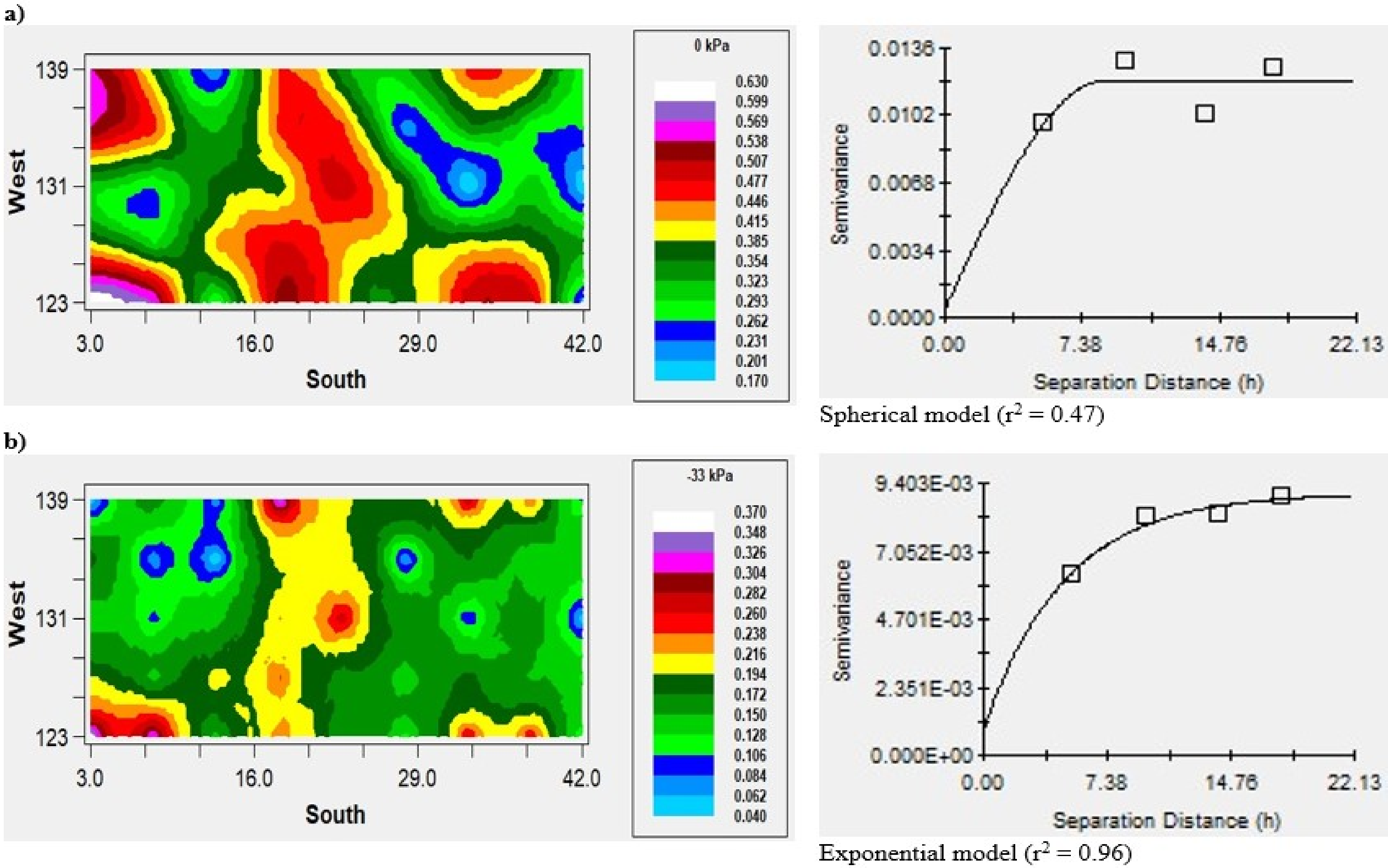

Figure 3. 3: **Spatial variability and model representation of volumetric water content at a) 0 kPa, and b) -33 kPa soil water matric potentials, across all five slope positions.**

The spherical and gaussian isotropic models indicate an inverse relationship between spatial autocorrelation and distance (Burrough, 1986; McBratney and Webster, 1986). Results from the current study suggest that, among other factors, the similarity between soil hydraulic properties may be dependent on θ (θ at -1500 kPa SWMP followed a liner model). In order to avoid similarities between soil hydraulic properties and capture enough variability for future studies, the distance between soil samples should be further apart under wet soil conditions (between saturation and -33 kPa soil water matric potential). The drier the soil, the closer the distance between soil samples.

Theoretically, the semivariogram value is zero at zero separation distance (no lag). However, the semivariogram often exhibits a nugget effect at an infinitesimally small lag, which is some value greater than zero. This discontinuity at the beginning of many semivariogram graphs (nugget effect) can be attributed to spatial sources of variation at smaller distances than the sampling interval, measurement errors, or both. To eliminate measurement errors, replicate samples were collected. Thus, the nugget effect in the current study can be attributed to spatial sources of variation at distances smaller than the sampling interval. The nugget effect of soil hydraulic properties was highest for micropores (summit, shoulder, foot, and toe slopes), mesopores, and K_{sat} (back slope). This higher microvariability suggest that micropores (at the summit, shoulder, foot and toe slopes), mesopores, and K_{sat} (at the back slope) had the highest spatial variability at smaller distances. Results also show that macropores, at all slope positions, had less variability at smaller distances (lower nugget effect). Macropores drain under gravity during wet soil conditions (between saturation and -33 kPa) (Leeds-Harrison et al., 1986; Smits et al., 2010; Zaibon et al., 2016). Mesopores and micropore drain out at lower pressures. As such, as the soil dries out, microvariability increases. This is in concert with results on spatial variability. Soil organic carbon had the highest variability in spatial dependence of all properties measured at all slope positions (Table 3.3) probably due to its dynamic nature.

The range of the spatial variability (A_0) of the semivariogram represents the distance between correlated measurements and can be utilized as an effective evaluation criterion of sampling designs and mapping soil properties (Haruna and Nkongolo, 2013). The A_0 of macropores, mesopores, and micropores at all slope positions was between 9.29 – 54.61m, 5.60 – 123.00m, and 19.00 – 71.01m, respectively. At all slope positions, total pores had a A_0 that ranged between 8.15 – 123.00m while that of K_{sat} ranged between 48.19 – 71.01m. Between saturation and -1500 kPa SWMP, A_0 of θ at all slope positions ranged between 2.90 – 123.00m (Table 3.3). In general, the differences in A_0 for soil water retention was smaller at -1500 kPa, which was in concert with results on spatial variability and nugget effect. The A_0 for SOC was 19.00m while that of ρb was between 19.00 and 71.01m at all slope positions. The A_0 of macropores was higher at the toe slope, compared with other slope positions. Similarly, the A_0 of K_{sat} was lower at the shoulder and back slopes compared to other slope positions, suggesting more variability in K_{sat} at these positions. For statistical analysis, an understanding of the A_0 for various soil physical and hydraulic properties can enable the construction of independent accurate datasets for similar slope positions in future soil sampling design. This can be used as a tool in the designation of areas for resampling, and to design future field experiments that avoid spatial dependence. Kerry and Oliver (2004) suggested that sample interval be less than half the A_0. As such, for future studies on the characterization of spatial dependency of soil physical and hydraulic properties in a similar area, it is recommended that these soil properties be sampled at distances smaller than half the A_0 found in the current study.

Table 3. 3: **Spatial and fractal characteristics of soil physical and hydraulic properties at the study site. Please note that log-transformed data was used for SOC, *ρb*, and K_{sat}**

	SOC	*ρb*	Macropores	Mesopores	Micropores	Total Pores	K_{Sat}	0 kPa	-33 kPa	-1500 kPa
Summit										
Model	Linear	Exponential	Linear	Gaussian	Linear	Linear	Gaussian	Linear	Linear	Exponential
Nugget	0.016	0.000	0.000	0.000	0.011	0.008	0.001	0.008	0.011	0.000
Sill	0.016	0.004	0.000	0.010	0.011	0.008	1.125	0.008	0.011	0.006
Nugget/Sill	0.000	0.951	0.000	0.999	0.000	0.000	0.999	0.000	0.000	0.998
A_0 (m)	19.000	67.020	19.000	9.093	19.000	19.000	71.014	19.000	19.000	2.900
R^2	0.64	0.92	0.39	0.12	0.28	0.63	0.91	0.63	0.28	0.13
DSD (%)	0.016	0.000	0.000	0.000	0.011	0.008	0.001	0.008	0.011	0.000
F_D	0.954	1.637	1.494	1.932	1.890	1.299	1.098	1.299	1.890	1.975
Shoulder slope										
Model	Linear	Gaussian	Spherical	Spherical	Linear	Exponential	Gaussian	Exponential	Linear	Linear
Nugget	0.011	0.000	0.000	0.000	0.006	0.006	0.001	0.006	0.006	0.004
Sill	0.011	0.020	0.005	0.002	0.006	0.028	2.011	0.028	0.006	0.004
Nugget/Sill	0.000	1.00	0.946	0.923	0.000	0.801	1.000	0.801	0.000	0.000
A_0 (m)	19.000	67.013	9.290	5.600	19.000	123.000	56.032	123.000	19.000	19.000
R^2	0.59	0.88	0.15	0.10	0.55	0.28	0.84	0.28	0.55	0.74
DSD (%)	0.011	0.000	0.000	0.000	0.006	0.007	0.001	0.007	0.006	0.004
F_D	1.369	1.232	1.781	1.867	1.691	1.873	1.006	1.873	1.691	1.463
Back Slope										
Model	Linear	Gaussian	Linear	Exponential	Gaussian	Gaussian	Gaussian	Gaussian	Gaussian	Gaussian
Nugget	0.015	0.000	0.000	0.001	0.000	0.000	0.001	0.000	0.000	0.000
Sill	0.015	0.005	0.000	0.006	0.144	0.200	2.011	0.200	0.144	0.140
Nugget/Sill	0.000	0.920	0.000	0.820	0.999	1.000	1.000	1.000	0.999	0.999
A_0 (m)	19.000	44.687	19.000	123.000	71.010	63.550	48.186	63.550	71.010	71.010
R^2	0.67	0.99	0.50	0.55	0.79	0.77	0.88	0.77	0.79	0.70
DSD (%)	0.015	0.000	0.000	0.001	0.000	0.000	0.001	0.000	0.000	0.000

F_D	0.784	1.485	1.471	1.812	1.369	1.445	1.055	1.445	1.369	1.510
Foot Slope										
Model	Linear	Gaussian	Spherical	Spherical	Linear	Spherical	Gaussian	Spherical	Linear	Linear
Nugget	0.017	0.000	0.000	0.000	0.002	0.000	0.001	0.000	0.002	0.002
Sill	0.017	0.010	0.000	0.001	0.002	0.004	1.126	0.004	0.002	0.002
Nugget/Sill	0.000	0.977	0.852	0.799	0.000	0.929	0.999	0.929	0.000	0.000
A_0 (m)	19.000	71.014	15.620	13.930	19.000	8.150	71.014	8.150	19.000	19.000
R^2	0.51	0.88	0.33	0.44	0.49	0.36	0.91	0.36	0.49	0.42
DSD (%)	0.017	0.000	0.000	0.000	0.002	0.000	0.001	0.000	0.002	0.002
F_D	1.567	1.508	1.831	1.855	1.694	1.966	1.112	1.966	1.694	1.762
Toe Slope										
Model	Linear	Linear	Gaussian	Gaussian	Linear	Linear	Gaussian	Linear	Linear	Linear
Nugget	0.017	0.001	0.000	0.000	0.008	0.018	0.001	0.018	0.008	0.008
Sill	0.017	0.0001	0.001	0.078	0.008	0.018	0.858	0.018	0.008	0.008
Nugget/Sill	0.000	0.000	0.888	0.999	0.000	0.000	0.999	0.000	0.000	0.000
A_0 (m)	19.00	19.000	54.610	71.010	19.000	19.000	71.014	19.000	19.000	19.000
R^2	0.36	0.58	0.92	0.78	0.49	0.13	0.94	0.13	0.49	0.58
DSD (%)	45.296	0.005	0.000	0.000	0.008	0.018	0.001	0.018	0.008	0.008
F_D	1.699	0.999	1.611	1.465	1.190	1.853	1.150	1.853	1.190	1.295

Table 3.3: SOC: soil organic carbon; ρb: soil bulk density; K_{sat}: saturated hydraulic conductivity; A_0: range of spatial autocorrelation; F_D: fractal dimensions,

The degree of spatial dependence (DSD) provides information on the relationship between the spatial proximity among observed units and the numeric similarity among their values (Lee, 2017). Results of the current study indicated strong spatial dependence (DSD ≤ 25%) for soil hydraulic properties and *ρb* across all slope positions. Except at the toe slope position, SOC exhibited strong spatial dependence across the investigated landscape positions (Table 3.3). The strong spatial dependence may be controlled by inherent variations in soil characteristics such as texture and mineralogy, while extrinsic factors such as soil management may control the variability of the weak spatially dependent parameters (Mulla and McBratney, 2002). The strong DSD of soil hydraulic properties and *ρb* in the current study suggests, regardless of slope position, their spatial autocorrelation depends more on intrinsic soil properties rather than extrinsic properties. As such, sampling design for future studies on soil hydraulic properties and *ρb* on similar landscape positions should be based on textural and mineralogical characteristics rather than soil management. For SOC, intrinsic properties only play a role at the steepest parts of the landscape. Therefore, to avoid redundancy and to capture variability, SOC sampling decisions at the toe slopes should be based on current land management.

Fractal Characterization of Soil Physical and Hydraulic Properties 3.6

In the current study, the surface F_D was determined from the slope of the semivariance vs. distance. Table 3 shows the F_D of soil properties across several landscape positions and matric potentials. The F_D of SOC ranged between 0.784 – 1.699, while that of *ρb* ranged from 0.999 – 1.637. The F_D of soil macropores, mesopores, and micropores at all slope positions ranged from 1.471 – 1.831, 1.465 – 1.932, and 1.190 – 1.890, respectively. Total pores at all slope positions had a F_D that ranged from 1.299 – 1.966.

Therefore, besides the summit and back slope positions (which can be better described by a length measurement), the fractals of soil porosity are better described by an area measurement on an infinitesimal scale. Since the F_D of K_{sat} ranged from 1.006 – 1.150, length measurements will provide the best description of K_{sat} at all slope positions. In general, soil water retention results show that the range of F_D was wider at lower soil matric potentials (Table 3.3). The F_D values in the current study are significantly higher than the ranges reported for row crops (1.060 – 1.290) by previous researchers (e.g. Rachman et al., 2005; Udawatta and Anderson, 2008; Udawatta et al., 2008; Kim et al., 2010). This shows the significant influence of root type and morphology on pore size dimension Thus, at all slope positions, the fractals of various soil pore sizes are better described by an area measurement.

The wider range of F_D at -1500 kPa soil water matric potential in the current study suggests that as the soil dries, soil properties influenced by θ tend to be less self-similar. This is in concert with results on the A_0. As such, in a more variable climate with increasing probability of longer periods of drought, current results suggest that soil properties across these slope positions will become more erratic, which indicates great disorder and antipersistence in the spatial structure.

Correlations Between Soil Parameters 3.7

Table 3.4 shows Pearson's correlations of soil physical and hydraulic properties. Log-transformed data was used for SOC, ρb, and K_{sat}. Results show significant ($p \leq 0.05$) correlation between measured soil properties. Soil organic carbon was positively correlated with mesopores (r = 0.42; p = 0.0036), K_{sat} (r = 0.29; p = 0.0504), θ at 0 kPa (r = 0.60; p < 0.0001), θ at -33 kPa (r = 0.51; p = 0.0003), θ at -1500 kPa (r = 0.49; p = 0.0007), and negatively correlated with ρb. Other significant positive correlation included macropores with total pores, mesopores with total pores, K_{sat} and θ at saturation, total pores with K_{sat} and θ at saturation, and K_{sat} with θ at saturation. Soil ρb was negatively correlated with K_{sat} and θ at 0, -33, and -1500 kPa SWMP (Table 3.4).

Table 3. 4: **Pearson correlation coefficient for soil physical and hydraulic properties at the study site. Please note that log-transformed data was used for SOC, *ρb*, and K_{sat}**

	SOC	*ρb*	Macropores	Mesopores	Micropores	Total pores	K_{sat}	0 kPa	-33 kPa	-1500 kPa
SOC	1.0000									
ρb	-0.6030 <0.0001	1.0000								
Macropores	0.1324 0.3860	0.0687 0.6538	1.0000							
Mesopores	0.4250 0.0036	-0.2129 0.1603	-0.0834 0.5862	1.0000						
Micropores	-0.1954 0.1984	0.0699 0.6480	-0.2887 0.0544	0.2893 0.0539	1.0000					
Total Pores	0.2477 0.1009	-0.1251 0.4131	0.5355 0.0002	0.7930 <0.0001	0.1443 0.3443	1.0000				
K_{sat}	0.2892 0.0504	-0.6504 <0.0001	0.0967 0.5273	0.3511 0.0180	0.2443 0.1059	0.3704 0.0123	1.0000			
0 kPa	0.6018 <0.0001	-0.6275 <0.0001	0.2123 0.1614	0.5775 <0.0001	0.0884 0.5638	0.6150 <0.0001	0.4759 0.0010	1.0000		
-33 kPa	0.5142 0.0003	-0.6679 <0.0001	-0.2429 0.1079	0.0280 0.8550	0.0605 0.6928	-0.1246 0.4149	0.2805 0.0620	0.7033 <0.0001	1.0000	
-1500 kPa	0.4851 0.0007	-0.5979 <0.0001	-0.1812 0.2335	0.1314 0.3897	0.0766 0.6169	0.0004 0.9978	0.1735 0.2545	0.7145 <0.0001	0.9019 <0.0001	1.0000

SOC: soil organic carbon; *ρb*: soil bulk density; K_{sat}: saturated hydraulic conductivity.

The significant positive correlation between SOC and other soil properties suggest that improvements in soil structure produced by SOC is beneficial for both saturated and unsaturated flow. Moncada et al. (2014), and Singh et al. (2019) reported similar findings. Conversely, Haruna et al. (2018b) reported no significant influence of SOC on water drainage beyond -33 kPa SWMP. Possible reasons for these differences could be the level of SOC in both studies and differences in management practices between both studies. The average SOC in the study of Haruna et al. (2018b) was 16 g kg^{-1}, while that in the current study is about 18 g kg^{-1}. Furthermore, the field in Haruna et al. (2018b) included some no-till and moldboard plow with corn/soybean rotation and cereal rye (*Secale cereale*) cover crop during winter months. The perennial roots of the fescue grass and little mechanical disturbance in the current study suggest that aggregates formed may last longer and be more effective at lower matric potentials. The negative correlation between SOC and ρb suggest that increased soil compaction can destroy soil structure and the stability of aggregates, which will have a negative influence on water movement under saturated and unsaturated conditions.

Macropores and mesopores were significantly related, directly, to total pores, suggesting that the effectiveness of soil porosity is significantly dependent on the proportion of macro- and mesopores. Since these pores are larger in diameter, they will facilitate higher rates of water transmission when the pores are filled with water or higher rates of gas transmission when the pores are filled with air. Kim et al. (2010) reported similar findings. The positive correlation between mesopores, K_{sat} and θ at 0 kPa SWMP suggests that this pore size is important for water movement under saturated conditions. Haruna et al. (2018b) reported similar findings. As expected, K_{sat} was positively correlated to θ at saturation because water movement at this matric potential occurs under saturated conditions influenced by gravitational potential.

Correlation results show that foot and toe slope positions may be more suitable for crop production due to higher SOC, θ, K_{sat}, and porosity. Due to the slope aspect, shoulder and back slopes will receive more solar radiation, increasing θ evaporation and depletion of SOC. Results from the current study also show less variability in soil physical and hydraulic properties at the foot and toe slopes. Further studies on the interaction effects between slope positions and various land management practices on soil hydraulic and thermal properties will provide more useful information on crop productivity in a rapidly changing global climate.

Conclusions

A study was conducted on a Paleudalf to evaluate the spatial and fractal characterization of soil physical and hydraulic properties across five slope positions: summit, shoulder, back, foot and toe slopes. Soil organic carbon was significantly higher at the foot and toe slope positions due to higher depositions and longer anaerobic conditions at these slope positions. Semivariogram analysis showed that the gaussian isotropic model provided the best fit for soil hydraulic properties across all slope positions. The A_0 of K_{sat} was lower at the shoulder and back slopes compared to other slope positions, suggesting more variability in K_{sat} at these positions. Soil hydraulic properties and ρb exhibited strong DSD, suggesting that their spatial autocorrelation is more dependent on soil texture and mineralogy as compared with soil management. Due to higher SOC, θ, K_{sat}, and porosity at the foot and toe slopes, these positions may lead to improved crop productivity as compared to other slope positions.

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CHAPTER FOUR

SOIL THERMAL PROPERTIES: SPATIAL VARIABILITY ALONG A CATENA

<u>Core Ideas</u>

- Spatial variability of soil thermal properties along a catena was analyzed
- Soil organic carbon was 71% higher at the toeslope compared with the backslope
- At 0 kPa, the volumetric heat capacity was spatially least variable at the toeslope
- At -33 kPa, thermal properties exhibited long-range variability at the summit

<u>Abbreviations</u>: A_0: range of spatial variability; C: Volumetric heat capacity; D: Thermal diffusivity; F_D: Fractal dimensions; SOC: Soil organic carbon; SWMP: Soil water matric potentials; ρb: bulk density; λ: Thermal conductivity.

Abstract

Characterizing the spatial and fractal variability of soil thermal properties is an important component of precision agriculture in a more variable global climate. The current study characterized the spatial and fractal variability of soil thermal properties across five slope positions: summit, shoulderslope, backslope, footslope, and toeslope. Triplicate soil samples (0-18 cm) were collected from each slope position from a pasture field planted to tall fescue (*Festuca arundinacea syn. sychedonorus arundinaceus*). Soil thermal properties (thermal conductivity [λ], volumetric heat capacity [C], thermal diffusivity [D]), volumetric water content (θ) (at 0 and -33 kPa soil water matric potentials), bulk density (ρb), and soil organic carbon (SOC) were determined. Results show that SOC was 26% higher, while ρb was 10% lower at the toe slope compared with the summit due to depositional forces. At saturation, C was 5% higher at the toe slope compared with the summit which is consistent with SOC and θ results. Semivariogram analysis showed that at saturation, the spherical isotropic models provided the best fit, respectively, for soil thermal properties (R^2 = 0.95). At saturation, the fractal dimensions of soil thermal properties across all slope positions ranged from 1.232 – 1.920, suggesting that, at the smallest possible scale, the variabilities in soil thermal properties can be described through length and area measurements. The foot and toe slope positions exhibited the least variability in soil thermal properties, suggesting that these slope positions may be more suitable for crop productivity as compared to other slope positions. Future studies should explore the influence of a combination of slope position and various cropping systems on soil thermal properties.

Introduction

Depositional and post-depositional processes can cause variability in soil properties, even within homogenous soil layers (Lacasse and Nadim, 1996) and this can play a major role on crop productivity. Spatial variability studies are important in predicting the influence of soil natural and anthropogenic factors on soil properties and in characterizing specific ecosystem functions of soils (Kosmas et al., 2000). Spatial variability information leads to better management practices aimed at maintaining and improving the sustainability of crop production systems (Ozgoz, 2009).

Classical measurements of variability include measures of central tendency and the spread of sample values around a mean. However, since measures of central tendency do not provide information about spatial correlation between soil samples at a given location, it is rather limited in its ability to describe the variability of a sampled population (Mulla and McBratney, 2002). Due to spatial autocorrelation (Oliver, 1987), it is important to study the structure of a population using approaches developed in Geostatistics (Isaaks and Srivastava, 1989; Cressie, 1991). These approaches involve spatial modeling (variography), spatial interpolation (kriging) and fractal characterization. This approach has been used by several authors to report spatial and fractal variability in soil physical, chemical and biological properties (e.g. Robinson and Metternicht, 2006; Fu et al., 2010; Haruna and Nkongolo, 2013; Bogunovic et al., 2014; Haruna and Nkongolo, 2014; Yang et al., 2016; Bogunovic et al., 2017).

Fractals arise from different sources and have been observed in nature. Fractal dimension (F_D) is a statistical index of complexity that compares how the details in a pattern changes over the scale at which it is measured (Kenneth, 2003). Thus, F_D can indicate if, at the smallest possible scale, variabilities in investigated soil properties can be determined through length, area, or volume measurements. Most phenomena with long-range variations would have a F_D tending toward 1 as the observation variance would change with lag. Variabilities in such properties will be better defined by length. Fractals can also fluctuate between 2 and 3, with the former representing an area and the latter representing a volume measurement (Burrough, 1981). As such, fractals are important tools in understanding minute and sensitive variabilities in soils. Fractals have been used previously to characterize soil parameters (e.g. Burrough, 1981; Perfect and Kay, 1995; Eghball et al., 1997). However, fractals have not been used to describe soil thermal properties.

Soil thermal properties influence water movement and storage, nutrient availability, seed gemination, and microbial activity (Shukla, 2014). Soil thermal properties can be evaluated through measurement of thermal conductivity (λ), volumetric heat capacity (*C*), and thermal diffusivity (*D*). These properties can be influenced by anthropogenic processes like tillage and cover cropping (Haruna et al., 2017). Several researchers have reported the influence of texture and management practices on soil thermal properties (e.g. Abu-Hamdeh and Reeder, 2000; Ochsner et al., 2001; Adhikari et al., 2014; Haruna et al., 2017; Sindelar et al., 2019; Haruna, 2019). Additionally, soil thermal properties can be influenced by pedogenic factors like topography and landscape position; factors that influence water content, soil organic carbon (SOC), and soil depth (Mulla and McBratney, 2002).

Currently, there are no studies on the variability and fractal characterization of soil thermal properties along a catena. This information is important since it can influence management decisions at various landscape positions in a changing global climate. Due to differences in soil properties that influence thermal properties (Bristow, 2002), soil thermal properties are hypothesized to vary across the catena. The objectives of the current study are to a) evaluate the spatial variability of soil thermal properties across several slope positions, and b) access the fractal characterization of soil thermal properties across several slope positions.

Materials and Methods

Site Description 4.1

The experiment was conducted at the Middle Tennessee State University Farm in Murfreesboro, TN (35.891103N, -86.267280W; average elevation – 191 m above sea level), with a total area of 177 ha. The majority (87%) of soil in the study area is classified (USDA) as a Typic Paleudalfs, with some Rhodic Paleudalfs (Soil Survey Staff). Five south-facing slope positions were identified on three different fields (Table 4.1; Fig. 4.1). Each field measured 181m x 60m. Tall fescue (*Festuca arundinacea syn. sychedonorus arundinaceus*) was planted on all fields and cut for hay production. The climate of the study area is Humid Subtropical. The mean 30-year annual temperature is 14.6 ºC, with the months of January (-3.7 ºC) and August (32.3 ºC) being the coldest and warmest months, respectively. The mean precipitation over the last three decades was 1357 mm, with the months of May (139 mm) and October (85 mm) recording the highest and lowest precipitation, respectively.

Table 4. 1: Selected soil properties and slope components at the various landscape positions at the study site.

Slope positions	Slope percent	Slope shape	Sand (%)	Silt (%)	Clay (%)
Summit	2	Linear	55.00	24.44	20.56
Shoulderslope	9	Convex	55.56	28.89	15.56
Backslope	14	Linear	53.33	29.44	17.22
Footslope	5	Concave	58.33	25.56	16.11
Toeslope	2	Linear	55.00	23.89	21.11

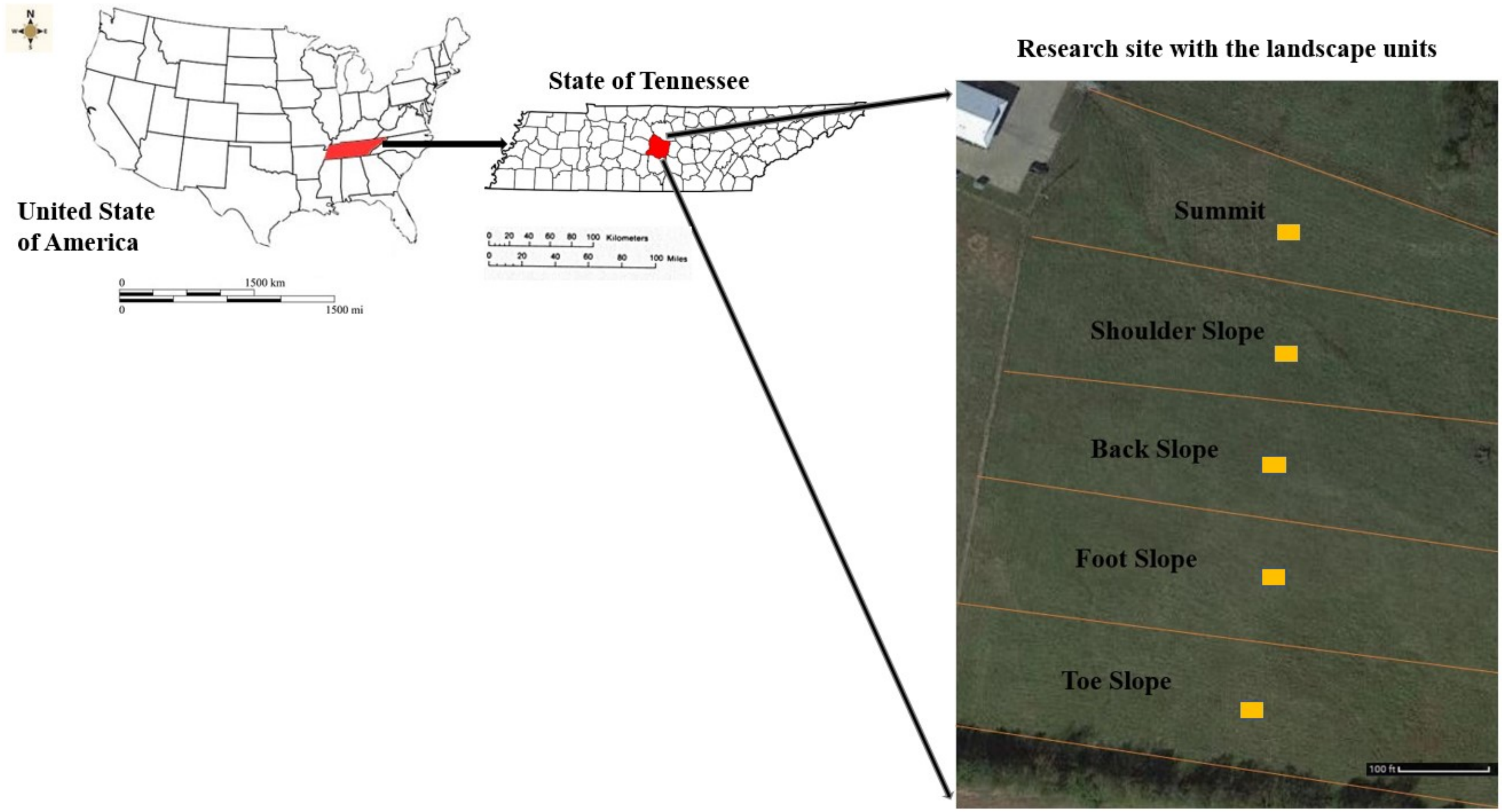


Figure 4. 1: **Study site in Tennessee and the slope positions. Plese note that the yellow boxes represent the approximate sample location at each landscape position.**

Soil Sampling and Analysis 4.2

The study area was divided into a regular grid with each box within the grid approximately 12m x 12m. Soil samples were collected from each grid. A trimble Geo 7 x GPS with an accuracy of 10 cm was used to record the georeferenced coordinates. Soil samples were collected at 0-18 cm depth because the fields were under perennial grass management with very little human influence. Triplicate soil samples were collected from the three adjacent fields in a cylindrical soil core (volume = 508.9 cm^3) using an uhland soil sampler (Uhland, 1950) during June 2019 (3 samples x 3 different fields x 5 slope positions = 45 samples). The soil samples were trimmed, covered at both ends with a plastic cap and transported to the laboratory. They were refrigerated at 4 ºC until analysis.

After soil cores were removed from the refrigerator, the plastic caps were gently removed. The bottom of each soil core was secured using a cheesecloth and rubber bands. They were placed in a tub and saturated with tap water from the bottom up for about 24 hr by gently raising the water level. The electrical conductivity of the water was 0.3 dS m^{-1} at 20 ºC. After saturation, the soil samples were weighed, placed on pressure plates, and equilibrated to -33 kPa of pressure (Dane and Hopmans, 2002). After equilibration, the soil samples were weighed and volumetric water content (θ) was determined for that pressure.

Soil thermal properties were determined using a KD2 (Decagon Devices, Pullman, WA) dual-probe heat-pulse sensor. This sensor has been used by several researchers in the past (e.g. Dahiya, et al., 2007; Adhikari et al., 2014; Haruna et al., 2017). Before measurement, the probe was calibrated and its accuracy was tested using performance verification standards. Soil thermal properties were measured at each pressure (0 and -33 kPa) by vertically inserting the probe into the soil. To avoid errors in measurement due to improper soil contact, the probe was inserted into new areas during each measurement and core walls were avoided.

After θ and thermal properties were measured, the soil was oven-dried at 105 ºC and bulk density (*ρb*) was measured using the core method (Grossman and Reinsch, 2002). The soil was then ground and passed through a 2 mm sieve. Twenty grams of the ≤2 mm aggregates were used for soil particle size analysis using the sedimentation method (Gee and Or, 2002). Another 50 g of the ≤2 mm aggregate was used for SOC determination using combustion analysis (loss on ignition at 360 ºC) (Schulte and Hopkins, 1996).

Statistical and Geospatial Analysis 4.3

Statistical analysis was conducted with respect to moments at each slope position in SAS ver. 9.4 (SAS institute, 2013). Normality was tested using Anderson-Darling statistics at $p \leq 0.05$. The data was normally distributed. To fully understand the nature of the variability, semivariogram analysis was conducted for each soil property at each slope position. Semivariogram analysis was conducted using GS+ (Gamma Design Software, Plainwell, Michigan) ver. 9. Generally, a semivariogram is defined by the following equation (Ayoubi et al., 2007):

$$\Upsilon(h) = \frac{1}{2m(h)} \sum_{i=1}^{m(h)} [z(x_i + h) - z(x_i)]^2 \qquad (1)$$

where $\Upsilon(h)$ is the experimental value of the semivariogram at a distance interval h, $m(h)$ is the sample value pairs within the distance interval h, and $z(x_i+h)$ and $z(x_i)$ are sample values at two points separated by distance h. Semivariograms were evaluated by fitting them to theoretical models. Four isotropic models provided the best fit for the data in the current study; linear, spherical, exponential, and Gaussian. Each of these models are defined in terms of nugget variance (C_0), sill (sum of structural variance, C_1, and nugget variance, C_0), and correlation range (A_0). Each of the four models are briefly defined below (McBratney and Webster, 1986);

Linear isotropic model

$$\Upsilon(h) = C_0 + \left[h\left(\frac{C_1}{A_0}\right)\right] \quad (2)$$

Spherical isotropic model

$$\Upsilon(h) = \begin{cases} C_0 + C_1[1.5\left({}^{h}/_{A_0}\right) - 0.5\left({}^{h}/_{A_0}\right)^3] & h \le A_0 \\ C_0 + C_1 & h > A_o \end{cases} \quad (3)$$

Exponential isotropic model

$$\Upsilon(h) = C_0 + C_1\left[1 - \exp\left(\frac{-h}{A_0}\right)\right] \quad (4)$$

Gaussian isotropic model

$$\Upsilon(h) = C_0 + C_1\left[1 - \exp\left(\frac{-h^2}{A_0^2}\right)\right] \quad (5)$$

From the errors (difference between observed and predicted data) produced from each model, the Root Mean Square Error (RMSE) was calculated according to the following formula;

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{n}\{Z(Xi) - \hat{Z}(Xi)\}^2} \quad (6)$$

where N is the number of samples, *Z(Xi)* is the observed value, and *Ẑ(Xi)* is the predicted value. The F_D was determined from the slope of the semivariance vs. distance. Also, the degree of spatial dependence (DSD = C_0 / (C_0 + C_1) x 100)) of each variable was determined. A ratio <25% represents a strong dependence, 25-75% shows a moderate dependence, and >75% shows a weak dependence (Cambardella et al., 1994).

Results

Descriptive statistics 4.4

The descriptive statistics of soil physical and thermal properties are shown in Table 4.2. Results show that SOC values was highest at the foot and toe slopes compared with other slope positions. In fact, SOC was 71% higher at the toeslope compared with the backslope, which had the lowest SOC. Soil *ρb* values was highest at the backslope compared to other landscape positions. Precisely, *ρb* was 5 and 14% higher on the backslope compared with the summit and toeslope, respectively. At 0 kPa SWMP, λ values at the backslope was 4, 6, 6, and 25% higher compared with the values at the summit, shoulderslope, footslope and toeslope, respectively. Thermal conductivity values were reduced with a decrease in SWMP from 0 to -33 kPa at the summit, shoulderslope and backslope. At 0 kPa SWMP, *C* values at the toeslope was 5, 15, 16, and 4% higher compared with values at the summit, shoulder, back, and foot slopes, respectively. In general, *C* values decreased with a decrease in SWMP from 0 to -33 kPa. Thermal diffusivity values followed a similar trend with λ at 0 and -33 kPa SWMP. At 0 kPa SWMP, θ at the toeslope was 16, 19, 42 and 13% higher compared with values at the summit, shoulderslope, backslope, and footslope, respectively. At each slope position, θ values were significantly lower at -33 kPa SWMP compared with 0 kPa SWMP.

Correlations Between Soil Parameters 4.5

Table 4.3 shows Pearson's correlations of soil thermal and physical properties at 0 kPa SWMP. Results show significant ($p \leq 0.05$) correlation between measured soil properties. Soil λ was positively correlated with *ρb* ($r = 0.58$; $p < 0.0001$) and negatively correlated with SOC and θ. Volumetric heat capacity was positively correlated with θ ($r = 0.54$; $p = 0.0001$) and SOC ($r = 0.78$; $p \leq 0.0001$) and negatively correlated with *ρb*. Thermal diffusivity was positively correlated with *ρb* ($r = 0.72$; $p < 0.0001$) and negatively correlated with θ and SOC.

Table 4. 2: Pearson Correlation Coefficient for soil physical and thermal properties at 0 kPa soil water matric potential

	Λ	*C*	*D*	θ	SOC	*ρb*
λ	1.0000					
C	-0.69 (<0.0001)	1.0000				
D	0.94 (<0.0001)	-0.89 (<0.0001)	1.0000			
θ	-0.43 (0.0033)	0.54 (0.0001)	-0.51 (0.0003)	1.0000		
SOC	-0.65 (<0.0001)	0.78 (<0.0001)	-0.75 (<0.0001)	0.63 (<0.0001)	1.0000	
ρb	0.58 (<0.0001)	-0.76 (<0.0001)	0.72 (<0.0001)	-0.62 (<0.0001)	-0.62 (<0.0001)	1.0000

λ: thermal conductivity; *C*: volumetric heat capacity; *D*: thermal diffusivity; θ: volumetric water content; SOC: soil organic carbon; *ρb*: soil bulk density.

Spatial Variability of Soil Physical and Thermal Properties 4.6

Soil physical and thermal properties were spatially distributed across five slope positions (Figs. 4.2-4; Table 4.4). Root Mean Square Error for the isotropic models used in the current study show a good prediction. Semivariogram model fit was determined from the coefficient of determination (R^2) values. The best model fit for thermal properties at the summit, shoulderslope, and backslope was a linear isotropic model (R^2>0.86). At the footslope, the gaussian isotropic model (R^2=0.89) provided the best fit, while the spherical isotropic model provided the best fit (R^2=0.95) at the toeslope position. The best model fit for soil thermal properties across all slope positions at 0 kPa SWMP was the spherical isotropic model (R^2= 0.95), while at -33kPa SWMP the best model fit across all slope positions was linear isotropic (R^2=0.95). At 0 kPa, soil thermal properties mainly responded to the gaussian isotropic model at all slope positions. At -33 kPa the linear isotropic model was the most common at all slope positions. At 0 kPa the spherical isotropic model provided the best fit for *λ* (R^2 = 0.95, toeslope), while at -33 kPa the linear isotropic model provided the best fit for λ (R^2=0.95, toeslope). At 0 kPa the gaussian isotropic model provided the best fit for *C* (R^2 = 0.94, toeslope) while at -33 kPa the linear isotropic model provided the best fit for *C* (R^2 = 0.91, shoulderslope). At 0 kPa the gaussian isotropic model provided the best fit for *D* (R^2 = 0.94 toeslope), while at -33 kPa the linear model provided the best fit for *D* (R^2 = 0.78). At 0 and -33 kPa SWMP, the gaussian isotropic model provided the best fit for θ (R^2 = 0.77 and 0.79, respectively, back slope). At all slope positions, the linear isotropic model provided the best fit for SOC (R^2 = 0.68, backslope), while the linear isotropic model provided the best fit for *ρb* (R^2 = 0.98, backslope).

The range of the spatial variability (A_0) of the semivariogram is the interval between correlated measurements and can be utilized as an effective evaluation criterion of sampling designs and mapping soil properties. At 0 kPa, the A_0 of soil thermal properties was between 6.4 and 104.9m at all slope positions. At -33 kPa SWMP, the A_0 of soil thermal properties was between 4.9 and 123m at all slope positions. At 0 and -33 kPa SWMP, the A_0 for θ at all slope positions was between 8.2 and 123m and between 19 and 71m, respectively. The A_0 for SOC was 19m, while that of *ρb* was between 19 and 71m at all slope positions.

The DSD provides information on the relationship between the spatial proximity among observed units and the numeric similarity among their values (Lee, 2017). Results of the current study indicated strong spatial dependence (DSD $\leq$ 25%) for thermal properties, *ρb*, and θ across all slope positions and matric potentials. Except for the summit, foot and toe slopes, SOC exhibited strong spatial dependence across the investigated landscape positions (Table 4.4). The strong spatial dependence may be controlled by inherent variations in soil characteristics such as texture and mineralogy, while extrinsic factors such as soil management may control the variability of the weak spatially dependent parameters.

Table 4. 3: Descriptive statistics of soil physical and thermal properties at 0 kPa and -33 kPa soil water matric potentials

Slope position		SOC	*ρb*	0 kPa Λ	0 kPa *C*	0 kPa *D*	0 kPa θ	-33 kPa λ	-33 kPa *C*	-33 kPa *D*	-33 kPa θ
		g kg^{-1}	g cm^{-3}	W m^{-1} k^{-1}	MJ m^{-3} K^{-1}	mm^{2} s^{-1}	cm^{3} cm^{-3}	W m^{-1} k^{-1}	MJ m^{-3} K^{-1}	mm^{2} s^{-1}	cm^{3} cm^{-3}
Summit											
	Mean	18.73	1.24	1.38	2.95	0.47	0.38	1.26	2.77	0.46	0.26
	Median	18.02	1.25	1.31	2.92	0.45	0.37	1.31	2.78	0.45	0.21
	Std. Dev	5.80	0.09	0.14	0.13	0.06	0.10	0.18	0.29	0.07	0.24
	CV	0.31	0.07	0.10	0.04	0.14	0.27	0.14	0.11	0.14	0.93
Shoulderslope											
	Mean	15.89	1.27	1.35	2.70	0.50	0.37	1.25	2.72	0.47	0.13
	Median	14.83	1.29	1.30	2.66	0.47	0.33	1.22	2.72	0.44	0.13
	Std. Dev	4.10	0.09	0.14	0.16	0.08	0.11	0.12	0.32	0.06	0.07
	CV	0.26	0.07	0.11	0.06	0.16	0.29	0.10	0.12	0.13	0.56
Backslope											
	Mean	13.76	1.30	1.43	2.62	0.55	0.31	1.37	2.68	0.53	0.15
	Median	12.79	1.33	1.42	2.62	0.56	0.33	1.34	2.78	0.47	0.13
	Std. Dev	4.57	0.08	0.11	0.13	0.06	0.10	0.26	0.36	0.15	0.07
	CV	0.33	0.06	0.07	0.05	0.11	0.32	0.19	0.14	0.28	0.51
Footslope											
	Mean	19.90	1.23	1.35	2.97	0.46	0.39	1.43	2.80	0.52	0.17
	Median	18.02	1.23	1.38	2.98	0.46	0.40	1.43	2.72	0.57	0.16
	Std. Dev	6.35	0.10	0.17	0.18	0.08	0.05	0.24	0.25	0.12	0.04
	CV	0.32	0.08	0.13	0.06	0.18	0.14	0.17	0.09	0.23	0.26
Toeslope											

Mean	23.58	1.14	1.25	3.10	0.41	0.44	1.30	2.82	0.47	0.23
Median	21.51	1.13	1.21	3.13	0.40	0.50	1.33	2.83	0.47	0.24
Std. Dev	7.09	0.08	0.14	0.17	0.07	0.14	0.17	0.24	0.09	0.10
CV	0.30	0.07	0.12	0.05	0.16	0.32	0.13	0.09	0.18	0.46

Table 4.3: SOC: soil organic carbon; ρb: soil bulk density; λ: thermal conductivity; *C*: volumetric heat capacity; *D*: thermal diffusivity; θ: volumetric water content; Std. Dev: standard deviation; CV: coefficient of variation

Fractal Characterization of Soil Thermal and Physical Properties 4.7

Table 4.4 shows the F_D of soil properties across several landscape positions and matric potentials. The F_D of SOC ranged between 0.743 – 1.699, while that of *ρb* ranged from 0.999 – 1.618. At 0 kPa, the F_D of θ ranged from 1.299 – 1.966, while at -33 kPa SWMP, it ranged from 1.190 – 1.694. At saturation on the summit, the dimensions of the *λ* and *D* fractals were easier to describe with a length than an area, while that of *C* was easier to describe with an area. At all other slope positions (at 0 kPa SWMP), the F_D of soil thermal properties resembles more of an area than a length. On the summit at -33 kPa SWMP, the F_D of soil thermal properties generally approach a length. On the shoulder and back slopes (-33 kPa SWMP) the dimensions of the *λ* and *D* fractals approach an area, while that of *C* approaches a length. At the foot slope (- 33 kPa SWMP), the F_D of soil thermal properties were easier to describe with an area. At the toe slope (-33 kPa SWMP), the F_D of *λ* and *C* were similar to an, area while that of *D* was similar to a length. In general, at saturation, F_D for soil thermal properties at all slope positions ranged from 1.232 – 1.920, while at -33 kPa SWMP ranged from 0.120 – 1.936.

Discussions

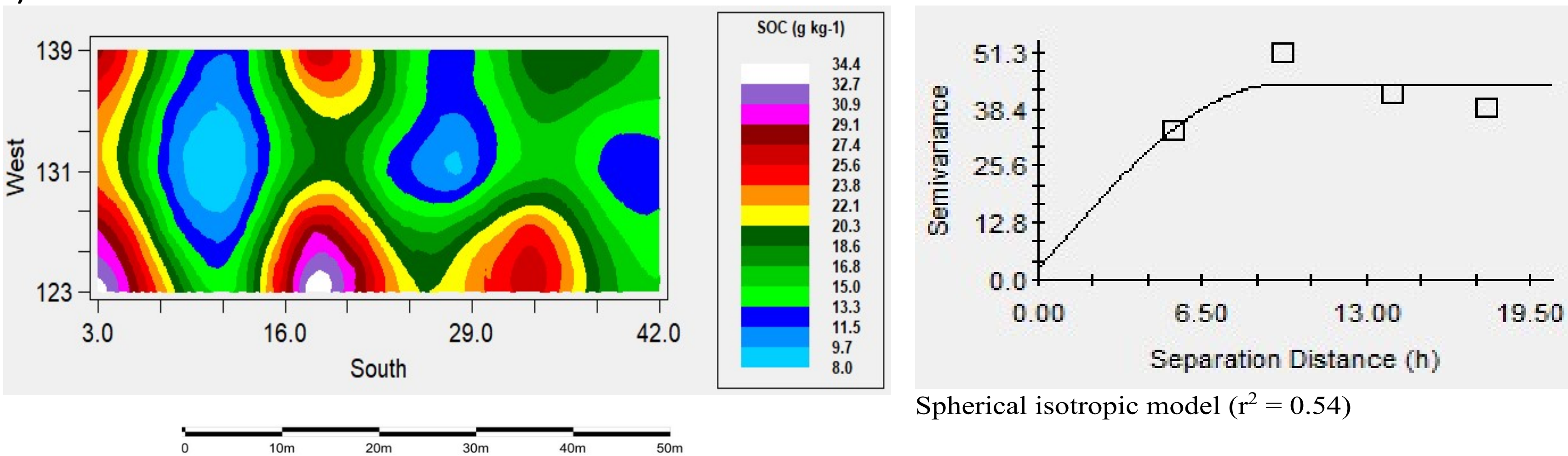
Descriptive statistics 4.8

The higher SOC at the toeslope was attributed to more deposition of residues by gravity, and by the action of water and/or wind at the back slope (Burke et al., 1999; Longbottom et al., 2014) and less microbial activity due to the anaerobic conditions prevalent at the toe slope (Garcia-Pausas et al., 2007). The lowest SOC values at the backslope was probably due to the slope steepness, higher erodibility at these positions, and greater microbial breakdown from a more favorable soil condition. Conversely, Garcia-Pausas et al. (2007) reported the lowest SOC at the summit due to temperature limitation of net primary productivity. One reason for this contrast could be the slope aspect. In the current study, the south-facing slopes are perpendicular to the sunlight, while the slopes in the study by Garcia-Pausas et al. (2007) were not. Soil ρb was consistent with SOC results and could be due to the susceptibility of the backslope to runoff, less moisture (which accelerates the breakdown of SOC), and less biopores. Due to the deposition of SOC usually noticed at the foot and toe slopes, ρb was lowest at these slope positions. Oztas et al. (2003) reported similar findings. In contrast, Khan et al. (2013) reported lower ρb on the summit compared to other landscape position due to soil textural differences. The summit had significantly higher sand content and lower clay content compared to other landscape positions (Khan et al., 2013). This contrast could also have resulted from differences in SOC content. The current study had 175, 50, and 39% higher SOC at the summit, back, and foot slopes, respectively, as compared to the study conducted by Khan et al. (2013).

The lower λ values at 0 kPa SWMP was attributed to higher ρb at the backslope position. Since the λ of soil minerals is higher than the λ of other soil constituents (Bristow, 2002), as ρb increases, the contact between soil particles also increase, thus increasing λ. As such, landscape positions with higher ρb values had higher λ values (Table 4.2). Additionally, the λ of SOC (0.25 W m^{-1} K^{-1}) is lower than that of clays (2.9 W m^{-1} K^{-1}) (Bristow, 2002) and SOC can lower ρb, therefore higher SOC can reduce λ. Water drainage between 0 and -33 kPa SWMP was probably responsible for the difference in λ values between these pressures at the summit, shoulderslope and backslope. As the water drains out of the soil pores, it is quickly replaced by air. Since the λ of air (0.025 W m^{-1} K^{-1}) is lower than that of water (0.57 W m^{-1} K^{-1}), a decrease in water content reduced λ from 0 to -33 kPa SWMP.

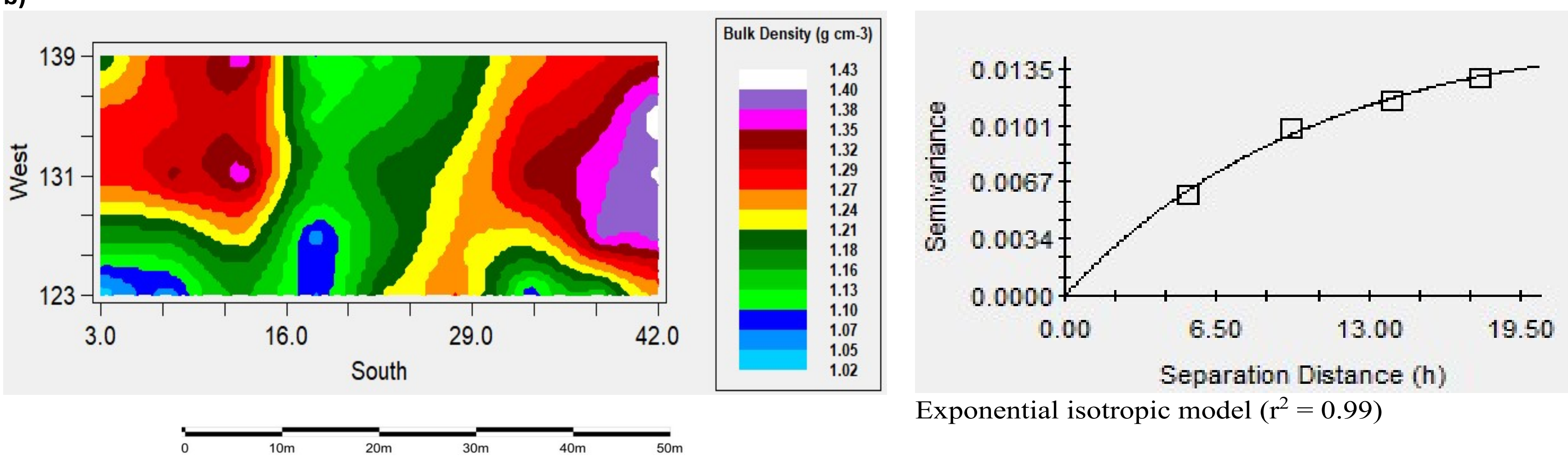
The highest *C* values at the toeslope was attributed to water content and SOC. The *C* of water is significantly higher than that of other soil constituents (Bristow, 2002), thus, higher water content leads to higher *C* values. Rapid water drainage between 0 and -33 kPa SWMP also resulted in a significant reduction in *C* values between these pressures. Furthermore, since SOC acts similar to colloids with higher surface area, they tend to increase water availability, which could be responsible for the higher *C* values at landscape positions with higher SOC values. Thermal diffusivity was similar to λ at all slope positions and SWMP because *D* is a function of the ratio of λ to *C*. Therefore, factors that increase λ and reduce *C* will increase *D* values (Haruna et al., 2017). Volumetric water content was higher at the toeslope probably due to the higher SOC values and lower ρb values at this slope position. In contrast, Mohanty and Mousil (2000) reported no significant differences in θ across various slope positions as a result of similarities between SOC across these slope positions.

a)



Spherical isotropic model ($r^2 = 0.54$)

b)



Exponential isotropic model ($r^2 = 0.99$)

Figure 4. 2: **Spatial variability and semivariogram of a) soil organic matter (SOC), and b) bulk density across all five slope positions. Please note that the x and y axis are the georeferenced x and y coordinates for the study site.**

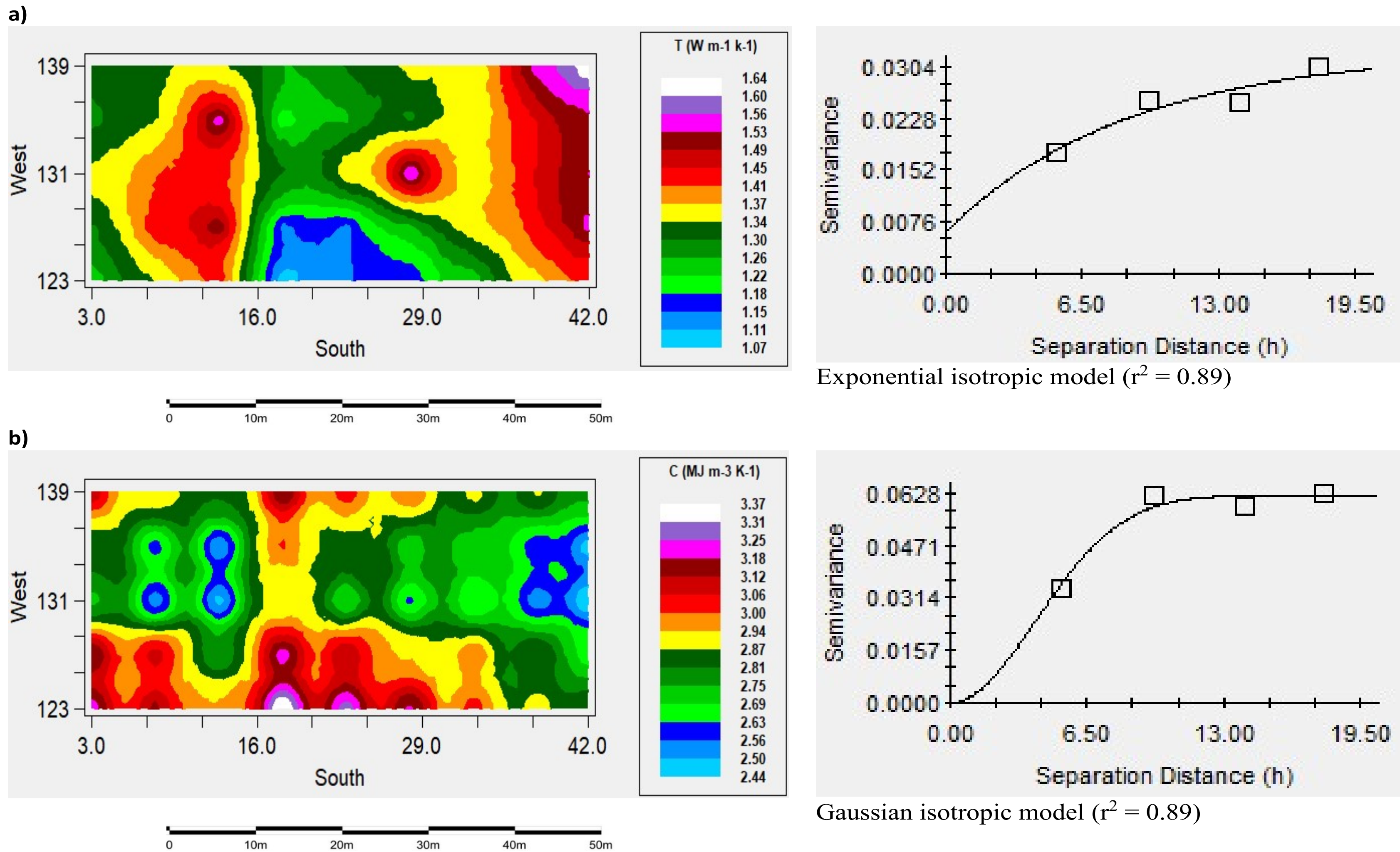


Figure 4. 3: **Spatial variability and semivariogram of a) thermal conductivity (T), and b) volumetric heat capacity (C) across all five slope positions. Please note that the x and y axis are the georeferenced x and y coordinates for the study site.**

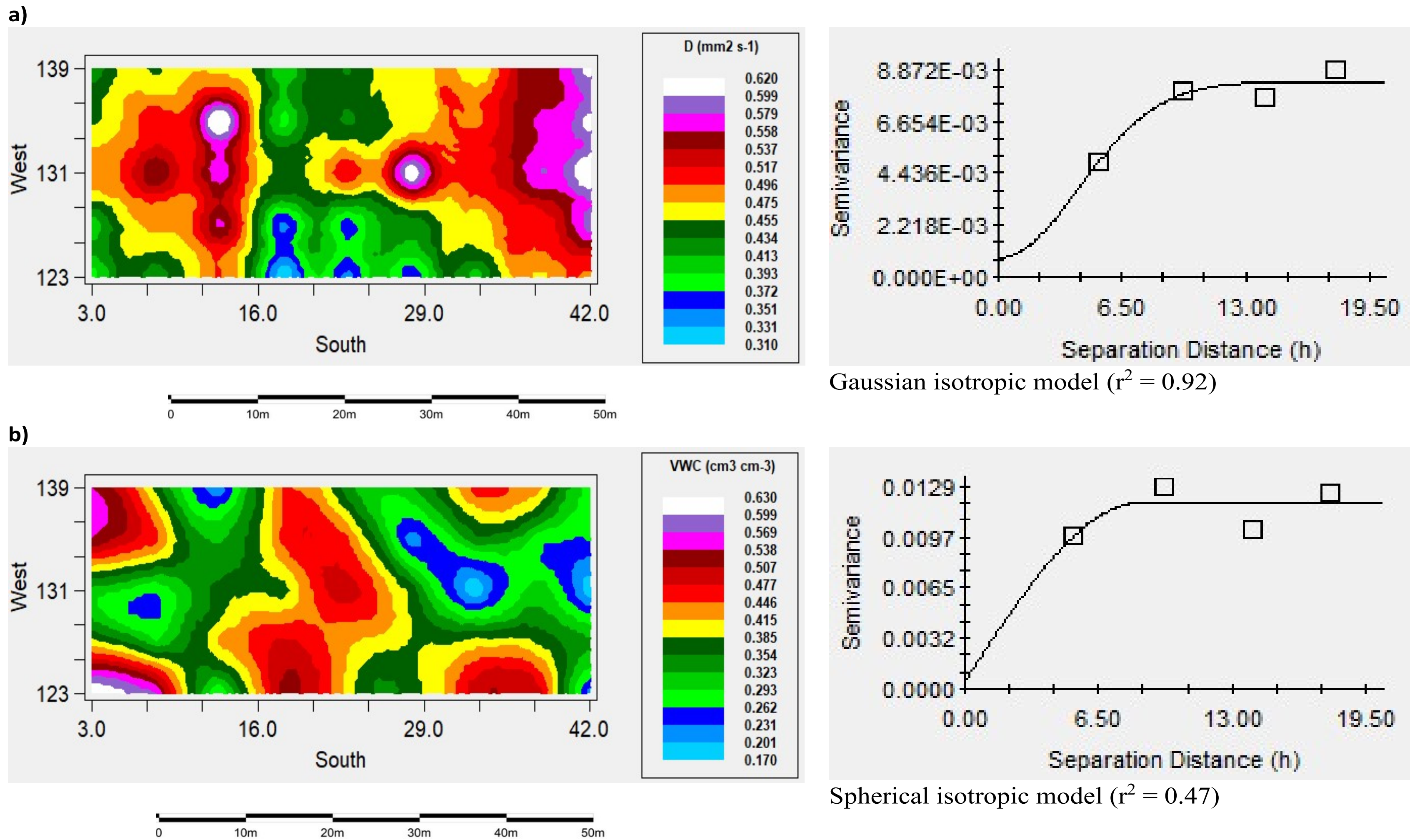


Figure 4. 4: **Spatial variability and model representation of a) thermal diffusivity (D), and b) volumetric water content (VWC) at saturation, across all five slope positions. Please note that the x and y axis are the georeferenced x and y coordinates for the study site.**

Correlations Between Soil Parameters 4.9

The significant correlation between *ρb* and *λ* shows that the soil can warm quickly and to a deeper depth at the shoulder and back slopes. As ρ_b increases, pore spaces reduce and the contact between soil minerals increases, thus conducting more heat. Additionally, as SOC and θ increased across different slope positions, C_V also increased. This increase was higher at the foot and toe slopes compared to other slope positions (Table 4.2). Similarly, Abu-Hamdeh and Reeder (2000) and Haruna (2019) reported an inverse relationship between SOC and *λ* under laboratory conditions.

Correlation results show that foot and toe slope positions may be more suitable for θ conservation and reducing soil thermal conductance. Nonetheless, thermal conductance is also dependent on the amount of solar radiation reaching the soil surface. Due to the slope aspect, shoulder and back slope will receive more solar radiation, increasing θ evaporation and depletion of SOC. This will further increase thermal conductance on the shoulder and back slope positions. Results from the current study suggests that, in a more variable climate, the foot and toe slope positions may be able to better buffer against extreme soil heat change compared with other slope positions. Further studies on the interaction effects between slope position and various land management practices on soil thermal properties will provide more useful information on crop productivity in a rapidly changing global climate.

Table 4. 4: Spatial and fractal characteristics of physical and thermal properties at 0 kPa and -33 kPa soil water matric potentials

			0 kPa				-33 kPa			
Slope Position	SOC	*Pb*	λ	*C*	*D*	θ	λ	*C*	*D*	θ
Summit										
Model	Linear	Spherical	Gaussian	Gaussian	Gaussian	Linear	Linear	Linear	Linear	Linear
Nugget	27.608	0.002	0.000	0.011	0.000	0.008	0.029	0.080	0.005	0.059
Sill	27.608	0.025	0.200	0.122	0.067	0.008	0.029	0.080	0.005	0.059
Nugget/Sill	0.000	0.913	1.000	0.910	0.999	0.000	0.000	0.000	0.000	0.000
A_0 (m)	19.000	36.460	55.530	71.014	71.014	19.000	19.000	19.00	19.000	19.000
R^2	0.65	0.89	0.76	0.76	0.77	0.632	0.90	0.46	0.57	0.05
RMSE	15.780	0.001	0.009	0.003	0.002	0.004	0.014	0.038	0.002	0.026
DSD (%)	27.608	0.002	0.001	0.012	0.001	0.008	0.029	0.080	0.005	0.059
F_D	0.857	1.618	1.232	1.714	1.271	1.299	0.862	0.484	1.062	1.542
Shoulderslope										
Model	Linear	Gaussian	Gaussian	Gaussian	Gaussian	Exponential	Spherical	Linear	Linear	Linear
Nugget	14.306	0.000	0.021	0.018	0.005	0.006	0.000	0.087	0.004	0.006
Sill	14.306	0.179	0.101	0.234	0.053	0.029	0.017	0.087	0.004	0.006

Nugget/Sill	0.000	0.999	0.798	0.922	0.897	0.801	0.999	0.000	0.000	0.000
A₀ (m)	19.00	71.014	71.000	71.014	71.014	123.000	4.870	19.000	19.000	19.000
R^2	0.61	0.91	0.69	0.68	0.73	0.28	0.24	0.91	0.25	0.55
RMSE	6.650	0.003	0.002	0.007	0.001	0.002	0.003	0.040	0.004	0.002
DSD (%)	14.306	0.000	0.026	0.020	0.006	0.007	0.000	0.087	0.004	0.006
F_D	1.374	1.237	1.836	1.690	1.727	1.873	1.932	0.120	1.936	1.691
Backslope										
Model	Linear	Gaussian	Linear	Exponential	Spherical	Gaussian	Exponential	Linear	Linear	Gaussian
Nugget	14.902	0.003	0.012	0.014	0.000	0.000	0.057	0.104	0.021	0.000
Sill	14.902	0.070	0.012	0.044	0.004	0.200	0.155	0.104	0.021	0.144
Nugget/Sill	0.000	0.964	0.000	0.683	0.934	1.000	0.635	0.000	0.000	0.999
A₀ (m)	19.000	58.128	19.000	104.850	6.420	63.549	123.000	19.000	19.000	71.014
R^2	0.68	0.98	0.46	0.31	0.05	0.77	0.20	0.86	0.75	0.79
RMSE	8.819	0.007	0.003	0.003	0.001	0.006	0.013	0.042	0.003	0.004
DSD (%)	14.902	0.003	0.012	0.021	0.000	0.000	0.089	0.104	0.021	0.000
F_D	0.743	1.433	1.743	1.869	1.920	1.445	1.913	0.808	1.788	1.369
Footslope										
Model	Linear	Gaussian	Gaussian	Gaussian	Gaussian	Spherical	Linear	Linear	Linear	Linear
Nugget	33.921	0.002	0.012	0.013	0.002	0.000	0.066	0.055	0.015	0.002
Sill	33.921	0.102	0.459	0.236	0.108	0.004	0.066	0.055	0.015	0.002

Nugget/Sill	0.000	0.981	0.974	0.944	0.980	0.929	0.000	0.000	0.000	0.00
A_0 (m)	19.000	71.014	70.010	58.006	71.014	8.150	19.000	19.000	19.000	19.000
R^2	0.62	0.84	0.89	0.52	0.76	0.36	0.03	0.73	0.12	0.49
RMSE	15.755	0.002	0.007	0.014	0.003	0.008	0.016	0.020	0.003	0.005
DSD (%)	33.921	0.002	0.012	0.014	0.002	0.000	0.066	0.055	0.015	0.002
F_D	1.372	1.503	1.459	1.728	1.513	1.966	1.853	1.484	1.826	1.694
Toeslope										
Model	Linear	Linear	Spherical	Gaussian	Gaussian	Linear	Linear	Linear	Linear	Linear
Nugget	45.296	0.005	0.009	0.010	0.003	0.018	0.023	0.057	0.006	0.007
Sill	45.296	0.005	0.062	0.219	0.037	0.018	0.023	0.057	0.006	0.007
Nugget/Sill	0.000	0.000	0.851	0.954	0.916	0.000	0.000	0.000	0.000	0.000
A_0 (m)	19.00	19.000	41.000	53.538	65.420	19.000	19.000	19.000	19.000	19.000
R^2	0.36	0.58	0.95	0.90	0.94	0.10	0.94	0.35	0.78	0.49
RMSE	13.912	0.002	0.001	0.005	0.005	0.004	0.008	0.022	0.003	0.003
DSD (%)	45.296	0.005	0.011	0.010	0.003	0.018	0.023	0.057	0.006	0.007
F_D	1.699	0.999	1.687	1.495	1.621	1.853	1.420	1.611	0.483	1.190

Table 4.4: SOC: soil organic carbon; *ρb*: soil bulk density; λ: thermal conductivity; *C*: volumetric heat capacity; *D*: thermal diffusivity; θ: volumetric water content; A_0: range of spatial variability; DSD: degree of spatial dependence; F_D: fractal dimension.

Spatial Variability of Soil Physical and Thermal Properties 4.1.1

The spherical, exponential, and gaussian isotropic models indicate an inverse relationship between spatial autocorrelation and distance (Burrough, 1986; McBratney and Webster, 1986). Since the spherical, exponential and gaussian isotropic models provided the best model fit for soil thermal properties at saturation (Table 4.4), results from the current study suggests that, among other factors, the similarity between soil thermal properties is highly dependent on volumetric water content at all slope positions. To avoid similarities between soil thermal properties and capture enough variability for future studies, the distance between soil samples should be further apart under wet soil conditions (between 0 and -33 kPa SWMP). The drier the soil, the closer the distance between soil samples (see range of spatial variability in Table 4.4). The reason could be because the λ and C of water is greater than that of air.

In theory, the semivariogram value is null at null separation distance (no lag). However, the semivariogram often exhibits a nugget effect at a very small lag, which is a value greater than zero. This nugget effect can be attributed to spatial sources of variation at smaller distances than the sampling interval, measurement errors, or both. To eliminate measurement errors, replicate samples were collected. Thus, the nugget effect in the current study can be attributed to spatial sources of variation at distances smaller than the sampling interval. At 0 kPa SWMP, the nugget effect of soil thermal properties was highest for C and λ at the shoulderslope. This suggests that at 0 kPa SWMP, C and λ were more spatially variable over small distances at the shoulderslope compared with other slope positions. At -33 kPa SWMP, C showed the highest spatial variability within small distances at all slope positions (besides footslope position) compared with other measured thermal properties.

This microvariability can be attributed to the sensitivity and dependence of *C* to dynamic soil properties (θ and SOC). Soil organic carbon had the highest variability in spatial dependence of all properties measured at all slope positions.

In general, the A_0 of soil thermal properties was less at the toe slope compared with other slope positions, suggesting that soil thermal properties are more homogeneous at this position compared with other slope positions. For statistical analysis, an understanding of the A_0 for various soil thermal properties can enable the construction of independent accurate datasets for similar slope positions in future soil sampling design. This can be used as a tool in the designation of areas for resampling, and to design future field experiments that avoid spatial dependence. Kerry and Oliver (2004) suggested that sample interval be less than half the A_0. As such, for future studies on the characterization of spatial dependency of soil thermal properties in a similar landscape, it is recommended that soil thermal properties be sampled at distances smaller than half the A_0 found in the current study (Table 4.4).

The strong DSD of soil thermal properties in the current study suggests, regardless of slope position, their spatial autocorrelation depends more on intrinsic soil properties rather than extrinsic properties. As such, sampling design for future studies on soil thermal properties on similar landscape positions should be based on textural and mineralogical characteristics rather than soil management. For SOC, intrinsic properties only play a role at the steepest parts of the landscape. Therefore, to avoid redundancy and to capture variability, SOC sampling decisions on the summit, foot, and toe slopes should be based on current land management.

Fractal Characterization of Soil Thermal and Physical Properties 4.1.2

Long- and short-range variation in soil properties have been related to the length and area description, respectively, of their F_D (Burrough, 1981). At saturation on the summit, λ and *D* exhibited long-range variabilities while *C* exhibited a tendency to change over short distances. At other slope positions, measured soil thermal properties exhibited a likelihood to vary over small distances. At -33 kPa SWMP, measured soil thermal properties exhibited long-range variability at the summit. This was probably due to the significantly lower θ at this pressure.

The wider range of F_D at -33 kPa SWMP suggests that as the soil dries, soil thermal properties tend to be less self-similar. This is in concert with results on the A_0. Results show that, under laboratory conditions, variability in soil matric potentials leads to a greater proportion of short-range variations in soil thermal properties. Further, results of the current study show that soil thermal and physical properties at each slope position is influenced by several intrinsic and dynamic soil characteristics. Therefore, management decisions should be tailored uniquely for each slope position rather than for the entire catena. In a more variable climate, with increasing probability of longer periods of drought, current results suggest that soil thermal properties across these slope positions will become more erratic, which indicates great disorder and antipersistence in the spatial structure.

Conclusion

A study was conducted on a Paleudalf to evaluate the spatial and fractal characterization of soil thermal properties across five slope positions: summit, shoulderslope, backslope, footslope, and toeslope. Semivariogram analysis showed that several isotropic models (e.g., spherical, gaussian, exponential and linear) provided the best fit for soil thermal properties at 0 and -33 kPa SWMP across the slope positions. The range of autocorrelation was wider at -33 kPa compared with 0 kPa SWMP for all soil thermal properties, suggesting that soil water content may be an important consideration when planning future sampling schemes to avoid spatial dependence. Significant correlations between soil thermal properties and soil properties (SOC, θ, and ρb) suggests that foot and toe slope positions can better buffer against extreme heat change and are more suitable for crop productivity as compared to other slope positions. Further studies are needed to evaluate the interaction effects between slope position and land-use on soil thermal properties.

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