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Statistical and Geostatistical Appraisal of Spatial Variability of Aggregate Stability and Aggregate-Associated Organic Carbon Content on a Catchment Scale in a Semi-arid Region, Central Iran

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Abstract

In a semiarid region of central Iran, effects of parent materials, physiography and landscape position, land use, and management practices on association of organic carbon with secondary (aggregates) particles and aggregate stability can have important consequences in terms of carbon sequestration and budgeting, deciding on the proper land use strategy and suitable soil conservation practices. It was used wet sieved aggregates to evaluate the effects of different factors on soil aggregate stability and organic carbon concentration within three aggregate size fractions (>2 mm, 1-2 mm, <1 mm). 111 soil samples were collected to measure water stable aggregates (WSA), aggregate organic carbon concentration (OC), and mean weight diameter (MWD). Some other related soil and terrain properties including bulk density, infiltration rate, saturated hydraulic conductivity and erodibility index were also measured. Analyses of variance indicated that water stability of aggregates was influenced by aggregate size. Higher percentage of water stable aggregates was found for microaggregates (< 1 mm), followed by mesoaggregates (1 to 2 mm). Aggregate organic carbon content was highest in mesoaggregates (9 g kg^{-1}), followed by microaggregates (7 g kg^{-1}), while the least OC concentration was found in macroaggregates (3 g kg^{-1}). Both aggregate size fraction and slope aspect significantly impacted aggregate organic carbon concentration. Although a significant effect of aggregate size on aggregate organic carbon content was found, however, our findings did not support the model of aggregate hierarchy. Both MWD and GMD were significantly impacted by aggregate size fractions. Geostatistical analysis showed that the measured soil attributes exhibited differences in their spatial patterns in both magnitude and space at each aggregate size fractions. The relative nugget variance for most aggregate-associated properties was lower than 45%. The range for water stable aggregates was almost similar (≅3 km) for the three studied aggregate size classes. The range for aggregate-associated organic carbon contents ranged from about 3 km for macroaggregates to about 6.5 km for mesoaggregates. Kriged maps of predicted WSA, OC and MWD for the three studied aggregate size fractions showed clear spatial patterns. However, a close spatial similarity (co-regionalization) was observed between WSA and MWD.

Keywords: Kriging; Organic matter; Variogram; Water stable aggregates

1. Introduction

Soil properties and their spatial distribution on different scales i.e. large and fine scales are required for different purposes (Shukla et al., 2007). Soil variability is usually associated with spatial, temporal, landscape- and management-related factors and each of theses sources can partially or fully contribute to the variability of a soil property under investigation (Van Es et al., 1999). Geostatistics is a useful tool for analyzing the structure of spatial variability, interpolating

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between point observations, and creating the map of interpolated values with an associated error map. Several attempts have been made to characterize the spatial dependency of soil properties and kriged maps of different soil properties are presented for scales ranging from a few meters to several kilometers (Sun et al., 2003; Lin et al., 2005).

Soil organic matter and aggregation are affected by various factors, among them parent materials, landscape position, climate, vegetation and management practices (Barthes et al., 2000; Krull et al., 2003; Hoyos and Comerford, 2005).

Soil organic matter is known to have a significant relationship with aggregate formation and stabilization (Tisdall and Oades, 1982; Six et al., 2000, 2002). This relationship could be reciprocal in the sense that soil organic matter content is critical for aggregate formation and stabilization. However, a portion of soil organic matter can be physically protected from decomposition by its association and incorporation into aggregates (Six et al., 2002). Soil organic matter can be also associated with primary mineral soils i.e., sand, silt, and clay. Such associations, which physically and chemically protect organic matter, are considered as the controlling factors of carbon storage and retention in soils (Shukla et al., 2007). It is reported that in many soils, most of the organic matter is stored in primary particles, particularly in the clay size fraction (Anderson et al., 1981; Shukla et al., 2007). Moreover, macroaggregates (>2 mm) in soils with a 2:1 dominant clay mineralogy are reported to have younger and more organic matter than meso- (1-2 mm) and microaggregates (<1 mm). In contrast, soils with dominant 1:1 clay mineralogy do not exhibit a higher carbon concentration in larger aggregates (Six et al., 2000, 2002).

For agricultural soils, variability of soil organic matter due to changes in the size of the secondary particles (i.e., micro-, meso, and macroaggregates) has been reported in some studies (Denef et al., 2004). However, studies on the spatial variability of soil organic matter in different aggregate fractions and relationships between aggregate stability, organic matter and soil erosion from both agricultural and rangeland soils of semi-arid regions on a catchment scale are rare. Thus, the objective of this study were: (i) to quantify the statistical characteristics of water stable aggregates (WSA), organic carbon content (OC), mean weight diameter (MWD), and geometric mean diameter (GMD) in different aggregate size fractions, (ii) to study the relationships among these properties with other related soil and landscape attributes including infiltration rate, bulk density, saturated hydraulic conductivity, soil erodibility index and terrain characteristics, (iii) to assess catchment scale spatial variability of water stable aggregates, organic carbon content in secondary particle sizes and the mean weight diameter of different aggregate size classes using geostatistical techniques.

2. Materials and Methods

2.1. Site description

The study area is located in central Zagros region of the ChaharMahal Va Bakhtiari province, Iran, about 65 km south-west of the city of Shahrekord (Figure 1). The main landform features within this 92 km^2 catchment include plateaus, upland terraces, gently rolling hills, and alluvial plains surrounded by mountains. Elevation ranges from 2393 to 2944 meters above sea level with slope gradients approximately 5% to 30%. The catchment is predominately underlain by quaternary deposits composed of sandstone and conglomerate. The annual mean precipitation is 400 mm most of which falls during winter and spring. The annual average temperature is 23 ^{o}C with the average minimum of 3.8 ^{o}C and the average maximum of 30.7 ^{o}C. The predominant soils in the catchment are entisols and inceptisols. The primary land uses within the catchment include natural pasture and dryland farming. Irrigated farming is conducted in a small portion of the catchment.

2.2. Soil sampling and analysis

The study area was sampled on a pseudo-regular initial grid spacing of 1 km during June and July 2007 (Figure 1). The minimum distance between samples was about 150 m. A total of 111 bulk soil samples were collected at the 0- to 10-cm depth. For bulk density and saturated hydraulic conductivity (Ks), at each sampling location, undisturbed soil samples were obtained from the upper 10 cm of the soil using 100-cm^3 stainless steel rings. After collection, each core was placed in a shallow tray of water and allowed to equilibrate at room temperature for two days. Ks was determined using the falling head method

(Klute and Dirksen, 1986). The infiltration test was performed at each sampling location using double-ring variable-water level infiltrometer (Bouwer, 1986). The internal diameter was 30 cm for inner and 45 cm for outer ring. To prepare the infiltration measurement surface, hay vegetation was removed and double-rings were than forced into the soil to a depth of 10 cm. The soil surface inside the ring and ring edges was then lined with a plastic wrap and water was added. The wrap was gently removed and the falling head was recorded. Subsequent to the first series of falling head measurements, water was again added to the infiltrometer, and the head drop was measured. This procedure was continued up to 120 min. Thus, the measured infiltration rate after 120-min period had approached an asymptotic value, which was recorded as the final (basis) infiltration rate. Erodibility K-factor determined for 111 sample points using Wischmeier graph (Wischmeier et al., 1971).

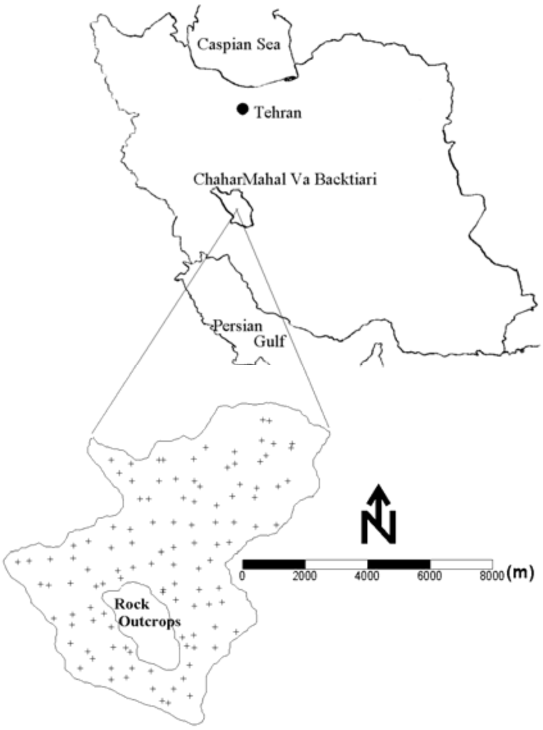


Fig. 1. Study area and sampling locations

To determine water stable aggregates, soil samples collected from the 0 to 10 cm depth were air-dried in the shade for 24 h and passed through 2 mm, 1 mm, and 0.05 mm sieves to obtain thee aggregate sizes (>2 mm, 1 to 2 mm and <1 mm). Each of these subsamples was treated as follows. Ten grams was oven-dried at 105 ^{o}C to determine the dry weight (W1). These were used to measure aggregate organic carbon content (OC). The wet sieving proceeded by spreading 10 g of the respective aggregate size sample on the sieve, and placing them on a saturated terry cloth sheet for 10 min to let aggregates absorb water slowly. Then, the tray with sieves was placed in a container filled with distilled water. Sieves were moved up and down through a vertical distance of about 3 cm at approximately one oscillation every 3 s. Wet sieving was performed for 30 min and the material retained on each sieve was oven dried at 105 ^{o}C and stored separately for determining their weight (W2). The weight of sand fraction (W3) of each subsample was determined by removing organic matter with peroxide, and chemical dispersion through the addition of sodium hexametaphosphate followed by 2 h shaking.

The percent of water-stable aggregation (WSA%) for each aggregate size was calculates as (Hoyos et al., 2005):

$$WSA\% = \frac{W2 - W3}{W1 - W3} \times 100$$

Furthermore, mean weight diameter (MWD) and geometric mean diameter (GMD) of the each aggregate size fractions were determined (Kemper and Rosenau, 1986). The portions retained on 2, 1 and 0.05 mm sieves were classified as macroaggregate, mesoaggregate, and microaggregate fractions, respectively. Organic carbon concentration was determined by dry combustion and reported as g kg^{-1} for each aggregate size.

Slope gradient, slope aspect, and contour curvatures were derived from a 100 meter resolution digital elevation model in accordance with the procedure of Moore et al. (1993). Contour curvature reflects the rate of change of the terrain aspect angle measured in the horizontal plane, and is a measure of the curvature of contours. Negative values indicate divergent water flow over the surface, and positive values indicate convergent flow.

2.3. Statistical and geostatistical analyses

Using classical statistical methods, descriptive statistics including mean, median, minimum, maximum, standard deviation, and coefficient of variation were calculated for all soil variables. To test the hypothesis of normality, the Kolmogrov-Smirnov normality test (Davis, 1986) for each property was conducted. The variability relative to the mean of soil properties can be expressed as a CV. Wilding (1985) ranked a CV <15% as the least, 15%<CV<35% as moderate, and CV>35% as the most variable. One way analysis of variance was used to test for statistical differences between the four studied soil variables (WSA, OC, MWD, and GMD) attributable to aggregate size fraction, land use, physiographic unit, landscape element, and terrain attributes. To distinguish differences between measurements where ANOVA indicated significant effects due to different factors, Fisher least significant difference (LSD) test at the 95% confidence level was used for mean separation.

The magnitude and structure of spatial variability of each soil variable was determined using variogram analysis (Webster and Oliver, 2001). Before applying the geostatistical analysis, each variable was checked for normality and anisotropy. Anisotropy analysis was conducted using surface variograms (Pannatier, 1996) and calculating directional variograms at four main geographical directions. Moreover, the existence of possible trend was explored by spatial data depicting and using background knowledge from the region. If a geographic trend was obvious, then a linear (first-order) model was developed between values of soil variable (as a dependent variable) and geographical coordinates.

Variogram (semivariance) function was calculated as:

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

where $N(h)$ is the number of pairs separated by a lag distance of h, $Z(x_i)$ is a measured variable at location i, $Z(x_i + h)$ is a measured variable at spatial location $i + h$. A typical variogram consists of three basic parameters including the nugget effect, the sill and the range. The nugget effect is a local variance component (noise) occurring at scales finer than the shortest sampling interval and could be attributed to the measurement error, fine scale spatial variations, and sampling error. The sill represents the total variance. The range determines the distance, which beyond that distance the values of the variable considered as not correlated. The theoretical models were fitted to experimental variograms. The selection of appropriate model was based on qualitative interpretation of which model best represented the overall behavior of the experimental variogram. The model parameters were calibrated based on a minimization of a weighted sum of the squared deviations between the fitted and computed values. The contour maps of each variable were created through ordinary kriging using their optimized search parameters and respective variogram models. In this study, the geostatistical analyses were carried out with Variowin (Pannatier, 1996), and maps were produced with Surfer 7.02 (Golden Software Inc., 2000).

3. Results and Discussion

3.1. Statistical properties of WSA, OC, MWD, GMD

Statistical properties of the studied soil variables for all sample points (n=111) are presented in Table 1. The average OC concentration within aggregates ranges from 2.8 g kg^{-1} for macroaggregates to 8.7 g kg^{-1} for mesoaggregates. Microaggregates contain average OC concentration of 4.9 g kg^{-1}. According to the Kolmogrov-Smirnov test, OC contents associated with meso- and microggregates followed a normal distribution, but OC concentration within macroaggregates showed slightly deviation from normality. The CV values for OC contents associated with each aggregates fractions indicated macroaggregates as the most variable (CV=71%). Among the aggregate fractions, microaggregate fraction (<1 mm) showed a lower CV value of 27%.

The mean values of water stability of aggregates ranged from 15% (for macroaggregates, >2 mm) to 84% (for microaggregates, 0.05-1 mm). The mean value of WSA for intermediate aggregates was about 23%. Among aggregate size fractions, macro- and mesoaggregates showed a slightly deviation from normal distribution. While, the coefficient of skewness for WSA was less than 1 for microaggregates. Among the aggregates size fractions, the CV value for WSA was largest for both macro- and mesoaggregates. Variability of WSA was the least for microaggregates (CV=13%). Overall, CVs for OC concentration and WSA were mostly decreased with decreasing aggregate size. The moderate to high variability of OC concentration in meso- and macroaggregates could be due to availability and rapid microbial activity and turnover of labile organic carbon (Cambardella et al., 1994; Shukla et al., 2007). In the same time, OC content is physically protected from decomposition by its incorporation into microaggregates.

For the mean values, no obvious trend was observed between OC concentrations and aggregate size. The same results were reported by Hoyos and Comerford (2005). However, the mean values of WSA were increased with decreasing aggregate size. In general, the low to moderate mean values of water stable aggregates (except, the high WSA for microaggregates) are not in the line with other studies. This could mainly due to the major differences in soils and climatic conditions. Many studies indicated percentages of water stable aggregates above 80% for different aggregate size fractions (Egashira et al., 1983; Rodriguez et al., 2002; Hoyos and Comerford, 2005; Shukla et al., 2007). In this research, only microaggregates present the mean water stability of more than 80%. However, the maximum WSA values for meso- and microaggregates were 79.4 and 99.3%, respectively. Results on the water stability of different aggregate sizes have been variable. Egarshia et al. (1983) found a mean value of 86% for 0.05-0.2 mm aggregates, while a mean WSA of 63% was reported for 0.2-2 mm. Rodriguez et al. (2002) found that aggregate larger than 2 mm were more stable (WSA=96%) than aggregates smaller than 2 mm (WSA=65%). Summary statistics of our WSA data seems to be in line with the findings of Egarshia et al. (1983). The important difference between their studies and this study is the type of soils.

The primary estimates of summary statistics of MWD and GMD indicated means were higher for microaggregates. The coefficient of skewness was also smaller (or close to zero) for microaggregates. The variability of MWD ranged from moderate (22% for microaggregates) to high (for both meso- and macroaggregates). The lower CV value for microaggregates can be attributed to the low variability of WSA for this aggregate size fraction, but this can also be affected by the mean, which was higher for microaggregates. In contrast with MWD, the variability of GMD is higher for microaggregates, although its CV value is much less than 15% for the least variability class of Wilding (1985).

Significant factors explaining the variability of water stable aggregates, organic carbon, mean weight diameter and geometric mean diameter, as the main effects, are presented in Table 2. Water stability of aggregates was influenced by aggregate size fractions (Figure 2). Macroaggregates (>2 mm) were statistically less stable, followed by intermediate aggregates, 1 to 2 mm. This result is in the line with findings of Egashira et al. (1983) where microaggregates were more stable than macroaggregates. However, it contrasts to the work of Rodrigues at al. (2002) who found that aggregates larger than 2 mm were more stable than aggregates smaller than 2 mm. Hoyos and Comerford (2005) found no meaningful difference in water stability between aggregates sizes. However, our findings indicate that aggregate water stability could be a significant concern in this landscape.

Table 1. Descriptive statistics of soil attributes (n = 111)

Variable	Mean ± SE	Median	Min.	Max.	SD	CV%	Kurtosis	Skewness
WSA, %								
Microaggregates	84.1+1.01	85.5	44.3	99.3	10.7	13	1.0	1.05
Mesoaggregates	23.4±1.45	19.6	1.1	79.4	15.3	65	2.6	1.47
Macroaggregates	14.9±0.97	12.5	1.4	45.1	10.2	68	0.7	-0.90
OC, g kg^{-1}								
Microaggregates	4.9±0.12	4.7	0.2	9.6	1.3	27	1.8	1.34
Mesoaggregates	8.7±0.33	8.6	2.6	15.7	3.5	40	-1.1	0.06
Macroaggregates	2.8±0.19	2.2	0.8	9.1	2.0	71	1.5	0.53
MWD								
Microaggregates	0.271±0.01	0.27	0.00	0.39	0.059	22	-0.6	0.03
Mesoaggregates	0.045±0.00	0.03	0.00	0.22	0.034	76	5.7	2.00
Macroaggregates	0.023±0.00	0.02	0.14	0.09	0.017	74	1.4	1.40
GMD								
Microaggregates	1.16±0.004	1.15	1.08	1.23	0.037	3	-0.6	0.03
Mesoaggregates	1.01±0.001	1.00	1.00	1.03	0.004	0.3	5.8	2.02
Macroaggregates	1.00±0.001	1.00	1.00	1.01	0.003	0.3	1.4	1.40

Table 2. Variables significant in explaining the variability of WSA, aggregate-associated OC contents, MWD and GMD (α=0.05)

Parameter	Variables considered	Variables significant
WSA, %	AS, LU, SLP ASP, CUR, PHY	AS
OC, g kg^{-1}	AS, LU, SLP ASP, CUR, PHY	AS, ASP
MWD	AS, LU, SLP ASP, CUR, PHY	AS
GMD	AS, LU, SLP ASP, CUR, PHY	AS

AS= aggregate size, LU=land use, SLP=slope gradient, ASP=slope aspect, CUR=plan curvature, PHY=physiographic units

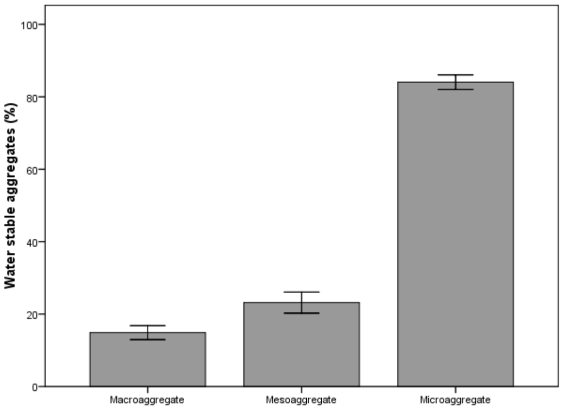


Fig. 2. Effects on water stable aggregates of aggregate size

The organic carbon concentration of aggregates was influenced by aggregate size fractions and slope aspect (Figure 3). Organic carbon was highest in mesoaggregates (≈9 g kg^{-1}), followed by microaggregates (≈5 g kg^{-1}), while the least OC concentration was found in macroaggregates (≈3 g kg^{-1}). For water stable aggregates, Holeplass et al. (2004) found a trend of increasing OC concentration with decreasing aggregate size, while Saroa and Lal (2003) reported that OC increased with increasing aggregate size. The latter trend reflects the concept of aggregate hierarchy proposed by Tisdall and Oades (1982). Present research findings however did not consistent with this conceptual model, since intermediate size aggregates (1 to 2 mm) had higher OC contents than both other aggregate fractions. Several authors reported divergences from the aggregate hierarchy model under different soils and management practices even for aggregate sparated by dry sieving (Hoyos and Comerford, 2005;

Zotarelli et al., 2005; Noellemeyer et al., 2008). Flowing data suggested that for the wet sieved aggregate size classes studied, the most important fraction for OC stabilization would be the intermediate class (1 to 2 mm), due to its higher OC concentration, followed by microaggregates (<1 mm). The OC concentration was the highest at eastern (6 g kg^{-1}) and northern (5.6 g kg^{-1}) aspects, while the lowest OC concentration was found at southern aspect (4.9 g kg^{-1}).

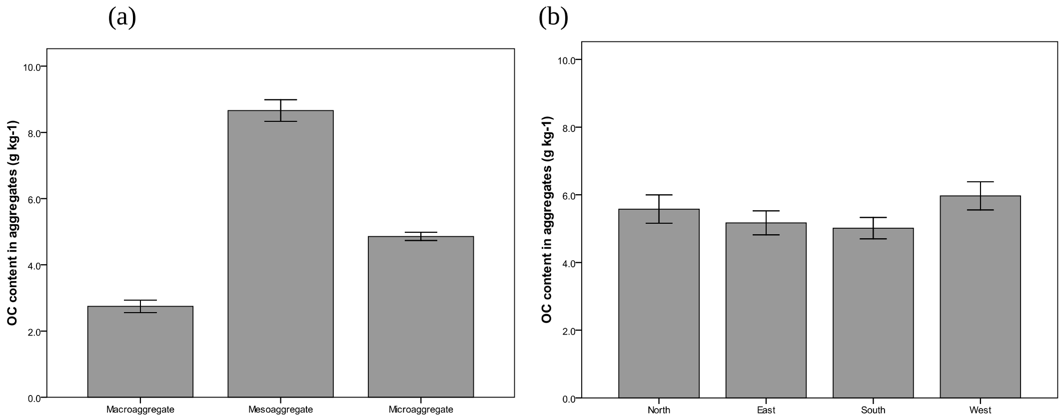


Fig. 3. Effects on organic carbon content of (a) aggregate size, (b) slope aspect

Both mean weight diameter (MWD) and geometric mean diameter (GMD) were significantly affected by aggregate size classes (Figure 4). Microaggregates had the highest MWD, while the macroaggregates represented the lowest MWD. Furthermore, MWD values were lower at southern slope aspect. These results are consistent with results obtained for aggregate-associated OC. However, the impact of slope aspect was not statistically significant at 95% confidence level.

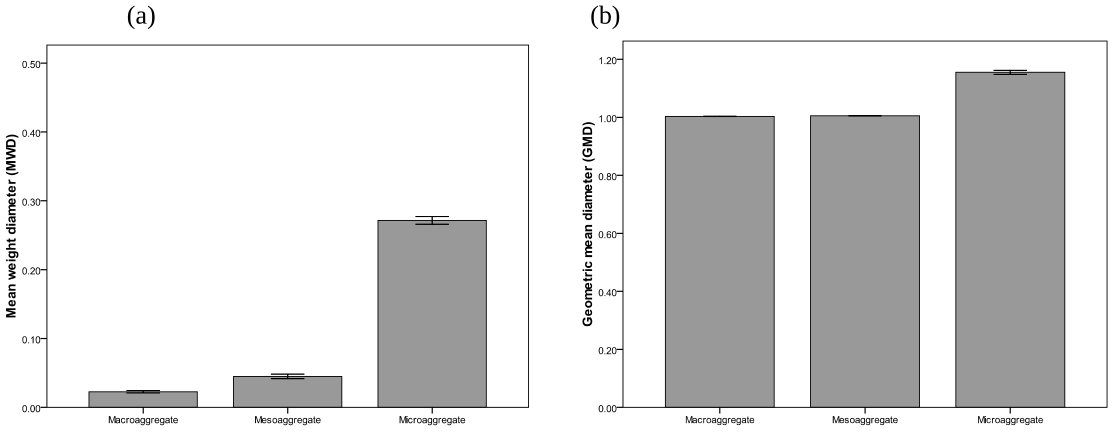


Fig. 4. Effects on (a) mean weight diameter and (b) geometric mean diameter of aggregate size

3.2. Relation among continuous soil variables

Correlation analyses showed that OC-associated with microaggregates was negatively correlated with bulk density, while no significant correlation was found between OC content of meso- and macroaggregates and bulk density (Table 3). This is in line with the findings of

Hoyos and Comerford (2005) where a negative correlation was found between total carbon and bulk density. Only OC (g kg^{-1}) content in intermediate aggregates (1-2 mm) showed negative correlations with infiltration rate (IR), saturated hydraulic conductivity (Ks), and erodibiltiy index (K). For all three aggregate size fractions, a positive and significant correlation was found between organic carbon contents and water stable aggregates (WSA). However, this relation was stronger for mesoaggregates than the other two aggregates size fractions. These results contrast to the work of Hoyos and Comerford (2005) where no correlation was found between water stable aggregates and carbon content. In general, there was a positive correlation between WSA and MWD for all three aggregate size fractions. The strength of this correlation was higher for both meso- and microaggregates. For mesoaggregates, a positive correlation was found between MWD and Ks, while for microaggregates, a negative correlation was found between MWD and bulk density. No correlation was found was found between water stable aggregates of different sized. The same was true for OC-associated with different aggregate size fractions.

Table 3. Significant correlation coefficients (Spearman r, α=0.05) among soil attributes

Variable	K	BD	IR	Ks	WSA1	WSA2	WSA3	OC1	OC2	OC3	MWD1	MWD2
K	-											
BD		-										
IR		0.29	-									
Ks		0.30	0.58	-								
WSA1	-0.20				-							
WSA2						-						
WSA3							-					
OC1					0.22			-				
OC2	-0.21		-0.20	-0.20		0.26			-			
OC3		-0.20					0.18			-		
MWD1					0.36						-	
MWD2				0.22		0.58						-
MWD3	-0.18	-0.24					0.57			0.32		

K=erodibility index, BD=bulk density (g cm^{3}), IR=infiltration rate (cm h^{-1}), Ks=saturated hydraulic conductivity (cm h^{-1}), WSA1=water stable macroaggregates (>2 mm), WSA2= water stable mesoaggregates (1-2 mm), WSA3= water stable microaggregates (<1 mm), OC1=organic carbon content in macroaggregates, OC2=organic carbon content in mesoaggregates, OC3=organic carbon content in microaggregates, MWD1= mean weight diameter of macroaggregates, MWD2= mean weight diameter of mesoaggregates, MWD3= mean weight diameter of microaggregates

3.3. Spatial variability of aggregate properties

Since majority of the measured and calculated soil variables closely resembled a normal distribution, no transformation was used on data sets. In order to check any anisotropic behavior in spatial variability of soil variables, the first surface variogram was calculated for all variables. There was no anisotropy seen in the surface variograms for any of the measured and calculated soil properties. Therefore, only isotropic models were fit. The experimental variograms for WSA, OC, and MWD of macro-, meso-, and microaggregate fractions were obtained to a lag of 1200 to 1300 m and a cut distance of 10 km. Table 4 lists the variogram parameters for the variables. The variograms of selected soil variables are shown in Figure 5. To define the degree of spatial dependency, spatial class ratios similar to those presented by Cambardella et al. (1994) were adopted. That is the ratio of nugget variance (noise) to total variance (sill) multiplied by 100. If the ratio of spatial class was less than 25% then the variable is considered to be strongly spatially dependent; if the ratio was between 25% and 75%, the variable was regarded as moderately spatially dependent; and if the ratio was more than 75%, the variable was considered weakly spatially dependent.

The exponential model provided good estimated of isotropic variogram parameters for the majority of variables. For OC contents of macro- and mesoaggregates, spherical model produced a better fit than exponential model, but these improvements were minor. These results are in the line with findings of Motaghian et al., (2008) where the same theoretical variogram models i.e., an exponential model were fitted to the studied soil variables including bulk density (BD), infiltration rate (IR), saturated hydraulic conductivity (Ks), clay, silts, and sand contents in the same study area. We also calculated the experimental variograms of both erodibility index (K) and organic matter content (OM) in the bulk primary soil particles of clay, silt and sand fractions (results not shown). Both variograms were fitted best by an exponential model.

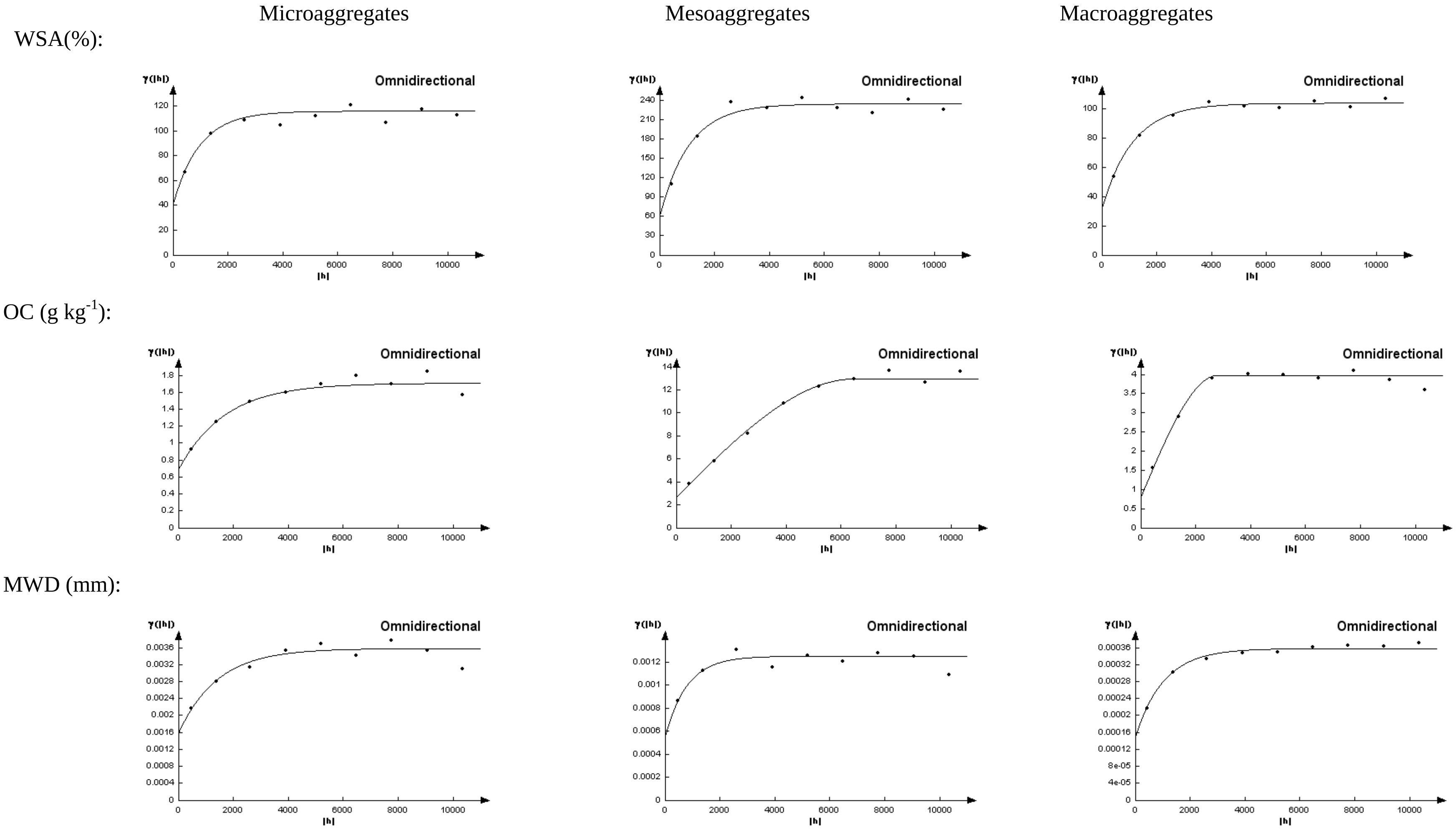
Variogram usually increases with lag distance to a constant value or sill (an approximation of total variance) at a given distance, known as the range of spatial dependence. Range values depend on the spatial interaction of soil properties affecting each variable at the sampling scale used (Trangmar et al., 1987). Theoretically, the variogram value at lag equal zero should be equal to zero but the experimental variograms frequently exhibit a discontinuity known as the nugget variance. Nugget variance represents the random variability at the sampling scale and reflects the variability at distances closer than the smallest sampling distance, measurement errors or errors in location (Webster and Oliver, 2001). All variogram models of WSA, MWD, and OC contents in macro-, meso-, and microaggregate fractions showed a positive nugget effect (Table 4).

Table 4. Variogram characteristics of soil attributes

Variable	Model	Nugget	Sill	Range (m)	Spatial dependency class
WSA, %					
Microaggregates	Exponential	42.0	116.59	2906	Moderate
Mesoaggregates	Exponential	61.86	236.13	3194	Moderate
Macroaggregates	Exponential	32.51	104.32	3364	Moderate
OC, g kg^{-1}					
Microaggregates	Exponential Spherical	0.697	1.717	5046	Moderate
Mesoaggregates	Spherical	2.760	13.021	6469	Strong
Macroaggregates		0.823	4.003	2803	Strong
MWD					
Microaggregates	Exponential	0.0016	0.0036	4201	Moderate
Mesoaggregates	Exponential	0.0006	0.0013	2371	Moderate
Macroaggregates	Exponential	0.0002	0.0004	3091	Moderate

The fitted variograms indicated the existence of moderate to strong spatial dependency for all soil properties. Among all variables, variograms of OC-associated with large and intermediate represented the strong spatial dependency, which suggested that these variables showed a considerable spatial dependence within sampling distances. However, MWD variograms showed high ratio of nugget variance to total variance (sill) for the three studied aggregate size fractions. This ratio for K index and bulk OM content was 5% (strong spatial dependency) and 25% (strong to moderate spatial dependency), respectively. Motaghian et al., (2008) reported a strong class of spatial dependency for BD and sand content, while the moderate spatial dependency was found for IR, Ks, clay, and silt contents.

Probabilistic determination of variations in a soil variable using a variogram function implies that the random field has similar properties in different parts of the studied domain (Shukla et al., 2007). If an experimental variogram reaches a sill value asymptotically, it implies that the random filed is second-order stationary (Schabenberger and Pierce, 2002). All variogram models of WSA, MWD, and OC concentrations in the three aggregate size classes showed a positive sill, and therefore without further testing we assumed that the random fields were second-order stationary. The variance stability also means that there is no drift in the data, and the mean of the variable is constant. The modeled sill values of the theoretical variograms for all variables were approximated well the sample variance, indicating a general absence of trends (Trangmar et al., 1987). A high sill value is an indication of higher variability of the soil variable being examined. Among the three aggregates size fractions, the sill value for WSA was highest in mesoaggregates. The same trend was observed for OC content and MWD.



Microaggregates Mesoaggregates Macroaggregates

WSA(%):

OC (g kg^{-1}):

MWD (mm):

Fig. 5. Experimental omnidirectional variograms (points) and the theoretical models (solid lines) for different soil attributes

The range of influence is considered to the maximum distance up to which two sample points in the study area remain correlated. Beyond the range, the average rate of change becomes independent of the separation distance between two observations. This value is important for finding the minimum sampling distance for ensuring independence. A definite and positive range for variograms showed that the most attributes were not completely random at the scale of sampling and measurement. The range for WSA varied from 2906 m (for microaggregates) to 3364 m (for macroaggregates). The range value for mesoaggregates was fallen in between (3194 m). Motaghian et al., (2008) reported range values of 3937 m, 3850 m, and 3080 m for IR, Ks, and BD, respectively. While, the range values of 6160 m, 7040 m, and 8250 m were found for sand, silt, and clay content. They distinguished two classes of the geostatistical range values and attributed to the geomorphological and land use management (topography, landforms and land use) and geological (parent materials) characteristics of the present landscape. The first class of range values (in average of 3 km) could be coincide with landscape morphology and land use practices; while the second class of range values (in average of 7 km) could be in agreement with geological structure of the study area. It seems to us that the range values of WSA for all the three studies aggregate size fractions can be grouped within the first above mentioned class of range values. In contrast to the WSA, range values for OC contents associated with all three aggregate fractions were not similar. Among the three aggregates fractions, macroaggregates showed a smaller range value of 2803 m, while the range value for meso- and microaggregates were 6469 m and 5046 m, respectively. A closer similarity between the latter range values with those reported for primary soil particles i.e., sand, silt, and clay content, points to the role of primary particles known to be significantly affects organic matter stabilization. Therefore, in the studied landscape, OC asscociated with primary particles might be a significant concern that should be investigated in detailed in the future. Almost the similar trend was observed in range values of MWD for the three aggregates size fractions. The range values for erodibility K index and bulk organic matter content (results not shown) were 2663 m and 3410 m, respectively. In contrast to this study, Shukla et al. (2007) reported that range values for WSA, MWD, C and N contents of macro-, meso-, and microaggregates varied from 28 to 176 m, which was much lower than those reported here. The important difference between their study and this study is the scheme and the size of grid for soil sampling. They used sampling of interval of 20 by 20 m for soil sampling. In addition, their study area included some small sites with low variability of intrinsic and extrinsic factors. In general, we did expect such a trend and variation in the range values because of the high variability of intrinsic and extrinsic factors across the present landscape. Being the larger range values than the minimum sampling distance (about 150 m); the soil sampling scheme used in this study was adequate for all attributes.

Kriged maps of WSA, MWD and OC associated with the three aggregate size fractions are presented in Figure 6. Measured soil properties exhibited differences in their spatial patterns in each aggregate size fractions. Furthermore, spatial patterns for some attributes also differed among aggregate size classes in both magnitude and space. However, for all three studied aggregate size fractions, a close spatial similarity (co-regionalization) was observed between WSA and MWD.

4. Conclusions

This study showed meaningful difference in water stability between aggregate sizes. The high percentage of water stable aggregates was obtained for microaggregates (<1 mm). This result indicated that in this landscape, aggregate water stability is a significant concern. These soils showed moderate amount of organic carbon contents. Nevertheless, there were significant differences among aggregate size fractions. Mesoaggregates contain higher organic carbon concentration, followed by microaggregates. These soils did not exhibit aggregate hierarchy, reflecting an important role of other factors playing in aggregation processes. The effect of slope aspect on aggregate organic carbon concentration was significant. The lower amount of aggregate organic carbon content was found at southern slope aspects. The study of organic matter fractions and organic matter associated with primary particles may help clarify the role of organic matter on the aggregation processes occurred in these soils, and the observed difference in soil organic carbon under different terrain positions. By calculating the mean weight diameter for each three studied aggregate size classes, in addition to WSA, a single MWD parameter was obtained to represent each aggregate size fraction.

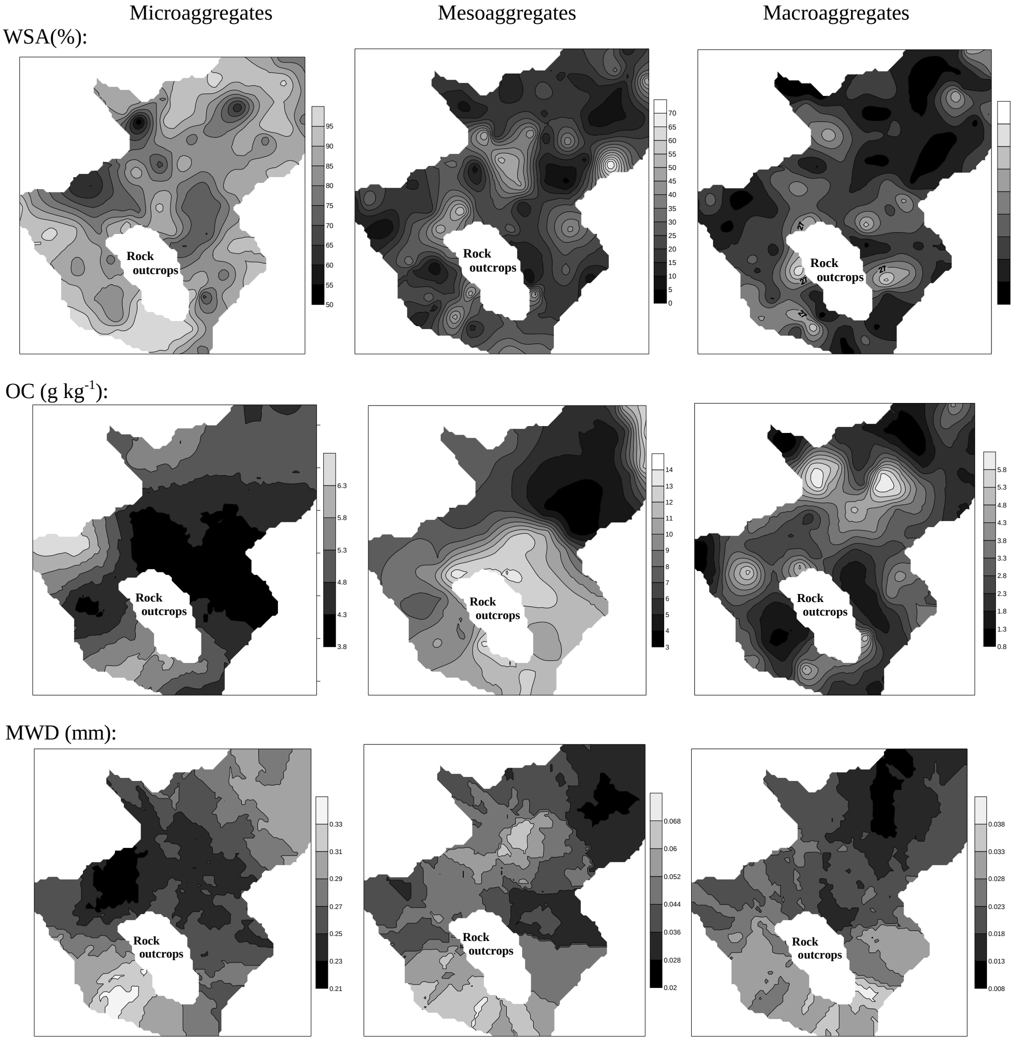


Fig. 6. kriged maps of different soil attributes

It was based on this hypothesis that the importance of each three studied aggregate size groups is not equal to the final MWD parameter. Nevertheless, the results obtained from MWD for each aggregates sized fractions showed a close similarity to those obtained for water stable aggregates. The statistical variability i.e., CV values, of all measured soil attributes decreased with decreasing the aggregate size. However, the CV alone cannot distinguish between the extrinsic and intrinsic sources of variation. Overall, the magnitude of the spatial dependency ranged from moderate to strong for most soil attributes. The range values for variograms of WSA ranged from 2906 to 3364 m, attributed to the spatial distribution patterns of landscape morphology and land use practices in the study area. Organic carbon associated with micro- and mesoaggregates showed higher range values, which could be explained with spatial distribution patterns of the geological (parent materials) characteristics of the present landscape. Our results showed that (i) wet sieved aggregates provide meaningful fractions for studies of the impact of land use, physiography and landscape positions on aggregate stability and OC concentration, (ii) aggregate stability and OC contents within all the three studied aggregate size fractions are a significant concerns in the studied landscape, (iii) important roles of landscape positions, physiographic characteristics, and land use management on both aggregate stability and carbon sequestration, and (iv) statistical and geostatistical approaches provide an excellent data mining framework for knowledge exploring about physical and chemical soil properties.

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