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Spatial heterogeneity of soil physico-chemical properties in contrasting wetland soils in two agro-ecological zones of Lesotho

T. Nkheloane[A,B], *A. O. Olaleye*[A], *and R. Mating*[A]

[A]Department of Soil Science & Resource Conservation, Faculty of Agriculture, The National University of Lesotho, Roma 180, Lesotho.
[B]Corresponding author. Emails: nkheloane@webmail.co.za; ao.olaleye@gmail.com

Abstract. Wetlands are complex ecosystems, often exhibiting considerable spatial variability, making the understanding of soil spatial relationships within them difficult. A study was conducted to evaluate spatial variability of soil physico-chemical properties in two contrasting wetlands in two agro-ecological zones (AEZs) of Lesotho. Soil samples were collected along two transects in mini-pits dug at different depths at 50-m intervals. The collected samples were analysed for particle size, pH, soil organic carbon (SOC), SOC pool, available phosphorus (Av-P), cation exchange capacity (CEC), and base cations. Results showed that within-site variability was very low for sand particles and pH (coefficient of variation <15% for both properties). Soil physical properties generally showed less spatial heterogeneity than chemical properties, which differed widely within and between the study sites. There was generally low correlation between soil properties, and SOC accounted for most of the variation observed at both sites, especially T'sakholo with partial $R^2 = 94\%$; at Thaba-Putsoa, partial $R^2 = 44\%$. Geostatistical analysis showed that all of the nugget to sill ratios (NSR) showed strong spatial dependence (i.e. NSR of 54–94%) except SOC (T'sakholo stream-bank) with no spatial dependence, with the nugget accounting for 23.43%. We therefore conclude that further wetland studies in Lesotho should attempt to quantify not only the soil properties or processes under investigation but also their spatial variability, because this spatial variability can provide insight into underlying ecosystem processes and may itself indicate wetland condition. In addition, results of stepwise multiple regression showed that SOC and texture could be used across these sites for the sustainable management of these wetlands.

Additional keywords: degradation, geostatistics, Lesotho, soil properties, spatial variability, wetlands.

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Introduction

Wetlands are complex and fragile ecosystems with considerable spatial variability (Reddy 1993). They are heterogeneous environments which can exhibit substantial spatial and temporal variability in soil properties (Lyons *et al.* 1998; Stolt *et al.* 2001; Bruland and Richardson 2004; Grunwald *et al.* 2006; Cohen *et al.* 2008). This variability can have important consequences for wetland biota and biogeochemistry. Understanding of the soil spatial patterns in wetland ecosystems is made difficult by the number of factors that affect soil properties and which operate at different spatial and temporal scales. Climatic factors such as precipitation and temperature, land form, topography, and complex interactions among physical, chemical, and biological processes play key roles in configuring soil properties (Sinowski and Auerswald 1999; Johnson *et al.* 2000). Human activities affect self-organisation in wetlands, which in turn affects spatial patterns of soil properties such as pH, nutrient concentrations, and organic matter content. The principal morphological differences between wetland soils and upland soils can be attributed to the fact that, in wetlands, specific biogeochemical processes take place because soil water frequently fills the soil pores and void spaces, resulting in saturated conditions (Hurt and Carlisle 2005).

Research on soil variability in the tropics has commonly used conventional statistics (e.g. coefficient of variation) to assess soil variability. Such statistics assume that variation is randomly distributed within mapping units. However, soil properties frequently exhibit spatial dependency. Generally, samples collected close to one another are more similar than samples collected at greater distances. Parametric statistics are inadequate for analysis of spatially dependent variables because they assume that measured observations are independent of their distribution in space (Kravchenko *et al.* 2006). Soil variability has been investigated by many researchers in the temperate zone (e.g. Wilding and Drees 1983; Cahn *et al.* 1994; Cambardella and Karlen 1999; Eltaib *et al.* 2002); however, there has been limited research on tropical soils (Ogunkunle 1993; Adderley *et al.* 1997; Wuddivira *et al.* 2000; Okae-Anti 2001; Akinbola *et al.* 2006) or in various countries (Cassel *et al.* 2000; Gaston *et al.* 2001; Corstanje *et al.* 2006; Iqbal *et al.*

2005). To our knowledge, there are no reports of studies on soil variability in the upland and wetland soils of Lesotho, Southern Africa.

It has been reported that human activity has adversely affected global carbon (C), nitrogen (N), and phosphorus (P) cycles, and this has contributed to climate alteration that will generate discernible feedbacks to all organisms and ecosystems on the Earth (Mitsch and Gosselink 2000; Wang *et al*. 2006; He *et al*. 2008). Understanding the stores and storage potential of C, N, and P has helped to discern how ecosystems will respond to natural and anthropogenic disturbances under different management strategies (He *et al.* 2008).

There has been migration of population, along with livestock, from other agro-ecological zones of Lesotho to the lowlands. As a result, many wetlands are being converted to grazing land. The rapid expansion of livestock numbers and the conversion of wetlands to cropped lands have caused significant degradation of these fragile ecosystems, accelerating peat decomposition and C loss, and causing a sharp decline in wetland biodiversity, despite some measures (e.g. banning pasture) to restore and protect these wetlands. Studies on the effects of human activities following wetland conversion on soil physico-chemical properties and on spatial patterns of soil properties are limited. Information on these effects will support decision making on best management of such wetlands for present and future generations. Brouwer *et al*. (1993) reported that knowledge of spatial variability within a farmer's field may help to reduce risk of severe and irreversible environmental degradation by revealing vulnerable areas. Similarly, in wetland soils, knowledge of the soil variability within and between fields can reduce the risk of irreversible environmental degradation.

In wetlands where spatial patterns in soil properties have been estimated, the information has proved useful. For example, in the case of the soil P spatial patterns in the Everglades, USA, the information provided insight on the extent and severity of P enrichment zones and processes that govern the enrichment processes (DeBusk *et al.* 1994, 2001; Grunwald *et al.* 2006). Spatial variability is also important when considering the environmental and ecological functions of a wetland (Stolt *et al.* 2001). Some of these functions, such as production of vegetal materials for handicraft and building components, fishing and hunting, cattle grazing (especially in summer), filtration of nutrients and other chemicals from river water, tourism, and absorbing temporary large quantities of water to release slowly, cannot be estimated directly.

Spatial variability in wetland soils has also provided insight into underlying ecosystem processes and may itself indicate wetland condition (Cohen *et al.* 2008; Bai *et al.* 2010). As such, it is important to distinguish systematic variability from random variability and determine the relative importance of each (Stolt *et al.* 2001). Systematic spatial relationships in wetland soils are the result of differences in parent material, elevation, erosional or depositional environment, frequency of flooding, vegetation, pedogenic effects, and hydrology (Johnston *et al.* 1984; Hayati and Proctor 1990; Gaston *et al.* 1990; Farrish 1991; Reese and Moorhead 1996). However, random effects are attributed to unrecognised differences in these parameters, as well as differences due to sampling and laboratory error (Wilding and Drees 1983). These random effects often obscure or confound soil–elevation, soil–vegetation, or soil–hydrology relationships; therefore, to understand spatial relationships in wetland soils, random variability needs to be recognised and separated from systematic variability (Stolt *et al.* 2001).

Numerous processes can influence soil spatial patterns at a particular location (Stolt *et al.* 2001), and Bruland and Richardson (2004) illustrate that wetland type may strongly affect spatial pattern. The uneven distribution of soil characteristics such as nutrient availability, organic content, and mineral content implicitly reflects the processes that occur within the larger ecosystem (Corstanje *et al.* 2006). Although the importance of spatial heterogeneity is well recognised in wetlands, the scale or extent to which it occurs and how it might affect coexistence and diversity of species is poorly understood in Lesotho. There is little information on the effects of human activities (i.e. livestock grazing and watering) on soil physico-chemical properties in Lesotho or their spatial variability. Most studies on soil spatial variability in other regions have been used to provide accurate information for site-specific recommendations. Furthermore, there is little published scientific information on the status of spatial variability of soil physico-chemical properties of wetlands in Lesotho. As such, the information presented in this study may be used to design efficient monitoring and management schemes by wetland managers. Bai *et al.* (2010) reported that the distributions and dynamics of P forms in soil, especially in the land/inland-water ecotone, can be significantly impacted by various biogeochemical and environmental factors (i.e. soil moisture, soil organic matter, and clay content). Thus, this study was conducted specifically to evaluate spatial variability of soil physico-chemical properties in two wetlands in two different agro-ecological zones of Lesotho with different levels of anthropogenic impacts.

Materials and methods

Study areas

Two locations were selected for this study: Thaba-Putsoa, 70 km south-east of the capital Maseru (27°58.234′E, 29°25.798′S; elevation 2638 m); and T'sakholo, ~76 km south of Maseru (27°10.360′E, 29°40.469′S; elevation 1570 m).

Thaba-Putsoa is in the Mountain agro-ecological zone (AEZ), while T'sakholo is in the Lowland AEZ. Lesotho is generally considered a semi-arid country with unusually high levels of climate variability. Thaba-Putsoa is characterised by very low temperatures in winter, ranging between –8°C and 7°C with frequent occurrences of snow. Mean annual temperatures range between –8°C and 30°C, and the highest annual rainfall (1000–1400 mm). The area is represented by a sequence of clastic sedimentary formations (Burgersdorp formation, Molteno formation, Elliot formation, and Clarens formation) overlain by a laterally continuous section of basalt up to 1600 m thick. Lithosols are the major soil group in this area. T'sakholo is characterised by maximum temperatures varying between 32°C in summer and –7°C in winter; average temperatures are 25°C and 15°C, respectively. Rainfall occurs predominantly between October and April, ranging between 600 and 900 mm annually. The geology of the site consists of rocks belonging to the

Burgersdorp formation, which underlies the western part of the country, with highly erodible duplex soils characterising the area. General site descriptions are given in Table 1.

The level of impact on wetlands in these two AEZs was characterised as low, medium, or high, based on local land-use characteristics (Hughes 1995; Teels and Adamus 2001) or the intensity of anthropogenic pressures such as mining, smelting, industrial pollution, and livestock grazing/watering. Low-level impacted wetlands has little (<5%) or no agricultural activity within 150 m of the wetland boundary (Chipps *et al.* 2006), whereas high-level impacted wetlands had agricultural activities within 10 m of at least one-third (33%) of the wetland boundary, and the medium-level impacted wetlands had agricultural activities within 10 m of 5–32% of the wetland boundary. The wetland at T'sakholo is characterised as high-level impacted, whereas that at Thaba-Putsoa is low-level impacted. The land-use types in the two wetlands are grazing and livestock watering.

Sampling methods

Soils were sampled along two transects running across each wetland. At T'sakholo, sampling was from the wetland centre and extended outwards into the stream-banks. At Thaba-Putsoa, sampling was at the wetland centre and extended outwards into the surrounding upland. At T'sakholo, samples were also collected along the stream-bank. In general, the transects ranged between 250 and 700 m and soil samples were collected at intervals of 50 m in mini-pits dug to a depth of $\leq$0.5 m. Data recorded on the morphology of the sites included drainage, vegetation, land use, and degree of erosion. The soil properties described included colour, horizon boundary, structure, consistency, texture, mottles, and roots density. Soil samples were taken from the last horizon up to the first horizon in each profile pit, and the maximum depth of soil examination was different for each pit. In total, 76 (T'sakholo wetlands) and 27 (Thaba-Putsoa) soil samples were used. The soils were classified using USDA Soil Taxonomy (Soil Survey Staff 1999).

Soil analyses

In each wetland, samples were collected, labelled, bagged, and transported to the laboratory for routine soil analysis. The soil samples were air-dried for 48 h and crushed to pass through a 2-mm sieve, and analysed for the following parameters: particle size by the hydrometer method (Bouyoucus 1962); soil pH in water, using a glass electrode pH meter at 1 : 2.5 soil : water ratio; soil organic carbon (SOC) by the method of Walkley and Black (1934); available P by Bray and Kurtz No. 1 method (Bray and Kurtz 1945); cation exchange capacity (CEC) using ammonium acetate at pH 7. Base cations (Ca^{2+}, Na^{+}, Mg^{2+}, K^{+}) were extracted using 1 N NH_4OAc and the filtered extracts were all determined with a flame atomic absorption spectrometer (AAnalysed 200, PerkinElmer Inc., Waltham, MA). The SOC pool (C-pool, kg C m^{-2}) was calculated using a relationship as given by Wairiu and Lal (2003):

$$\mathrm{C-pool = d \times BD \times C\ content}$$

where d is soil layer thickness (m), BD is bulk density (kg m^{-3}), and C content units are g g^{-1}.

Statistical analyses and mapping

Classical statistics provides the overall variability of the soil properties; however, it does not provide the spatial trend. Data collected from these two wetland were subjected to summary statistics (mean, range, standard deviation (s.d.), skewness) using the Means Procedure of Statistical Analysis Systems (SAS Institute 1999). Data distributions were tested for normality. If data were not normally distributed, they were log-transformed. In addition the mean (x) and coefficient of variation (CV) for each property along transects were also calculated, where CV = (s.d./x) × 100. The higher the CV, the more variable is the property (Wilding and Drees 1978; Wilding 1988). The descriptive statistics of the soil data suggested that soil properties at the sites were all normally distributed (skewness of between 1 and –2) except exchangeable Na and Mg (T'sakholo rangeland), exchangeable Na and Ca (Thaba-Putsoa rangeland), and all base cations (T'sakholo stream-bank); these data were log-transformed as the skewness ranged between 1.03 and 6.06 before the calculation of semi-variance (Baxter *et al.* 2003). Pearson correlation analysis was implemented to determine the relationship between the soil properties. Geostatistical analysis was performed using GS+ Geostatistics for the Environmental Sciences Version 9 software (Gamma Design Software, LLC, Plainwell, MI) to characterise the spatial variability in soil properties. This analysis produces variograms which reveal random and structured aspects of spatial dependence in a dataset of multiple samples collected at increasing distances from each other (the lag interval). A semivariogram (also known as a variogram) is a graphic representation of spatial autocorrelation that is made by plotting the semivariance for several distance intervals (Robertson and Gross 1994). The semivariance is calculated as:

$$\gamma(h) = [1/2(h)] \sum [Z_i - Z_{i+\mathrm{h}}]^2$$

where $\gamma(h)$ is semivariance for interval distance class h; Z_i is measured sample value at point i; Z_{i+h} is measured sample value at point $I + h$; N(h) is total number of sample couples for the lag interval h.

The spatial structure of each variable has been defined from semivariogram parameters: nugget, sill (or total semivariance),

Table 1. General site descriptions

Site	Topography	Wetland type	Altitude (m a.s.l.)	Land use	Vegetation	Anthropogenic impact
Thaba-Putsoa	Steep rolling	Lacustrine	2638 m	Grazing	Afro-montane grassland, e.g. *Themeda triandra*	Little
T'sakholo	Flat to gentle	Riverine	1570 m	Grazing/livestock watering	Highveld grassland, e.g. *Eragrostis curvula*	High

and range. Nugget is the variance at distance zero and represents the experimental error, and sill is the semivariance value at which the semivariogram reaches the upper bound after its initial increase. The nugget to sill ratio quantifies the importance of the random component and provides a quantitative estimation of the spatial dependence. According to Cambardella *et al*. (1994), nugget to sill ratios can be grouped into three classes: (*i*) <25%, which means strong spatial dependence; (*ii*) 25–75%, moderate spatial dependence; (*iii*) >75%, spatially independent or pure nugget (i.e. when slopes of semivariograms are close to zero). The ratio of the spatially structured variance to the sample variance ($C_o/C+C_0$) reveals the degree of spatial dependence as outlined by Robertson and Gross (1994).The ecologically significant functions of a semivariance analysis of soil resources are to determine whether spatial dependence or patchiness exists for a resource, how distinct the patches are, and at what scale they occur. Contour maps of soil kriging estimates were prepared using Surfer 8.0 (Golden Software Co., Golden, CO) for spatial distribution of silt to clay ratio, organic carbon, and SOC pool. The silt to clay ratio is an indicator of wetland degradation, while the organic carbon and SOC pool are indicators of wetland health. Point kriging with no search radius was used as an unbiased, weighted, linear interpolation method that minimises total parameter variance by incorporating semivariogram functions to create contour maps (Isaaks and Srivastava 1989). The Stepwise Multiple Regression Analysis (SMRA) (Prog Reg procedure; SAS Institute 1999) was used to examine which of the soil properties accounted for most variation in each site.

Results

Soil morphological properties

Description of the sites' morphological properties in terms of land use, colour, horizon boundary, texture, structure, consistency, concretions, roots, and drainage showed that these properties differed greatly between sites (results not presented). In Thaba-Putsoa, soils exhibited mainly black and very dark greyish colours, whereas in T'sakholo, most horizons had light-brown to brown and reddish brown colours. Many of the horizons in Thaba-Putsoa had hues of 10YR and 5Y with low chroma ($\leq$3) colours, which reflects poor drainage or seasonal mottling. Features such as grey or low chroma observed in Thaba-Putsoa indicate soil wetness brought about by oxidation–reduction cycles due to groundwater fluctuations. Wetland soils in a reduced state typically have a dark, grey, mottled appearance with chroma colours $\leq$2. In T'sakholo, soil colour ranged between light-brown to brown and reddish brown with hues 2.5Y, 7.5YR, and 10YR with chroma values 2–8. These colours indicate a relatively high amount of iron-oxide, which may be due to the parent material. Boundaries ranged mostly between wavy and clear on both sites with mainly sandy-loam texture in Thaba-Putsoa and a fairly variable texture (sandy, sandy-clay, silt-loam, and clay) in T'sakholo. Structure was mainly crumb and single-grain at both sites, with more concretions in T'sakholo than in Thaba-Putsoa. Both sites had many roots in the top horizons, decreasing down the profile. Drainage was poor in T'sakholo and moderate in Thaba-Putsoa.

Summary statistics

Summary statistics are presented in Table 2 for all land-use types at both sites. Results showed that the standard deviation was higher for soil physical properties than chemical properties. In Thaba-Putsoa, soil physical properties were more negatively skewed than chemical properties. In T'sakholo, only percentage silt and clay and pH, Na^+, and K^+ were negatively skewed in rangeland, whereas along the stream-bank, percentage sand and CEC were negatively skewed. The SOC values were 17.20 ± 5.34 (Thaba-Putsoa), 1.93 ± 0.85 (T'sakholo rangeland), and 1.12 ± 1.22 (T'sakholo stream-bank). The SOC in Thaba-Putsoa was less than half that reported by Bai *et al*. (2010) for alpine wetland in the south-eastern Qinghai–Tibet plateau (35.81 ± 3.24). The value reported by Bai *et al*. (2010) was ~19 and ~32 times the SOC values for T'sakholo (rangeland and stream-bank, respectively). This indicates that drainage and small anthropogenic impacts may have led to an increase in SOC

Table 2. Summary statistics for the study sites
Number of samples: T'sakholo 76, Thaba-Putsoa 27

Variable	Sand	Silt	Clay	SOC	pHw	Avail. P	CEC	Na^+	Mg^{2+}	Ca^{2+}	K^+
					Thaba-Putsoa (rangeland)						
Mean	65.82	24.39	9.79	17.20	5.00	1.55	0.59	0.47	0.03	0.48	0.25
Range	26.70	26.72	14.00	21.79	1.31	6.63	0.57	0.76	0.59	1.88	0.37
Skewness	–0.05	–0.37	–0.56	0.27	–0.003	1.80	0.29	0.21	0.06	2.02	0.70
s.d.	6.37	6.39	3.46	5.34	0.27	1.15	0.14	0.18	0.14	0.39	0.10
					T'sakholo (rangeland)						
Mean	46.24	32.23	21.91	1.93	7.42	2.74	0.50	2.73	0.14	0.12	0.97
Range	18.00	16.02	10.00	3.71	1.71	9.68	0.53	1.54	1.09	0.21	0.93
Skewness	0.39	–0.49	–1.48	0.45	–1.60	0.92	0.13	–0.01	4.59	0.32	–0.86
s.d.	5.80	4.87	2.02	0.85	0.35	3.03	0.14	0.45	0.16	0.054	0.23
					T'sakholo (stream-bank)						
Mean	56.54	25.23	18.55	1.12	7.17	2.74	0.53	2.74	0.83	1.02	3.50
Range	30.00	21.00	18.00	7.67	1.29	8.99	0.87	1.66	1.46	2.16	4.48
Skewness	–1.05	0.54	0.76	3.78	0.09	0.86	–0.06	0.48	1.98	0.11	1.69
s.d.	6.21	5.52	2.96	1.22	0.27	2.59	0.14	0.24	0.24	0.34	0.69

Table 3. Correlation matrix of soil properties for each site

$\dagger P < 0.1$, $*P < 0.05$, $**P < 0.01$

Variable	Sand	Silt	Clay	pH	Avail. P	SOC	CEC	Ca^{2+}	K^{+}	Na^{+}
					Thaba-Putsoa					
Sand	1.00	–0.89**	–0.22	0.16	0.09	–0.12	0.14	0.19	0.21	0.008
Silt		1.00	–0.19	–0.15	–0.16	0.14	–0.11	–0.26	–0.10	–0.05
Clay			1.00	–0.35**	0.10	0.04	0.04	0.19	–0.19	0.16
pH				1.00	0.05	0.16	0.12	0.39**	0.15	–0.13
Avail. P					1.00	–0.16	0.01	0.02	–0.09	–0.12
SOC						1.00	0.35**	0.23	0.19	0.08
CEC							1.00	0.24†	0.18	0.09
Ca^{2+}								1.00	1.00	0.008
					T'sakholo					
Sand	1.00	–0.89**	–0.64**	–0.31**	–0.29**	–0.17*	–0.02	0.02	0.02	0.05
Silt		1.00	0.31**	0.29**	0.22**	0.08	0.05	–0.06	–0.07	0.03
Clay			1.00	0.24**	0.22**	0.27**	0.007	0.07	0.07	–0.18*
pH				1.00	0.17*	0.07	–0.04	–0.02	–0.01	–0.01
Avail. P					1.00	–0.01	–0.04	–0.02	–0.02	0.05
SOC						1.00	–0.17*	0.72**	0.71**	–0.03
CEC							1.00	–0.02	–0.02	0.05
Ca^{2+}								1.00	0.99**	–0.05
K^{+}									1.00	–0.05
Na^{+}										1.00

contents in Thaba-Putsoa soils. However, in T'sakholo rangeland and stream-bank, the SOC content was very low, which be attributed to the extensive impact of anthropogenic pressures coupled with climate change (i.e. declining rainfall in the region). This has resulted in the wetlands being colonised by invasive weed species.

Pearson's correlation stepwise multiple regression analyses

Pearson's correlation analysis was conducted to examine the levels of association between the soil properties within each site, and correlations between soil properties are summarised in Table 3. Statistically significant ($P < 0.001$) negative correlation was observed between percentage silt and percentage sand in Thaba-Putsoa. Soil pH had a strong significant ($P < 0.01$) and negative correlation with percentage clay and it also correlated strongly and positively with Ca^{2+}. The CEC had a significant positive ($P < 0.01$) correlation with SOC at this site. In T'sakholo, correlation analysis showed more associations between soil properties. Soil pH and available P exhibited significant positive correlation ($P < 0.01$) with silt and clay percentages, and negative correlation ($P < 0.01$) with percentage sand. SOC had a significant positive ($P < 0.01$) correlation with percentage clay and significant negative ($P < 0.05$) correlation with percentage sand. The correlations between CEC and SOC, and between K^{+} and SOC, were significantly positive ($P < 0.05$) and negative ($P < 0.01$), respectively. Sodium had a significant negative ($P < 0.05$) correlation with percentage clay, and calcium (Ca^{2+}) had a significant positive ($P < 0.01$) correlation with SOC and K^{+}. The results of stepwise regression analysis (Table 4) also revealed that SOC accounted for most of the variation observed at both sites (partial R^2 at Thaba-Putsoa 44%, and at T'sakholo 94%).

Table 4. Summary of stepwise multiple regression analysis for physico-chemical properties

Variable entered	Thaba-Putsoa			T'sakholo		
	Partial R^2	Model R^2	Pr. > *F*	Partial R^2	Model R^2	Pr. > *F*
SOC	0.4424	0.4424	<0.0001	0.94	0.9412	<0.0001
Silt	0.0073	0.9245	0.0213	0.0008	0.9740	0.0400
Sand	0.0229	0.9474	<0.0001	0.03	0.9711	<0.0001
Clay	0.0150	0.9580	<0.0001	0.002	0.9660	0.0007
Avail. P	0.0035	0.9645	0.0209	–	–	–
CEC	–	–	–	0.001	0.9732	0.0239
K^{+}	–	–	–	0.0012	0.9723	0.0145

Soil properties

Soil physical properties

Considering variability both within and among the soil pits in terms of CV for textural fractions, sand was the least variable at both sites (Table 5). Clay content varied between the two sites but was more uniform in T'sakholo, with many pits having CV <15%. The CV for a particular property is considered low if it is <15%, moderate if it is 15–30%, and high if it is >35% (Wilding and Drees 1978). Silt content was moderately variable in T'sakholo (CV 15–30%), whereas in Thaba-Putsoa it was moderately variable in transect 1 and highly variable in transect 2.

Soil chemical properties

Of the soil chemical properties, pH across all pits at both sites had low variability (CV <15%) (Table 5). Available P showed extreme variability at both sites, with CV values in the highly variable range (CV >35%). The SOC was moderately variable in Thaba-Putsoa, with CV values mostly 15–33%. However, in

Table 5. Comparison of variability of soil properties between two sites
Number of samples: T'sakholo 76, Thaba-Putsoa 27. Coefficient of variation (CV): low <15%, moderate 15–30%, high >35% (Wilding and Drees 1978). s.d., Standard deviation

Property	Thaba-Putsoa				T'sakholo			
	Transect 1		Transect 2		Transect 1		Transect 2	
	CV	s.d.	CV	s.d.	CV	s.d.	CV	s.d.
Sand	5.1	63.6	7.9	70.6	11.5	46.4	7.8	56.7
Clay	15.4	11.1	57.4	8.6	8.3	22.1	10.2	18.7
Silt	15.4	25.2	32.2	28.5	15.0	31.8	13.5	25.0
pHw	2.7	4.9	4.2	5.0	2.3	7.4	2.5	7.2
Avail. P	76.6	1.7	70.8	1.5	84.0	2.9	80.4	2.7
SOC	26.1	16.7	27.4	15.0	28.1	1.8	62.7	1.1
CEC	19.8	0.6	17.4	0.6	16.1	0.5	23.4	0.5
K^+	30.0	0.2	24.8	0.3	31.1	0.0	66.8	0.0
Na^+	34.8	0.4	38.5	0.3	46.4	0.0	54.0	0.0
Mg^{2+}	26.3	1.0	29.5	1.1	51.2	0.2	28.2	0.2
Ca^{2+}	44.2	0.4	53.4	0.5	31.1	0.1	66.8	0.1

T'sakholo SOC was highly variable, especially in transect 2 with CV values mostly >35%.

Geostatistical analysis

The geostatistical analysis (Table 6) indicated different spatial distribution models and spatial dependence levels for the soil properties. The coefficient of determination (R^2) of all of the variables ranged between 54 and 94% for all properties, indicating a good fit, except for available P (in Thaba-Putsoa rangeland), and CEC and exchangeable K (T'sakholo rangeland), with R^2 of 22–25%. Soil properties showed only a pure nugget effect fitted by the exponential, spherical, and Gaussian models at different sites. Gaussian model best describes the soil textural properties at both sites and SOC at Tsakholo-Rangeland; Spherical model best describes SOC and SOC-pool (Thaba-Putsoa), Exponential model best describes Silt:Clay ratios (Thaba Putsoa and Tsakholo-Rangeland). It is important to determine the spatial dependence of soil properties because properties with strong spatial dependence are more readily managed, and an accurate, site-specific fertilisation scheme for precision farming can be more easily developed. The geostatistical analysis suggests that all soil properties showed moderate and strong spatial dependence (nugget to sill ratio <50%; Table 6). The kriged estimates for silt to clay ratio, SOC, and SOC pool were contoured and mapped so that their patterns of variation across land-use types are presented in Fig. 1. The patterns of variation in these properties varied slightly differently across sites.

Discussion

A high degree of soil variability was observed at both sites, especially with regard to soil chemical properties except pH. The observation of pH as the least variable in this study is in line with findings by workers such as Mausbach *et al.* (1980). However, it has been established that chemical properties of soils appear to be more variable than physical properties (Olaniyan 1998), and this has been attributed to the

Table 6. Sum of geostatistical parameters for silt to clay ratio, soil organic carbon (SOC), and SOC pools
x, Mean; s.d., standard deviation; CV, coefficient of variation

	x	s.d.	CV	Nugget (Co)	Sill (Co+C)	Range	Co/(Co+C)	R^2	Model
				Thaba-Putsoa rangeland					
Silt : clay	3.26	2.54	77.9	0.01	20.02	11.37	0.001	0.756	Exponential
SOC	17.20	2.27	30.7	0.01	22.59	21.96	0.004	0.108	Spherical
SOC pools	84.90	38.63	45.5	136.00	1422	140.57	0.095	0.03	Spherical
Sand	65.96	6.48	9.8	0.10	81.20	19.02	0.001	0.936	Gaussian
Silt	24.09	6.06	25.2	0.10	237.51	37.15	0.0004	0.90	Gaussian
Clay	9.92	3.35	33.70	7.33	85.28	40.90	0.085	0.850	Gaussian
Avail. P	1.59	1.15	72.30	1.06	4.00	190.00	0.265	0.250	Gaussian
				T'sakholo rangeland					
Silt : clay	2.44	2.07	84.8	0.04	0.45	11.37	0.09	0.710	Spherical
SOC	10.16	8.56	84.25	0.21	1.37	28.32	0.153	0.154	Gaussian
SOC pools	49.93	48.99	102.21	1.98	6.13	169.17	0.323	0.485	Exponential
Sand	56.50	11.05	19.55	0.10	294.64	37.20	0.0003	0.876	Gaussian
Silt	27.83	6.85	24.60	0.10	237.51	37.15	0.0004	0.90	Gaussian
Clay	16.06	6.52	40.59	0.42	72.05	78.87	0.006	0.84	Gaussian
CEC	0.55	0.15	27.23	0.01	0.06	3.07	0.167	0.216	Gaussian
K	0.13	0.40	307.70	0.011	0.057	346	0.175	0.232	Spherical
				T'sakholo stream-bank					
Silt : clay	1.39	0.41	29.50	0.02	0.199	7.67	0.100	0.393	Spherical
SOC	1.12	1.21	108.04	1.56	1.55	58.1	1.01	0.436	Spherical
SOC pools	5.25	6.38	121.52	0.10	373.67	11.78	0.001	0.964	Gaussian
Sand	54.83	7.26	13.20	0.10	142.30	26.05	0.0007	0.89	Gaussian
Silt	26.25	5.82	22.17	0.10	133.33	36.39	0.0008	0.836	Spherical
Clay	19.22	3.43	17.85	1.31	96.60	43.70	0.0145	0.536	Spherical
CEC	0.53	0.15	28.30	0.009	0.061	0.670	0.148	0.751	Spherical
K	0.0003	0.0004	133.30	–	–	–	–	–	–

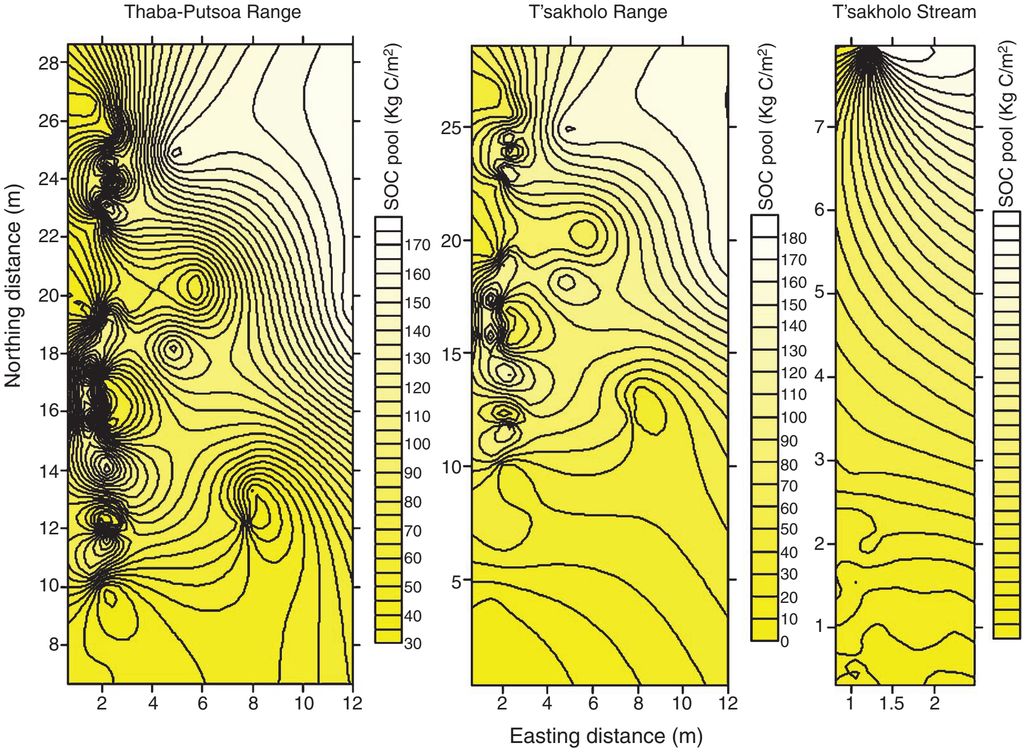

Fig. 1. Maps of the kriged estimates for soil organic carbon pool stocks of the study sites.

inherent heterogeneity in the parent material, residual effects of fertiliser application, differences in physiography, soil depth, or horizon, and cultural practices (Ogunkunle and Beckett 1987; Akinbola *et al.* 2006). The soil chemical properties presented in this study have yielded much higher CV values than the physical properties, and thus indicate their high degree of variability. The CV values for SOC exceeded 20%, indicating considerable variability. In studying soil and vegetation C pools in a mountainous watershed of Nepal, Shrestha and Singh (2007) reported that SOC showed considerable spatial variability, both horizontally according to land use and vertically within the soil profile. Nevertheless, soil texture (though considered uniform as it is a physical property) is reported as exhibiting significant spatial and temporal variability in riparian wetlands (Lyons *et al.* 1998; Darke and Walbridge 2000; Johnston *et al.* 2001). Soils in wetlands often exhibit characteristic, complex spatial patterns that indicate heterogeneity in soil resources which affect patterns of soil process rates (Ettema *et al.* 1998). Bruland and Richardson (2005) show that the combined action of processes such as surface runoff, erosion, overbank flooding, sediment deposition, groundwater inputs, fire, animal burrowing, litter production, and root activity contribute to a high degree of spatial variability in wetlands.

Anthropogenic pressures and climate variability are among other factors that induce spatial variability in wetland soil properties. The most peculiar anthropogenic pressure in the wetlands of Lesotho (including those under study) is overgrazing. Grazing affects the spatial patterns of soil properties through tramping and wallowing, which can increase soil compaction (Knapp *et al.* 1999) and change nutrient distribution via excreta input (Augustine and Frank 2001). In addition, grazing animals can indirectly influence spatial distribution of soil properties through changing vegetation patterns (Lin *et al.* 2010). Olofsson *et al.* (2008) found that the impact of grazers on soil nutrient heterogeneity can be consistent with their influence on vegetation patterns. Soil properties that showed strong spatial dependence indicated that structural factors strongly influence the spatial variability of these properties (Cambardella *et al.* 1994; Jiang *et al.* 2010). All of the nugget to sill ratios showed strong spatial dependence except SOC (T'sakholo stream-bank) with no spatial dependence. The texture analysis showed that silt exhibited strong spatial dependence, with the nugget accounting for 23.43%. Sand and clay displayed moderate spatial dependence, with nugget to sill ratios of 32.26% and 49.96%, respectively Liu and Tang (2003) also reported strong spatial dependence for soil texture (i.e. silt content).

Conclusions

Spatial distributions of wetland soil properties showed marked variability across pits at both sites. Soil chemical properties showed more spatial variability than physical properties. Correlation and stepwise analysis showed that low correlation among soil properties on both sites, and SOC accounted for most of the variation observed on both study sites. Thus, further wetland studies in Lesotho should attempt to quantify not only the soil properties or processes under investigation but also their spatial variability, because spatial variability in wetland soils can provide insight into underlying ecosystem processes and may itself indicate wetland condition and subsequent management.

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