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Research Article

Soil texture fractions and fractal dimension of particle size distribution as predictors of interrill erodibility

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Abstract: Choosing a particular textural fraction as an erodibility predictor is often confusing because various fractions of soil particles have been introduced as erodibility index by many researchers. Recently, advances in fractal theory have introduced a scaling parameter for characterizing soil fragments. The objectives of this study were (i) to test the applicability of fractal dimension of particle size distribution (PSD) for estimation of interrill erodibility and (ii) to study the relationship between interrill erodibility and soil texture components. Samples from 36 soil series with contrasting characters were collected from northwest Iran. The sand fractions were obtained by sieving, while silt and clay fractions were determined by hydrometer. Fractal dimension (D_B) of PSD was estimated. A rainfall simulator with drainable tilting flume (1×0.5 m^2) at a slope of 9% was used and interrill erodibility (K_i) was calculated for 20, 37, and 47 mm h^{-1} rainfall intensities. The results showed a positive correlation between K_i and clay content. The degree of dependence of K_i to soil texture fractions (sand, silt, and clay contents) was greatly affected by the rainfall intensity level. Using either texture fractions (sand, silt, very fine sand and sand) or D_B did not affect the accuracy of the K_i- predicting models. As use of fractal dimension could follow the principles of uniqueness, fractal dimension of PSD may be applied as an alternative of texture fractions for prediction of interrill erodibility.

Key words: Erosion predictor, fractal dimension, interrill erodibility, soil texture

Introduction

Soil texture is an important character contributing to soil erodibility. Soils high in silt and very fine sand (USDA classification system of particles), or expanding clay minerals tend to have high erodibility. Erodibility is low for clay-rich soils with a low shrink-swell capacity, as clay particles mass together into larger aggregates that resist detachment and transportation (ÓGeen et al. 2006). Aba Idah et al. (2008) stated that sandy soils have low cohesive force and are more prone to detachment and transportation by water and wind. Wischmeier and Smith (1978)

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used sand and silt fractions as indices for estimation of soil erodibility factor in the USLE model. Duiker et al. (2001) in their erosion test found that average soil loss is negatively correlated with clay content but positively correlated with very fine sand and silt+very fine sand contents. They concluded that very fine sand content alone is not the best predictor of interrill erodibility.

Flanagan and Nearing (1995) introduced clay fraction as a predictor to estimate the interrill erodibility of cropland soils containing less than 30% sand. They also introduced very fine sand fraction as a predictor to estimate the interrill erodibility of cropland soils containing 30% or more sand. León (2005) proposed very fine sand besides silt content as suitable variables for the interrill erodibility estimation. Obi et al. (1989) found that erosion was well predicted by sand percentage with a negative relationship.

Choosing of a particular texture fraction as an erodibility predictor, however, is often confusing because various fractions of soil have been introduced as an erodibility index by various researchers. A good index used to describe soil erodibility should follow the principles of uniqueness and applicability. Recently advances in fractal theory have introduced a scaling parameter for characterizing soil fragments. This scaling parameter is called fractal dimension and its value depends on the shape of individual objects within the distribution. Fractal dimensions are characterized by a power-law relation between the mass or number and size of objects. The fractal dimension of particle size distribution (PSD) has been significantly correlated with soil texture fractions by many researchers (e.g. Huang and Zhan 2002; Millan et al. 2003; Su et al. 2004). Fractal theory offers the possibility of quantifying and integrating information about biological, chemical, and physical phenomena in soil (Perfect and Kay 1995; Anderson et al. 1998). The objectives of this study were (i) to test the applicability of fractal dimension of PSD for estimation of interrill erodibility and (ii) to study the relationship between interrill erodibility and soil texture parameters.

Materials and methods

Soil sampling and analysis

To provide a wide range of particle size distribution 36 soil series (Bordbar 1967) with diverse properties were selected from the northwest of Iran and 36 samples were taken from the Ap or A horizon of soil profiles. The samples were air dried at room temperature. A sub-sample of about 2 kg of each soil was sieved using 2-mm sieve apertures. Soil texture (Gee and Or 2002), organic matter, pH, EC, cation exchange capacity (CEC), sodium adsorption ratio (SAR), calcium carbonate equivalent (CCE), and $CaSO_4$ were determined using standard laboratory methods (Sparks 1996).

Soil particle size distribution was described according to percentage of clay (<0.002 mm), fine silt (0.002-0.005 mm), medium silt (0.005-0.02 mm), coarse silt (0.02-0.05 mm), very fine sand (0.05-0.1 mm), fine sand (0.1-0.25 mm), medium sand (0.25-0.5 mm), coarse sand (0.5-1 mm), and very coarse sand (1-2 mm). The sand fractions were obtained by sieving, and silt and clay fractions were determined by hydrometer (Gee and Or 2002).

Fractal parameters estimations:

Fractal dimension of the soil particles (D_B) was estimated by Bird et al.'s (2000) model:

$$M_s\,(d \le d_i) = c d_i^{3-D_B} \tag{1}$$

where $M_s(d \le d_i)$ is the total mass of particles of size less than d_i, and c is a composite scaling constant defined by Perrier et al. (1999) and Bird et al. (2000). To obtain D_B for each soil, log ($M_s(d \le d_i)$) was regressed against log (d_i) and D_B was calculated from the slope of the regression lines.

Soil erosion test

A rainfall simulator with a single scanning nozzle located 4 m above the soil surface, and a drainable tilting flume (1-m length, 0.5-m width, and 0.1-m depth) was used as erosion/runoff plot. To prepare the erosion test sample, the flume was laid in a horizontal position and a 1-cm thick water-permeable mat was placed in the flume. Air-dried soil, passed through a 4.75-mm sieve, was loosely packed in the flume with

0.09-m thick layer and then was saturated from the base by a constant-head water supply for 24 h. Excess water was allowed to drain from the soil by gravity for 5 min before the start of each experiment, and the drainage outlet remained open during the experiment; then the slope of the flume was adjusted to the 9% and was subjected to the rainfall for at least 90 min. Rainfall intensity treatments were 20 mm h^{-1}, 37 mm h^{-1} and 47 mm h^{-1}, which will be designated hereafter as I_A, I_B, and I_C, respectively. The flume provided sufficient runoff and soil erosion for interrill erodibility analysis, but could not supply sufficient flow for producing bed shear stress to induce rill erosion. Outflow runoff samples were collected continuously manually at different time intervals, from less than 60 s at the beginning to up to 15 min near the end of the test. At the end of the experiment, the volume of runoff samples (V) was measured and they were allowed to evaporate. The remaining mass was oven dried at 105 °C for 24 h and weighed (M_d), allowing the sediment load to be determined at each time interval during the erosion test. Sediment concentration in each runoff sample was computed as M_d /V. These data were used to calculate runoff and erosion rates. The observed interrill erodibility values were calculated using Eq. (2) (Kinnell 1993):

$$K_i = \frac{D_i}{I_e \sigma_{ir} S_f} \tag{2}$$

where K_i is interrill erodibility (kg s m^{-4}), D_i is interrill erosion rate (kg m^{-2} s^{-1}), I_e is rainfall intensity (m s^{-1}), σ_{ir} is interrill runoff rate (m s^{-1}), and S_f is the slope factor (dimensionless) calculated as (Liebenow et al. 1990):

$$S_f = 1.05 - 0.85 \exp^{(-4 \sin(\theta))} \tag{3}$$

where θ is the slope angle (degrees).

D_i and σ_{ir} were considered, respectively, as the ratios of mean sediment mass ($\bar{M}_d$) per unit area and the mean runoff volume ($\bar{V}$) per unit area to the mean time intervals ($\bar{t}$) at which steady-state conditions were realized and the sediments and runoffs were measured.

Statistical analysis

Statistical analysis of the experimental data was accomplished using the STATISTICA software package (StatSoft 2004). This included normality analysis of the acquired data distribution using the Kolmogorov-Smirnov test of the data and correlation analysis between K_i as dependent variable, and clay, silt, sand, silt+vfs and fractal dimensions of soil particles, as independent variables.

The functional relationship between K_i and soil textural parameters was evaluated by regression technique. Two outliers (data points) of I_A dataset on the scatter plots (on the base standard residual >2sigma) were discarded to improve considerably the regression fit (Figure 1). Coefficient of determination (R^2) and Morgan-Granger-Newbold (MGN) test (Harvey 1997) were applied to compare predictive accuracy of the regression modeling. Two different

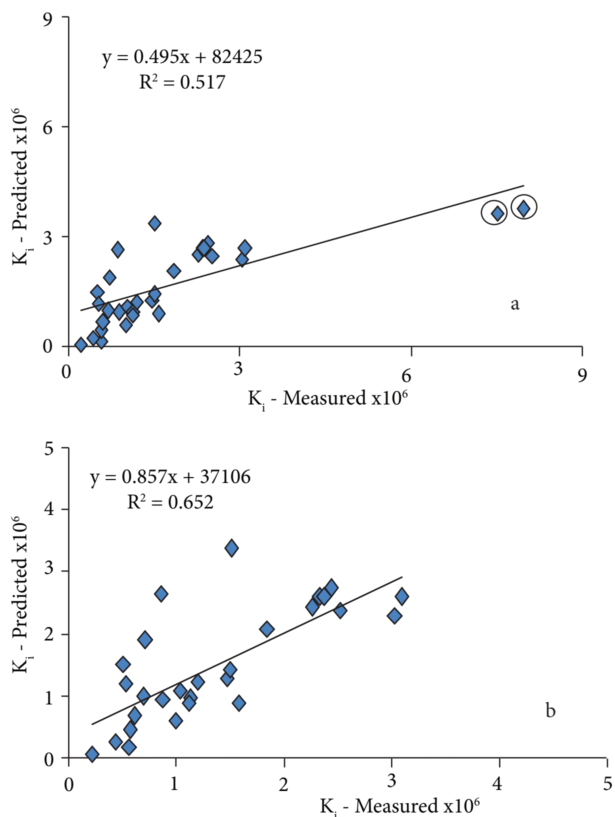

Figure 1. Comparison of measured and predicted K_i for the all 36 soils (a) and for the 34 soils (b) after dropping 2 outlier data points (encircled).

approaches were adopted in the model structure. In the first approach, texture fractions were included as independent variables and non-significant variables were excluded from the model by the stepwise method. In the second approach fractal parameters were included in simple linear regression modeling.

Results

Soil properties and fractal dimensions of PSD

Table 1 summarizes the range, mean, and standard deviation of some physical and chemical properties of the examined soils. There were considerable differences in SAR, EC, organic matter, CCE, clay, silt, and sand contents among the soils used in this experiment. The greatest coefficients of variation occurred for SAR (130.3%). This high variation in soil properties imparts a generality to the findings and allows them to be applied with greater reliability to other soils.

Table 1 contains statistics of the fractal dimensions of PSD in 36 examined soils. The values for D_B ranged from 2.60 to 2.89 and are comparable to those reported by Bayat (2009) for 124 soil samples from the west and northwest of Iran. Results in Table 1 showed that the PSDs of all 36 examined soils have fractal behavior, because they have fractional (non-integer) dimensions ($D_B < 3$). The results (Table 2) also showed that the low D_B values were obtained for soils containing high sand, while greater D_B values were associated with soils that had high silt and clay contents. Therefore, D_B seems to be able to differentiate between soil textures.

Interrill erodibility

Interrill erodibility parameters (K_i) of the examined soils calculated at 3 rainfall rates using Eq. (2) are listed in Table 3. The values ranged from 1.03 to 79.71 × 10^5 kg s m^{-4}, depending on the soil and rainfall intensity.

Table 2. Mean and standard deviation (SD) of fractal dimensions (D_B) of each texture class.

Texture class	Number of samples	D_B Mean	D_B SD
silty clay	2	2.88	0.01
clay	1	2.85	-
silty clay loam	5	2.84	0.01
clay loam	7	2.82	0.03
sandy clay loam	1	2.78	-
loam	13	2.74	0.03
sandy loam	6	2.69	0.05
sand	1	2.63	-

Table 1. Overall minimum, maximum, mean, standard deviation (SD), and coefficient of variation (CV) of some properties of the studied soils.

Soil properties		Min	Max	Mean	SD	CV (%)
pH		6.81	8.3	7.79	0.29	3.7
SAR	$(cmol\ kg^{-1})^{0.5}$	0.31	34.72	5.84	7.61	130.3
CEC	$(cmol_c\ kg^{-1})$	6.8	59.9	23.96	11.07	46.2
EC	$(dS\ m^{-1})$	0.41	8.56	2.19	2.15	98.7
SP	(%)	24.01	69.08	41.81	12.94	31.0
$CaSO_4$	(%)	0	0.61	0.21	0.12	57.1
CCE	(%)	3.7	26.3	16.18	6.48	40.1
OM	(%)	0.06	4.38	1.91	1.35	70.7
Clay	(%)	8.5	50.2	26.0	10.9	42.1
Silt	(%)	1.4	53.0	34.6	11.4	33.0
Sand	(%)	6.5	90.1	39.4	20.2	51.2
Very fine sand	(%)	0.0	22.0	10.1	5.5	54.5
D_B	-	2.60	2.89	2.77	0.07	2.54

Table 3. Minimum, maximum, mean, standard error (SD), and coefficient of variation (CV) of interrill soil erodibility (K_i) values.

Dataset	Rainfall intensity ($mm\ h^{-1}$)	Min.	Max.	Mean	SD	CV (%)
		$\times 10^5$ ($kg\ s\ m^{-4}$)				
I_A	20	2.10	79.71	15.52 ^{ns}	14.58	93.94
I_B	37	1.03	39.69	13.27 ^{ns}	8.75	65.95
I_C	47	3.17	44.38	15.15 ^{ns}	8.87	58.54
Combined	-	2.39	46.47	13.98	8.62	61.64

^{ns}: Not significant at the 0.05 level

Soil erodibility (K_i) and texture parameters

Table 4 shows the relation between K_i and soil texture parameters (percent clay, silt, and sand, and fractal dimensions of PSD).

High soil loss with increasing silt content (significant positive correlation between K_i and silt content, Table 4) was observed for various soils. Unlike the finding reported by Elliot et al. (1989), Table 4 shows a highly significant positive correlation between K_i and clay. The correlation of K_i to the fractal dimensions of particle size distribution is also shown by the significant positive correlation between K_i and D_B.

Table 5 shows the regression equations constructed using stepwise ridge regression analysis and the corresponding coefficient of determination. At I_A rainfall rate, clay content, at I_B rainfall rate sand and vfs contents, and at I_C rainfall rate none of the texture fractions remained in the model. By using the combined dataset, clay fraction in the regression model accounted for 24% of the variation in K_i.

Interrill erodibility parameter, K_i, was also predicted by the second approach where fractal dimensions were included in the linear regression analysis (Table 5). Accordingly, D_B was included in the models of I_A and I_B and the combined dataset, and accounted for 66%, 16%, and 19% of the variation in K_i, respectively.

Table 4. Simple correlation coefficient (r) of interrill erodibility (K_i) at 3 rainfall intensities to textural fractions and PSD fractal dimensions.

Texture parameters	K_i I_A	I_B	I_C	Combined
clay	0.804**	0.481**	0.286	0.436**
silt	0.596**	0.466**	0.221	0.458**
sand	-0.735**	-0.525**	-0.278	-0.496**
vfs	-0.076	-0.061	0.023	-0.116
vfs+silt	0. 466**	0.464**	0.346*	0.428**
D_B	0.812**	0.398*	0.213	0.370*

I_A, I_B and I_C present rainfall intensities of 20, 37 and 47 mm h^{-1}, respectively

* and ** mean significant at the 0.01 and 0.05 level

Table 5. Regression equations to estimate interrill erodibility (K_i) from soil texture fractions and fractal dimensions of soil particles.

Rainfall intensity	Equation	R^2	MGN
I_A (20 mm h^{-1})	K_i=8658254 D_B -22510000	0.66**	-
	K_i=5766325 clay-55490	0.65**	2.09^{ns}
I_B (37 mm h^{-1})	K_i=4884291 D_B -12200000	0.16**	-
	K_i=1985941-3189005 sand +2690122 vfs	0.37**	2.03^{ns}
Combined data	K_i=4909085 D_B -12210000	0.19**	-
	K_i=3572701 clay + 554920	0.24**	1.45^{ns}

* and ** mean significant at the 0.01 and 0.05 level
^{ns}: Not significant at the 0.05 level

Discussion

Our results show that the lower values of D_B were related to the soils that had the greater sand content, while the higher values were related to the soils with greater silt and clay contents. Therefore, it seems that fractal dimension is able to differentiate between soil textures. Wang et al. (2006) stated that the lowest and the highest fractal dimension of PSD corresponded to sandy and clay soils, respectively. Giménez et al. (1997), on the other hand, reported that fractal dimension values showed an unclear trend with soil texture. Huang and Zhan (2002) also found that the fractal dimension of PSD increased with clay but decreased with sand contents.

The lack of significance among difference in K_i values at the 3 rainfall rates implies that K_i is independent of rainfall intensity. In other words, according to Eq. (2), it appears that changes in D_i and σ_{ir} become almost proportional to the variation in the rainfall rate in a way that keeps K_i unaltered. Kinnell (1993) has also considered K_i as an independent factor from rainfall intensity in the steady-state condition of soil erosion. However, Asadi et al. (2008) reported that K_i increased with rainfall rate, indicating that there is a structural uncertainty hidden in Eq. (2).

Correlation of K_i to soil texture parameters was higher in low rainfall intensity (I_A) than in high (I_C) rainfall intensity (Table 4). These results imply that with increasing rainfall intensity other soil properties rather than texture may control K_i. Asadi et al. (2008) also reported a bias and systematic error in predicting K_i from the WEPP-recommended model using soil texture fractions at higher rainfall intensities. They concluded that neglecting the dominancy of flow-driven erosion at high rainfall rates and ignoring the effect of water depth on interrill erosion were probably the most important problems concerning the interrill component of the WEPP model. Chaves and Nearing (1991) concluded that this uncertainty arises from the inadequacy and incompleteness of the model in representing the physical system being studied.

There was a significant positive correlation between K_i and silt content. Silt-sized particles are small enough to reduce the permeability of a soil and are also easily transported by runoff (FDER 1988). Ross et al. (1988) also reported that soils with high contents of silt are generally more erodible. A negative correlation between sand fraction and K_i means that it takes more energy to transport sand particles. There was no correlation between very fine sand (vfs) and K_i. Duiker et al. (2001) reported that very fine sand content alone is not the best parameter to use to predict interrill erodibility. Our findings (Table 4) also show that K_i has a higher correlation with vfs + silt than vfs alone.

A positive correlation between K_i and clay may relate to the nature of the clay minerals present in the soils of the current study (Lado et al. 2004). Khormali and Abtahi (2005) and Samadi et al. (2008) reported that expanding clays are the major clay minerals in the soils of west and northwest of Iran. They swell markedly and adversely affect resistance to erosion (Ross et al. 1988; Mermut et al. 1997). Udeigwe et al. (2007) also found a positive relationship between clay content and soil erosion. They reported that clay mineralogy could have an important effect on erodibility. Yılmaz et al. (2005) reported that there is a positive relationship between structural stability and kaolinite, and there is a negative relationship with smectite.

At the low (I_A) and moderate (I_B) rainfall intensities, clay and sand contents, respectively, showed the highest correlation with K_i (Table 4). This means that at different rainfall intensities various fractions of soil texture may control the discharge of sediment. Kinnell (2009) also showed that at low rainfall intensity (20 mm h^{-1}) the proportion of coarse material in sediment load decreased because the rates of particles moving through interrill erosion by raindrop impact induced saltation were lower than the rates that occurred during the high rainfall intensity (50 mm h^{-1}).

At the high rainfall intensity (I_C) K_i was correlated only with vfs + silt contents; this may be due to greater flow depth and lower raindrop impact induced saltation of coarser soil particles (Asadi et al. 2008). Decreasing in correlation coefficients between K_i and soil texture fractions at I_c intensity level may imply that under high rainfall intensities the detachment-limiting sediment process dominated. Assouline and Ben-Hur (2006) stated that the earlier stage of erosion is mostly a transport-limited regime, which shifts to a detachment-limited regime especially at higher rainfall intensities. Tromp-van et al. (2008) in their studies assumed that rainfall detachment is nonselective with respect to particle size.

The results of the predictive accuracy test (MGN, Table 5) showed that a nonsignificant difference was found between accuracy of the models derived using either texture fractions (sand, silt, very fine sand and sand) or D_B. On the other hand, since using fractal dimension could follow the principles of uniqueness, fractal dimension of PSD could be applied as an alternative of texture fractions for prediction of interrill erodibility.

Conclusions

Unlike the results reported by several researchers, our findings showed a positive correlation between K_i and clay content. It could be due to differences in clay mineralogy. The clarification, however, needs further research.

The degree of dependence of interrill erodibility (K_i) to soil texture fractions (sand, silt and clay contents) was greatly affected by the rainfall intensity level. No unique regression model could be constructed to predict K_i equally well at various intensity levels.

Using either texture fractions (sand, silt, very fine sand and sand) or D_B did not affect the accuracy of the K_i-predicting models. On the other hand, since using fractal dimension could follow the principles of uniqueness, fractal dimension of PSD could be applied as an alternative of texture fractions for prediction of interrill erodibility.

As our data set is restricted to a semi-arid area, further study is needed at different soil and climatic conditions to generalize the findings of this study.

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