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Effect of Different Land Use Treatments on Soil Structural Quality and Relations with Fractal Dimensions

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Abstract: In this study, the feasibility of making the use of fractal dimension to quantify soil aggregate stability in different land use systems was investigated. For this purpose the non-linear fractal dimension (D_{nl}) and the Mean Weight Diameter (MWD) of aggregates were compared. In October 2005, soil samples from three sites with four adjacent land-use types namely: forest area (F), cultivated lands adjacent to forest (CAF), pasture (P) and cultivated lands adjacent to pasture (CAP) were collected. Cultivated pasture (CAP) had the largest value of D_{nl}, while pasture (P) had the smallest value of D_{nl}. Difference of D_{nl} between forest and pasture was not significant, while both of them significantly differed from that of cultivated forest (CAF) and cultivated pasture (CAP) in this parameter. There were significant differences between forest and pasture for the measured MWD. Coefficient of variations (CVs) between MWD and D_{nl} were also contrasted and the low value of CV indicated the higher precision of the method used. The lowest CVs belonged to D_{nl}, demonstrating that D_{nl} was more accurate than MWD methods. Fractal dimension had negative correlation with MWD, SOM, Hydraulic Conductivity (HC) and macroaggregates (>0.25 mm) and positive correlation with Bulk Density (BD) and Total Porosity (TP).

Key words: Fractal dimension, mean-weight diameter, soil aggregate stability, land use

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INTRODUCTION

Rapid population growth in the residential areas of central Zagrous in Iran, has increased the demand for farmland and food production. One way to expand the cropland is clear cutting the forests and converting pastures to agricultural fields. This would result in lowering soil structure, loss of soil quality and consequently destruction of natural ecosystem (Hajabbasi *et al*., 1997).

Soil structure is critical for germination and growth of plants and also transport of water and contaminants through the unsaturated zone underlying agricultural fields (Pirmoradian *et al*., 2005).

A scale is needed to quantify soil structure variation. Aggregate-size distribution (ASD), is a representative of soil structure and is potentially a useful way, even if not exhaustive, of expressing soil structural quantity. The need to characterize soil ASD with a single parameter has long been recognized. Early workers simply used the percentage by weight of aggregates greater than some specified, but arbitrary, sieve size (Pirmoradian *et al*., 2005). However, much information is lost by this approach. As a result several empirical indices have been proposed for describing the entire distribution with a single value. Van Bavel (1949) used mean-weight diameter (MWD) to integrate aggregate-size distribution obtained by mechanical sieving. Mazurak (1950) suggested that the geometric mean diameter may be more appropriate.

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Recent findings in fractal theory introduced scaling parameters, as fractal dimension that may be suitable for characterizing aggregate-size distribution in soil (Pirmoradian *et al*., 2005; Gulser, 2006). According to Mandelbrot (1982), fractals are characterized by a power-law relation between the number and size of objects. The value of fractal dimension D is equal to the absolute value of the exponent in the relation:

$$N{>}x = K(x)^{-D} \tag{1}$$

where, N>x is the cumulative number of objects greater than x and k is a constant corresponding to the number of fragments of unit length. The value of D depends on the shape of individual objects within the distribution and the overall extent of aggregate fragmentation. The higher value of D is associated with the greater aggregate fragmentation. This means that the shape of aggregate may be similar in various ranges of aggregate size. However, it may be assumed that the value of D is scale invariant in shape. Rasiah *et al*. (1992) used the fractal dimension to evaluate the influence of cropping and wetting treatments and aggregate size on the fragmentation of soil aggregates. Significant relation between aggregate number and fragmentation fractal dimension was observed. The estimated D value varied with cropping and wetting treatments. Perfect and Kay (1991), Rasiah *et al*. (1992), Pirmoradian *et al*. (2005) and Gulser (2006) reported that fractal theory may be used to characterize soil-aggregate size distribution from different cropping treatments. Higher D values will indicate greater soil fragmentation. Gulser (2006) measured the relation between fractal dimension and Organic Carbon (OC) content and bulk density. He proposed that fractal dimensions decreased with increasing SOC content, MWD and with decreasing Bulk Density (BD).

The objectives of this study were to determine the effect of different land use treatment on soil structural quality, investigate the ability of fractal dimension to quantify soil aggregate stability in different land use and find relationships between fractal dimension and some soil parameters such as mean-weight diameter, bulk density and soil organic matter.

MATERIALS AND METHODS

Study Area

The study area is located within the northern parts of Karoon watershed in the central Zagros, Iran (31°11′ N and 51°14′ E) with an altitude of about 2050 m above the sea level. The soil was classified as coarse-silty, carbonatic, calcixerollic and xerocherpts. The land-used pattern included: forest, unaltered pastures and cultivated lands both adjacent to the forests and pastures. The prevailing climate is Mediterranean with a long term mean annual precipitation of 502 mm. The forest area is approximately 340,000 hectare with a history of at least 20 years of anthropogenic activities such as cropping and pasture grazing. Dominant tree species of these sparse forests is oak (*Quercus brontii*). This area has been subject to deforestation and tillage disturbance where barley and wheat have been cultivated continuously since 1987. Plant cover of long term pastures ranges from 70 to 90% depending on the severity of grazing. Dominant grass species in pasture include *Astragalus* spp.

Soil Analyses

A two-factor analysis of variance under randomized complete block design consisting of four replications was used. Soil samples were collected from three sites with four adjacent land-use types: forest area (F), cultivated lands adjacent to forest (CAF), pasture (P) and cultivated lands adjacent to pasture (CAP) in October 2005. Some characteristic of the soil used in this study were evaluated in soil samples taken from the 0-7 and 7-15 cm soil depth of the field (Table 1). After soil samples were air dried and passed through a sieve with 2 mm size opening, some soil properties determined were as follows:

Table 1: Some soil physical and chemical properties of the experiment site

Land uses treatments*	Sand	Silt	Clay	EC	pH
	------------(g kg^{-1})------------		------------------(dS m^{-1})------------------		
F	270	330	300	0.58	8.1
CAF	330	400	270	0.87	7.9
P	250	400	350	0.51	7.7
CAP	270	410	320	0.67	8.0

*F: Forest area, CAF: Cultivated lands adjacent to forest, P: Pasture and CAP: Cultivated lands adjacent to pasture

Particle size distribution was determined by hydrometer method (Gee and Bauder, 1986). Soil Organic Mater (SOM) content was determined by modified Wallkley-Black method (Nelson and Sommers, 1982). Saturated Hydraulic Conductivity (HC) in each site was measured as three replicates by the constant head method according to (Klute and Dirksen, 1986). The samples were used for saturation and consecutively oven-dried at 105°C to determine the Total Porosity (TP) and Bulk Density (BD). Total porosity was calculated in undisturbed water-saturated samples of 100 cm^3 assuming no air trapped in the pores and validated using dry bulk density and a particle density of 2.65 g cm^{-3} (Danielson and Sutherland, 1986).

Aggregate Size Distribution

The wet sieving method of Kemper and Rosenau (1986) with a set of 2, 1, 0.5, 0.25 and 0.1 mm diameter sieves was used to determine aggregate size distribution. After passing soil sample through an 8 mm sieve, approximately 50 g of the soil was put on the first sieve of the set and was gently moistened to avoid sudden rupture of the aggregate. After moistening, the set was sieved in water at 50 oscillations per minute. After 10 min of oscillation, soil remaining on each sieve was dried and then sand and aggregate were separated (Kemper and Rosenau, 1986). For determination of aggregate size distribution, the weight ratio of aggregates of each sieve (>2, 2-1, 1-0.5, 0.5-0.25 and < 0.1 mm) to the total weight of aggregates was calculated.

Mean weight diameter was calculated as follows:

$$\mathrm{MWD} = \sum_{i=1}^{n} X_i W_i \tag{2}$$

where, X_i is the mean diameter in mm of the openings of two consecutive sieves and W_i the weight ratio of aggregates remaining on the ith sieve.

Estimation of Fractal Dimension

The number of aggregates left on ith sieve of a nest of sieves can be computed from aggregate mass data as follows (Tyler and Wheatcraft, 1992):

$$N_i = \frac{M(x_i)}{x_i^3} \tag{3}$$

where, N_i is the number of aggregates left on ith sieve of a nest of sieve, $M(x_i)$ is the aggregate massing on the *i*th sieve of a nest of sieves and X_i is the size of aggregate in mm. Inserting Eq. 3 into Eq. 1 and assuming scale-invariant density and shape of aggregates, the following equation is derived for the estimation of D from mass-size distribution:

$$\sum_{x=1}^{x} \frac{M(x)}{x^3} = K\ x^{-D} \tag{4}$$

where, M(x) is the total mass of aggregate with sizes less than x. Soil samples were used in a dry sieve and aggregate bulk density of different size classes was measured by Rasiah and Biederbeck (1995).

Fractal dimension in Eq. 4 was determined by non-linear D_{nl} method. Marquradt's (1963) optimization technique was used for non-linear fitting. Statistical analysis of data was conducted using the SAS computer software package.

RESULTS AND DISCUSSION

Aggregate Bulk Density

Since the bulk density was measured on pooled samples, statistical analysis was not possible. However, the variation in the data was small (1290-1410 kg m^{-3}). Therefore, the aggregate bulk density was scale-invariant and the average of these values (1332 kg m^{-3}) was used as the bulk density of soil aggregate for determination of D in Eq. 4.

Soil Properties

Effects of the change in land use on the mean values of Soil Organic Matter (SOM), Bulk Density (BD), saturated Hydraulic Conductivity (HC) and Total Porosity (TP) are given in Table 2. Soils under cultivation had higher bulk density than the adjacent soils under forest and pasture. The forest soil had the lowest and the cultivated pastures had the highest bulk density values. Soil bulk density was not different between the pasture and forest sites. The loss of SOM by the conversion of the pasture and forest into cultivated fields probably caused a higher bulk density in the cultivated soils. Relative to SOM of the forest and pasture soils, SOM of the cultivated soils decrease by 30 and 31% for 0-15 cm layer, respectively (Table 2). Similar finding were reported by Hajabbasi *et al*. (1997) that deforestation and subsequent tillage practices resulted in a 50% decrease in SOM for a soil depth of 0-30 cm in central Zagrous Mountain regions. There was a significant difference in total porosity between cultivated soils and forests and pastures soils. Relative reduction in the total porosity was about 8 and 13% for forest and pasture soil, respectively (Table 2). The forest and pasture soils did not differ in total porosity for the layer of 0-15 cm. Similar finding were reported by Celik (2005) that cultivation of forest and pasture resulted a 5% decrease in total porosity for soil in depth of 0-10 cm. In this study, there was a significant difference in saturated Hydraulic Conductivity (HC) between forest and the rest of treatments. No significant difference between pasture and cultivated forest and pasture was observed. While the forest had highest hydraulic conductivity, the cultivated forest had the lowest value at the depth of 0-15 cm.

Fractal Dimension Variation for Different Land Use Treatments

Statistical analysis of data indicated that there was no significant difference between values of D_{nl} in different depths (probability $p = 0.05$). Therefore, the mean values of D_{nl} were used in further statistical analysis. The values of D_{nl} for different land use treatments ranged from 2.853-3.024 (Table 3). Cultivated pasture (CAP) had the largest value of D_{nl} while pasture (P) had

Table 2: Effect of changing land use on some parameters

Land uses treatments*	OM (%)	BD (g cm^{-3})	HC (cm h^{-1})	TP (m^3 m^{-3})
F	3.66^a	1.19^b	0.25^a	0.54^a
CAF	2.59^b	1.30^a	0.14^b	0.50^b
P	3.19^a	1.21^b	0.19^b	0.55^a
CAP	2.21^b	1.38^b	0.17^b	0.48^b

*F: Forest area, CAF: Cultivated lands adjacent to forest, P: Pasture and CAP: Cultivated lands adjacent to pasture. Means followed by same letter(s) in each column are not significantly different at 1% level of probability the smallest value of D_{nl}. Difference of D_{nl} between forest and pasture was not significant, while both of them were significantly different when compared to cultivated forest (CAF) and cultivated pasture (CAP) in this parameter.

Changes in soil structure are often accompanied by changes in management practices and may affect the effectiveness of these changes. Quantification of these changes requires the adoption of certain parameters. Soil aggregate composition has been found to be a good indicator of the changes in soil structure. The fragmentation fractal dimension can be inferred from the role of biological processes in soil structure formation. Inorganic and relatively persistent organic binding agents are important in the stabilization of microaggregates (<0.25 mm in diameter) by implementation of different kinds of mechanisms (Zhao *et al*., 2006). In forest and pasture sites, soil environment is more favorable for microbial activity, so there were more water stable aggregates in forest soil and pasture compared to cultivation lands. Study results showed that changing forest and pasture to cultivated land increased the values of non-linear fractal dimension. In most studies, it has been found that the value of fractal dimensions increases with increasing fragmentation and higher fractal dimension values indicate a distribution dominated by smaller fragment (Perfect and Kay, 1991; Millan *et al*., 2002). In this study, the higher fractal dimensions were observed in soils dominated by smaller aggregates in cultivated forest and cultivated pasture. The lower fractal dimensions have always been observed in soils with larger aggregates present in forest and pasture.

Mean Weight Diameters

Statistical analysis of data showed no significant difference between values of MWD at different depths thus, the mean values of MWD were used in further statistical analysis. Mean-weight diameters (MWD in mm) for different land use treatments are shown in Table 3. The observed range of MWD was between 0.26-0.58 mm. The mean-weight diameter of soil aggregates was significantly greater in the forest and pasture soils than in the cultivated forest and cultivated pasture. Cultivation caused an approximate decrease of 48 and 32% MWD in the forest and pasture, respectively compared to that of the undisturbed sites. The presence of the macroaggregates is positively associated with organic matter concentration (Duiker *et al*., 2003). Cultivation broke up soil aggregates and exposed previously inaccessible organic matter to microbial attack and accelerated decomposition and mineralization of SOM (Shepherd *et al*., 2001). In this study, a significant difference in MWD between forest and pasture was observed, while Celik (2005) was not able to detect a significant difference between forest and pasture in Mediterranean highland which is practically more acceptable.

Relationship between the values of D_{nl} and MWD is shown in Fig. 1. The best-fit equation for this relationship is as follow:

$$D_{nl} = -0.22\ \ln(\mathrm{MWD}) + 2.7 \qquad (5)$$

with a value for R^2 of 0.47. Non-linear relationship between D_{nl} and MWD indicated that MWD was unable to quantify soil aggregate stability in the similar manner as that of D_{nl}.

Table 3: Non-linear D_{nl} and mean-wight diameter MWD for different land use

Land use treatments*	MWD (mm)	CVs of MWD (%)	D_{nl}	CVs of D_{nl} (%)
F	0.588^a	50	2.865^a	6.5
CAF	0.310^c	30	2.99^b	5.0
P	0.420^b	35	2.853^a	8.0
CAP	0.260^c	53	3.024^b	6.0

F: Forest area, CAF: Cultivated lands adjacent to forest, P: Pasture and CAP, Cultivated lands adjacent to pasture. Means followed by same letter(s) in each column are not significantly different at 1% level of probability

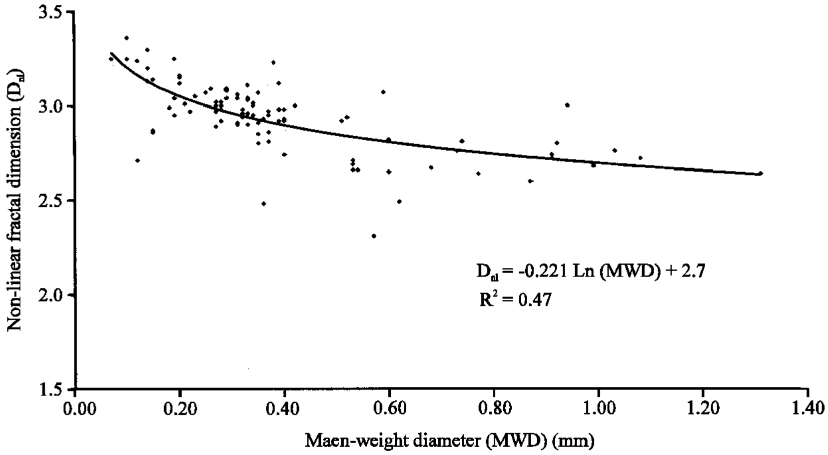

Fig. 1: Relationship between the non-linear fractal dimension D_{nl} and the mean-weight diameter MWD, R^2, coefficient of determination

Table 4: Relationships among the fractal dimensions and MWD and some soil parameters

Parameters	D_{nl}	MWD	>0.25 mm	HD	OM	BD	TP
D_{nl}	1.00	-0.75**	-0.67**	-0.65**	-0.78**	0.68**	-0.52*
MWD	-0.75**	1.00	+0.73**	0.56**	0.64**	-0.68**	0.53*

*Correlation is significant at 5% level. **Correlation is significant at 1% level

There was no systematic variation for MWD to describe the aggregate stability (Table 4). For example, the value of MWD of pasture (P) was lower than that of forest (F). This trend of variation for MWD cannot be explained theoretically, because soil aggregate fragmentation should be practically similar in forest and pasture. D_{nl} in this study was not significantly different between forest and pasture. These results implicated that practically D_{nl} may be more appropriate. Comparison of CVs of MWD with fractal dimension showed larger CVs of MWD. These findings indicated that fractal dimension was more accurate and more precise than MWD.

Relationship Between Fractal Dimensions and Other Parameters

Non-linear fractal dimension was found by applying Equation 5 into each wet sieving soil data set. The relationships among fractal dimension D_{nl}, MWD, SOM and other parameters are given in Table 4. Fractal dimension had negative correlation with MWD, SOM, HC and macroaggregates (>0.25 mm) and a positive correlation with BD and TP.

The significant negative correlations between fractal dimensions and MWD indicated that D_{nl} values increased with decreasing aggregate size due to changes in land use. Perfect and Kay (1991), Pirmoradian *et al.* (2005) and Gulser (2006) reported that MWD was negatively correlated with fractal dimension. Fractal dimensions had a significant negative correlation with SOM content. Forest provided the highest SOM content and the lowest fractal dimension. Increments in SOM content in forest and pasture treatments increased the proportion of larger aggregates in the distribution and caused a decrease in fractal dimensions. In numerous studies, it was found that fractal dimensions were negatively correlated with SOM content and values of aggregate stability (Rasiah *et al.*, 1993; Gulser, 2006). Fractal dimensions had a significant linear correlation with bulk density and total porosity. The highest values of fractal dimensions and BD were obtained in the cultivated pasture. Decreasing macroaggregation content in soil due to changes in land use caused an increase in fractal dimension, bulk density and an increase in total porosity.

CONCLUSION

Cultivated forest and pasture significantly decreased SOM, MWD and TP and increased BD when compared to forest and pasture. Changing forest to cultivated forest had higher negative effects on SOM and MWD than changing pasture to cultivated pasture.

The proportion of macroaggregates in the fractions (>0.25 mm) was decreased due to change in land use. Increases in the number of stable macroaggregates are associated with good sustainable soil structure. The values of D_{nl} decreased as the number of stable macroaggregates in the soil increased. Lower fractal dimension values indicated a distribution dominated by larger fragments rendering aggregates more resistant to fragmentation. The relationships between the fractal dimensions and the other parameters showed that fractal dimensions decreased with increasing SOM, MWD and macroaggregates (>0.25 mm) and decreased with BD and TP. When the values of coefficient of variations (CVs) between MWD and D_{nl} were compared, lower value of CV indicated the higher precision of the method. In this study the lowest CVs were detected in D_{nl}, resembling D_{nl} as more accurate and precise than MWD. Due to strong theoretical base of the fractal dimension, results of this analysis can be used to evaluate the soil aggregate stability. As a result, change in land use decreases soil structure through decreasing macroaggregates.

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