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Application of Fractal Theory to quantify Soil Aggregate Stability as influenced by Tillage Treatments

N. Pirmoradian[1]; A.R. Sepaskhah[1]; M.A. Hajabbasi[2]

[1]Irrigation Department, College of Agriculture, Shiraz University, Shiraz, I.R. of Iran; e-mail of corresponding author: sepas@shirazu.ac.ir
[2]Soil Science Department, Isfahan University of Technology, Isfahan, I.R. of Iran

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Soil structure is critical for the seed germination, growth of plants, and water and contaminants transport. Soil structure is modified by tillage treatments. A scale is needed to quantify the tillage-induced changes in soil structure. The present study investigated the ability of fractal dimension to quantify soil aggregate stability in a calcareous soil in an arid region as influenced by tillage treatments. Furthermore, the non-linear fractal dimension D_{nl} was compared with mean-weight diameter D_{mw} and geometric mean diameter D_{gm} of aggregates. Results indicated that fractal dimension D_{nl} was more appropriate than D_{mw} and D_{gm} to quantify soil aggregate stability induced by tillage treatments. The mouldboard plough plus disc (MD) and twice chisel plough, orthogonal to each other plus disc (2CD) treatments, due to higher soil aggregate fragmentation, are not recommended. On the other hand, the no-till (NT) and till-planting (TP) treatments resulted in the best soil aggregate stability, but low yield may be obtained in the NT treatment. Furthermore, the chisel plough plus disc (CD), and Khishchi tined implement plus disc (KD) treatments were not significantly different from the NT and TP treatments. However, temporal analysis of the non-linear fractal dimension indicated that the values of D_{nl} were increased during the experiment years, particularly, in the MD, CD, CR, and 2CD treatments, while the fractal dimension in the TP and NT treatments started to increase late in the 4th year. Therefore, the tillage-planting and the NT treatments may be the most appropriate tillage treatment in the conservation of soil aggregate stability.

1. Introduction

Soil structure is critical for the germination and growth of plants (Braunack & Dexter, 1989) and for the transport of water and contaminants through the unsaturated zone underlying agricultural fields (Thomas & Phillips, 1979; Bevan & German, 1982). Soil structure may be defined as 'the spatial heterogeneity of the different components or properties of soil'. In other words, it is the variation of solids and voids as a function of scale that defines soil structure (Dexter, 1988).

A scale is needed to quantify soil structure variation. Distribution of aggregates of different sizes, abbreviated to aggregate-size distribution, is a consequence of soil structure and is a potentially useful way, even if not exhaustive, of expressing structure quantitatively. The need to characterise soil aggregate-size distribution with a single parameter has long been recognised. Early workers simply used the percentage by weight of aggregates greater than some specified, but arbitrary, sieve size. However, much information is lost by this approach (Puri & Puri, 1939). 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 D_{mw} to integrate aggregate-size distribution obtained by mechanical sieving. Mazurak (1950) suggested that the geometric mean diameter D_{gm} may be more appropriate. More recently, Baldock and Kay (1987) used the following power function to describe the cumulative percentage of aggregates by weight less than a characteristic linear

Notation

A, B	regression constants
D	fractal dimension
D_l	linear fractal dimension
D_m	mass-size fractal dimension
D_n	number-size fractal dimension
D_{nl}	non-linear fractal dimension
D_{mw}	mean-weight diameter of aggregates, mm
D_{gm}	geometric mean diameter, mm
E	estimated drag force of tillage implements, $kN\,m^{-1}$
K	a constant corresponding to the number of fragments of unit length
$M(x_i)$	aggregate mass on the ith sieve of a nest of sieve, g
$N_{>x}$	cumulative number of objects greater than x
W	cumulative weight of aggregate, %
w_i	weight ratio of aggregates remained on the ith sieve
x	characteristic linear dimension, mm
x_i	average diameter of the sieve opening or size of aggregate, mm

dimension x (*e.g.* equivalent diameter or height);

$$W_{<x} = A(x)^B \tag{1}$$

where: W is the cumulative percentage weight of aggregate; x is the characteristic linear dimension; and A and B are regression constants. Since the coefficient B exhibited maximum variation, it was used as the index of aggregate size distribution. Previous indices to quantify soil structure, often, were empirical. Recent advances in the fractal theory introduced scaling parameters, as fractal dimension that may be suitable for characterising aggregate-size distribution in soil. According to Mandelbrot (1982), fractals are characterised 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

$$N_{>x} = k(x)^{-D} \tag{2}$$

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 larger the value of D, the greater the aggregate fragmentation. This means that the shape of aggregate may be similar in various ranges of aggregate size. However, it may be assumed the value of D is scale invariant in shape.

According to the fractal fragmentation model of Turcotte (1986), the fractal dimension in soil is expected to be <3 since the inequality $D \geqslant 3$ would require that the probability of grain fragmentation be $\geqslant 1$ which is not valid. Perfect and Kay (1991), however, indicated that the value of D determined from aggregate-size distribution is a measure of soil fragmentation and showed that it can be as high as 3·5. Fractal dimension has been used to characterise the influence of soil properties and cropping systems on the size distribution of aggregate, subsequent to fragmentation (Rasiah *et al.*, 1992, 1993). These investigators have reported values of $D>3$. McBratney (1993) has also questioned the merit of values $D>3$ and their physical significance. Perfect *et al.* (1993) showed, however, that values of $D>3$ are theoretically possible if the fragmentation process exhibits multifractal behaviour. Physically, values of $D>3$ mean that fragments are retained at each level in the hierarchy than is possible for fractal fragmentation. Rasiah and Biederbeck (1995) have shown that values of D obtained using the non-linear fitting procedure in general were smaller and more accurate than those obtained using the linear procedure.

Perfect and Blevins (1997) have shown that fractal parameters are sensitive to tillage treatment. Mouldboard ploughing increased soil aggregate fragmentation in comparison with no-till. Sepaskhah *et al.* (2000) compared indirect number-size fractal dimension D_n, mass-size fractal dimension D_m, and mean-weight diameter D_{mw}, as measures of soil aggregate stability. The fractal dimensions D_n and D_m decreased with increasing amount of mulch application indicating an increase in aggregate stability as a result of the addition of the mulch.

The present study investigated the ability of fractal dimension to quantify soil aggregate stability in a calcareous soil in an arid region as influenced by tillage treatments. Furthermore, the fractal dimension was compared with mean-weight diameter D_{mw} and geometric mean diameter D_{gm} of aggregates.

2. Materials and methods

The original data of this research were obtained from Hajabbasi and Hemmat (2000) on the effect of seven different tillage systems on soil aggregation and organic carbon that were taken during 4 yr (1994–1997) at the

Table 1
Soil physical and chemical properties of the experiment site

Depth, cm	*Bulk density, kg m^{-3}*	*Sand, g kg^{-1}*	*Silt, g kg^{-1}*	*Clay, g kg^{-1}*	*N, mg kg^{-1}*	*P, mg kg^{-1}*	*K, mg kg^{-1}*
0–15	1410	240	400	360	890	21·9	171·7
15–30	1430	120	440	440	810	13·9	176·7

Kabootarabad Research Station of Isfahan Agricultural Research Center, 40 km southeast of Isfahan (central I.R. of Iran). The soil is fine-loamy mixed, Typic Haplocambids (Calcic Cambisol). Some of the soil's physical and chemical properties are shown in Table 1. The soil samples were obtained from several places in the field and then pooled. The pooled sample was used for determination of physical and chemical properties. Therefore, the data in Table 1 are average of the field, and standard deviation was not calculated. Furthermore, clay particles are transferred to the lower depth (15–30 cm) due to the consecutive irrigation water application in the irrigated field. Tillage treatments were as follows: (1) mouldboard plough plus disc (MD); (2) chisel plough plus disc (CD); (3) chisel plough plus rotary tiller (CR); (4) twice chisel plough (orthogonal to each other) plus disc (2CD); (5) Khishchi plus disc (KD); (6) till-planting with a cultivator combined drill (TP); and (7) no-till with a cultivator combined drill with no cultivator shank (NT). The Khishchi is a locally made secondary tillage implement used in the region. It has 15 straight rigid shanks, fixed on a two-row chassis at a spacing of 14 cm with a vertical clearance of 35 cm. Each shank is equipped with a triangular 5 cm wide point with a rake angle of 44°. The TP and NT treatments were direct drilling systems.

A randomised complete block design consisting of four replications was used. During the first 3 years of study, two samples out of each plot were taken from the 0–15, and 15–30 cm soil depth. For all the treatments during the 4th year, the depth of cultivation was considered as the first depth of sampling (0–20 cm for MD and 0–15 cm for other treatments). To be comparable with the other treatments, 0–15 cm was also taken as the first sampling depth for the drilling system. The second depth of sampling was 10 cm below the first sampling depth of each treatment. The wet sieving method of Kemper and Rosenau (1986) with a set of sieves of 2, 1, 0·5, and 0·25 mm diameter was used to determine aggregate size distribution. After passing the soil sample through a 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, then sand and aggregates were separated (Gee & Bauder, 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 <0·25 mm) to the total weight of aggregates was calculated.

Mean weight diameter D_{mw} and geometric mean diameter D_{gm} were calculated as follows:

$$D_{mw} = \frac{\sum_{i=1}^{n}(x_i w_i)}{\sum_{i=1}^{n} w_i} \tag{3}$$

$$D_{gm} = \mathrm{Exp}\left[\frac{\sum_{i=1}^{n} w_i \ \ln\ x_i}{\sum_{i=1}^{n} w_i}\right] \tag{4}$$

where x_i is the average diameter in mm of the openings of two consecutive sieves and w_i the weight ratio of aggregates remaining on the ith sieve.

The number of aggregates left on ith sieve of a nest of sieves can be computed from aggregate mass data as follows (Tyler & Wheatcraft, 1989):

$$N_i = \frac{M(x_i)}{x_i^3} \tag{5}$$

where: N_i is the number of aggregates left on ith sieve of a nest of sieves; $M(x_i)$ is the aggregate mass in g on the ith sieve of a nest of sieves; and x_i is the size of aggregate in mm. Substituting Eqn (5) in Eqn (2) and assuming scale-invariant density and shape of aggregates, the following equation is derived for the estimation of D from mass-size distribution

$$\sum_{x=1}^{x} \frac{M(x)}{x^3} = kx^{-D} \tag{6}$$

where $M(x)$ is the total mass of aggregate of size less than x. Pooled soil sample from soil surface was used in a dry sieve analysis and the aggregate bulk density of different size classes was measured by Chepil (1950) as reported by Rasiah and Biederbeck (1995).

Fractal dimension in Eqn (6) was determined by linear D_l and non-linear D_{nl} method. In the linear method, according to Eqn (6), D was obtained by regression between $\log N\,(x > X)$ and $\log x$. Marquardt's (1963) optimisation technique was used for non-linear fitting. Statistical analysis of the data was conducted using the SPSS8 computer software package and means for each year were compared using Student–Newman–Keuls test.

3. Results and discussion

3.1. *Aggregate bulk density*

The measured bulk density of different size classes of aggregates are shown in Table 2. Since the bulk density was measured in pooled samples, therefore, statistical analysis was not possible. However, according to the variation in measured data (1290–1410 kg m^{-3}) differences between these values were considered not significant. Therefore, the aggregate bulk density was scale-invariant and the average of these values (1340 kg m^{-3}) was used as the bulk density of soil aggregate for determination of D in Eqn (6).

3.2. *Fractal dimension*

All data were pooled and correlation between D_{nl} and D_l values was obtained (*Fig. 1*). The slope and intercept of the linear regression line were 0·31 and 1·26, respectively. Statistical comparison between this line and the 1:1 line (the null hypothesis was: intercept of 0 and slope of 1) indicated that slope and intercept of this line was significantly different from line of 1:1. Therefore, the values for D_l were different from those for D_{nl}. Therefore, appropriate values for D must be selected to quantify soil structure variation, according to theoretical consideration, statistical analysis and the literature. The values of D by linear and non-linear fitting methods, varied between 1·55–3·12 and 1·49–2·38, respectively. The values of D obtained using the non-linear procedure were always smaller than the corresponding values obtained using linear procedure. By the non-linear method, the values of D were always less than 3, while in the linear method some values of D were greater than 3. The standard error of D_l and D_{nl} were 0·043 and 0·024, respectively. These results are consistent with those reported by other investigators (Rasiah *et al.*, 1995; Perfect *et al.*, 1994; Rasiah & Biederbeck, 1995). Using a detailed error structure analysis, Rasiah *et al.* (1995) have also shown that values of D_{nl} were more accurate than D_l. For log-transformations in particular, smaller values are weighted more heavily than larger values (Smith *et al.*, 1980). Thus, when the log-transformed form (linear method) was used for fitting, considerably more emphasis or bias was placed on smaller values of N_i, *i.e.* on larger values of x_i. On the other hand, when the non-linear method was used for fitting, the estimates of D_{nl} was not biased toward any size class compared with D_l. Based on these results, it is suggested that D_{nl} is more accurate than D_l. Therefore, D_{nl} was used to quantify soil structure variation.

Table 2
Aggregate bulk density of different size classes

Aggregate size, mm	*Density, kg m^{-3}*
<0·25	1290
0·25–0·6	1300
0·6–1·0	1310
1·0–2·0	1360
2·0–5·0	1410
5·0–10	1360
Mean	1340

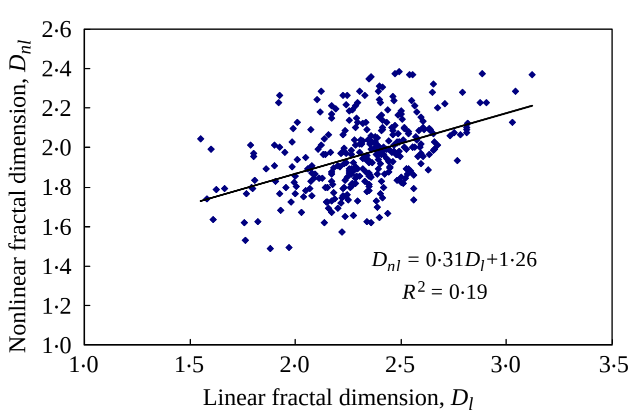

Fig. 1. Relationship between the fractal dimension D_l (obtained from linear relationship) and D_{nl} (obtained from non-linear relationship); R^2, coefficient of determination

3.2.1. *Fractal dimension variation in tillage treatments*

Statistical analysis indicated that there was no significant difference between values of D_{nl} in different depth (probability $P = 0·05$). Therefore, the mean values of D_{nl} were used in further statistical analysis. The values of D_{nl} for different tillage treatments and in different experimental years ranged 2·028–2·324 (Table 3). Maximum and minimum values of D_{nl} were related to mouldboard plough plus disc (MD) in the 4th year and chisel plough plus rotary tiller (CR) treatment in the 1st year, respectively. Decreasing arrangement of D_{nl} was obtained as follows:

(1) mouldboard plough plus disc (MD); (2) twice chisel plough plus disc (2CD); (3) chisel plough plus disc (CD); (4) chisel plough plus rotary tiller (CR); (5) Khishchi plus disc (KD); (6) till-planting (TP); and (7) no-till (NT).

As higher values of D_{nl} correspond to more fragmentation of soil aggregates, therefore, this arrangement is

Table 3
Non-linear fractal dimension D_{nl} for tillage treatments in the experiment years

Tillage treatments	*Fractal dimension*			
	Experiment years			
	1	*2*	*3*	*4*
Mouldboard plus disc (MD)	$2{\cdot}091^{b*}$	$2{\cdot}195^{a}$	$2{\cdot}218^{a}$	$2{\cdot}324^{a}$
Chisel plus disc (CD)	$2{\cdot}043^{b}$	$2{\cdot}173^{a}$	$2{\cdot}157^{a}$	$2{\cdot}231^{b}$
Chisel plus rotary (CR)	$2{\cdot}028^{b}$	$2{\cdot}094^{b}$	$2{\cdot}176^{a}$	$2{\cdot}267^{ab}$
Twice orthogonal chisel plus disc (2CD)	$2{\cdot}175^{a}$	$2{\cdot}103^{b}$	$2{\cdot}184^{a}$	$2{\cdot}298^{a}$
Khishchi plus disc (KD)	$2{\cdot}034^{b}$	$2{\cdot}097^{b}$	$2{\cdot}184^{a}$	$2{\cdot}240^{b}$
Plant-till (TP)	$2{\cdot}098^{ab}$	$2{\cdot}101^{b}$	$2{\cdot}142^{a}$	$2{\cdot}205^{b}$
No-till (NT)	$2{\cdot}071^{b}$	$2{\cdot}124^{ab}$	$2{\cdot}124^{a}$	$2{\cdot}209^{b}$

*Means followed by the same letters in each column are not significantly different at 5% level of probability according to Student–Newman–Keuls test.

acceptable in physical sense. The obtained order is explainable with tillage method and effect of applied equipment on soil structure. Soil turning upside down by the mouldboard plough and shattering of soil particles by the disc (MD) resulted in the highest soil aggregate fragmentation and the largest value for D_{nl} in this treatment. The chisel plough, due to its tine spacing distance, disturbs only 25% of soil surface. Therefore, for the 2CD treatment, aggregate fragmentation is lower than for the MD and its value for D_{nl} is smaller. In the CD treatment, soil is turned over only in one direction. Therefore, aggregate fragmentation is lower than for the 2CD treatment. The difference between the CD and CR treatments is that the disc was used in the CD treatment and rotary tiller in the CR treatment. The rotary tiller has L-shaped blades and it resulted in breaking the soil into pieces. Therefore, aggregate fragmentation in this treatment is lower than in the CD treatment and it was placed in the next order. The next treatment is the Khishchi plus disc (KD). The Khishchi, due to its design (explained in Section 2), displaced the soil, whereas, the chisel plough broke the soil. Therefore, aggregate fragmentation and the value of D_{nl} in the KD treatment were lower than that for the CR treatment. The next order was TP treatment, where soil was till-planted with a cultivator combined with drill. Therefore, aggregate fragmentation was lower than previous treatment. The last order was NT treatment. In this treatment, a cultivator combined drill was used with no cultivator shank. Therefore, aggregate fragmentation and the value of D_{nl} were the lowest. The effects of tillage treatments on mass fractal dimension D_m for the soil moisture retention equation was investigated by Perfect *et al.* (2004). They observed a significant difference in the values of D_m for tillage treatments, with smaller values for NT compared with those in the ploughed-disced treatment. Furthermore, the range of variation in the values of D_m was very low (2·948–2·963) which is even lower than that obtained in our experiment for D_{nl} in the 4th year (2·139–2·298).

Furthermore, it was assumed that the drag force of the tillage implements was somewhat proportional to the crushing force of aggregates, therefore, the estimated drag force of the tillage implements (ASAE, 2002) was related to the value of D_{nl}. The relationship is as follows:

$$D_{nl} = 1{\cdot}94 + 0{\cdot}12\mathrm{Ln}(E) \qquad (7)$$

with a value for the coefficient of determination R^2 of 0·91 where, E is the estimated drag force of tillage implements in kN m^{-1}. It is indicated that there is a good correlation between D_{nl} and E.

Our results are in accordance with those reported by Perfect and Blevins (1997). They showed that fractal parameter can be used to characterise both soil aggregation and fragmentation, and this parameter is sensitive to tillage treatment. According to their results, MD ploughing increased soil fragmentation in comparison with NT. This effect was partially reversed by secondary cultivation, indicating that discing broke up large clods and/or coalesced small fragments produced by mouldboard ploughing.

3.2.2. *Fractal dimension variation during experiment years*

Minimum variation in the values of D_{nl} during the experiment years was obtained in the NT treatment (Table 3). Therefore, minimum variation for aggregate fragmentation due to tillage practices for different years was obtained in this treatment. The TP treatment was in the next order.

Generally, for all treatments, increasing values of D_{nl} during the experimental years was observed. However,

Table 4
Mean-weight diameter D_{mw} for tillage treatments in the experiment years

Tillage treatments	*Mean weight diameter, mm*			
	Experiment years			
	1	*2*	*3*	*4*
Mouldboard plus disc (MD)	$0{\cdot}453^{b*}$	$0{\cdot}528^{a}$	$0{\cdot}467^{a}$	$0{\cdot}512^{c}$
Chisel plus disc (CD)	$0{\cdot}433^{b}$	$0{\cdot}464^{b}$	$0{\cdot}489^{a}$	$0{\cdot}540^{bc}$
Chisel plus rotary (CR)	$0{\cdot}423^{b}$	$0{\cdot}494^{ab}$	$0{\cdot}489^{a}$	$0{\cdot}519^{c}$
Twice orthogonal chisel plus disc (2CD)	$0{\cdot}480^{ab}$	$0{\cdot}435^{c}$	$0{\cdot}491^{a}$	$0{\cdot}526^{c}$
Khishchi plus disc (KD)	$0{\cdot}461^{b}$	$0{\cdot}456^{bc}$	$0{\cdot}499^{a}$	$0{\cdot}546^{b}$
Plant-till (TP)	$0{\cdot}542^{a}$	$0{\cdot}458^{b}$	$0{\cdot}500^{a}$	$0{\cdot}590^{ab}$
No-till (NT)	$0{\cdot}443^{b}$	$0{\cdot}470^{b}$	$0{\cdot}519^{a}$	$0{\cdot}627^{a}$

*Means followed by the same letters in each column are not significantly different at 5% level of probability according to Student–Newman–Keuls test.

this increase in value of D_{nl} in NT and TP treatments was less pronounced in the 4th year. On the other hand, the increase in value of D_{nl} in the MD, CD and CR treatments was enhanced in the 4th year. Furthermore, a pronounced increase in the value of D_{nl} in the KD and CR treatments occurred in the 3rd year. Also, the value of D_{nl} in the CD and MD treatments was enhanced in the 2nd year. The results indicated that for a long-term (4 yr) use of different tillage methods, NT and TP treatments were more effective in aggregate stability (lower D values).

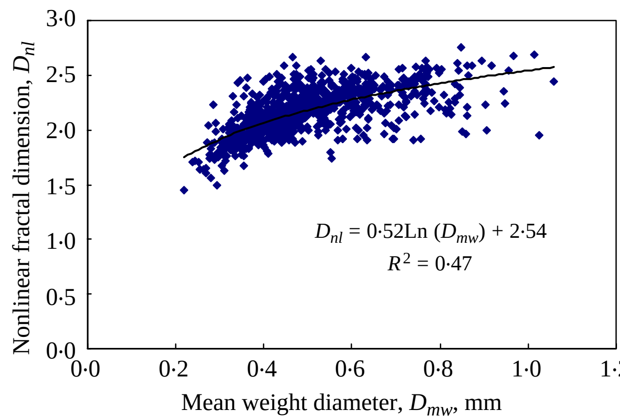

Fig. 2. Relationship between the non-linear fractal dimension D_{nl} and the mean-weight diameter D_{mw}; R^2, coefficient of determination

3.3. *Mean-weight diameters*

Statistical analysis indicated that there was no significant difference between values of D_{mw} at different depths. Therefore, the mean values of D_{mw} were used in further statistical analysis. Mean-weight diameters (D_{mw}, in mm) for different tillage treatments and different experiment years are shown in Table 4. The range of D_{mw} was obtained between 0·22 and 1·06 (*Fig. 2*) with an average of 0·495 mm. By considering the decreasing D_{mw} as an effect of increasing soil aggregate fragmentation, the order of tillage treatments were obtained as follows:

(1) chisel plough plus rotary tiller (CR); (2) chisel plough plus disc (CD); (3) twice chisel plough plus disc (2CD); (4) mouldboard plough plus disc (MD); (5) Kishchi plus disc (KD); (6) no-till (NT); (7) till-planting (TP)

The order of tillage treatments from (1) to (4) is quite different from that obtained according to fractal dimension analysis. The order (1) to (4) could not be explained as was expected and it seems that D_{mw} may not be able to quantify soil structure variation as influenced by tillage treatments. For example, 2CD treatment was placed in third order after CD, while, it must be practically reversed. Also, the MD treatment was placed in fourth order after CR, CD, and 2CD. This placement is not practically logical. Furthermore, a systematic variation in D_{mw} at different tillage treatments and experiment years was not obtained (Table 4), while this was not similar to those obtained for fractal dimension.

Furthermore, it was assumed that the drag force of the tillage implements was somewhat proportional to the crushing force of aggregates, therefore, the estimated drag force of tillage implements (ASAE, 2002) was related to the D_{mw}. The relationship is as follows:

$$D_{mw} = 0{\cdot}78 - 0{\cdot}089\mathrm{Ln}(E) \quad (8)$$

with a value for R^2 of 0·48. It is indicated that there is a weak correlation between D_{mw} and E.

Table 5
Geometric mean diameter D_{gm} for tillage treatments in the experiment years

Tillage treatments	*Geometric weight diameter, mm*			
	Experiment years			
	1	*2*	*3*	*4*
Mouldboard plus disc (MD)	$0{\cdot}246^{b*}$	$0{\cdot}272^{a}$	$0{\cdot}239^{a}$	$0{\cdot}261^{b}$
Chisel plus disc (CD)	$0{\cdot}234^{b}$	$0{\cdot}242^{b}$	$0{\cdot}245^{a}$	$0{\cdot}260^{b}$
Chisel plus rotary (CR)	$0{\cdot}236^{b}$	$0{\cdot}246^{b}$	$0{\cdot}246^{a}$	$0{\cdot}253^{b}$
Twice orthogonal chisel plus disc (2CD)	$0{\cdot}261^{a}$	$0{\cdot}226^{b}$	$0{\cdot}247^{a}$	$0{\cdot}270^{a}$
Khishchi plus disc (KD)	$0{\cdot}254^{ab}$	$0{\cdot}241^{b}$	$0{\cdot}247^{a}$	$0{\cdot}269^{ab}$
Plant-till (TP)	$0{\cdot}275^{a}$	$0{\cdot}240^{b}$	$0{\cdot}246^{a}$	$0{\cdot}282^{a}$
No-till (NT)	$0{\cdot}241^{b}$	$0{\cdot}239^{b}$	$0{\cdot}246^{a}$	$0{\cdot}278^{a}$

*Means followed by the same letters in each column are not significantly different at 5% level of probability according to Student–Newman–Keuls test.

3.4. *Geometric mean diameter*

Statistical analysis indicated that there was no significant difference between values of D_{gm} at different depths. Therefore, the mean values of D_{gm} were used in further statistical analysis. Geometric mean diameters (D_{gm}, in mm) for different tillage treatments and different experiment years are shown in Table 5. The values of D_{gm} at different tillage treatment and experiment years did not show a systematic variation that was evident for the fractal dimensions. The range of D_{gm} was between 0·226 and 0·282 with an average of 0·250 mm. The values of D_{gm} were not similar for different treatments and there was significant difference between treatments. However, the range of statistical difference between tillage treatments was smaller than those obtained for D_{mw} (Table 4). Therefore, D_{gm} was less effective to describe the soil structure variation. This might be due to the fact that the aggregate size distribution may not show a log-normal distribution to justify the use of Eqn (4) in the present investigation.

3.5. *Comparison between D_{nl} and D_{mw} to quantify soil aggregate stability*

Relationship between the values of D_{nl} and D_{mw} is shown in *Fig. 2*. The best-fit equation for this relationship is as follows:

$$D_{nl} = 0{\cdot}52\text{Ln}(D_{mw}) + 2{\cdot}54 \tag{9}$$

with a value for R^2 of 0·47. Non-linear relationship between D_{nl} and D_{mw} indicated that D_{mw} was not able to quantify soil aggregate stability in the similar manner as D_{nl}.

Statistical analysis for D_{nl} indicated that the differences between MD and 2CD with other treatments were significant ($P = 0{\cdot}05$) in the 4th year (Table 3). Higher values of D_{nl} for these treatments referred to more aggregate fragmentation. On the other hand, CD and KD treatments were not significantly different from the NT and TP treatments. Furthermore, there was a pronounced trend of temporal increase in D_{nl} values for the MD, CD, CR, and 2CD treatments, while the temporal increase for the TP and NT treatment was not considerable. Therefore, it may be anticipated that in the long term, the difference between TP and NT and other treatments may become greater.

There was no systematic variation for D_{mw} to describe the aggregate stability (Table 4). For example, the value of D_{mw} for the NT treatment was lower than that for the MD. This trend of variation for D_{mw} cannot be explained theoretically, because maximum soil aggregate fragmentation should be practically created by the MD treatment and the NT treatment should result in minimum soil aggregate fragmentation.

4. Conclusion

Results indicated that the non-linear fractal dimension D_{nl} was more appropriate than the mean weight diameter D_{mw} and the geometric mean diameter D_{gm} to quantify the induced soil aggregate stability by tillage treatments. Due to strong theoretical base of the fractal dimension, results of this analysis can be used to evaluate the soil aggregate stability.

The mouldboard plough plus disc (MD), and twice chisel plough plus disc (2CD) treatments, due attention to higher soil aggregate fragmentation, are not recommended. On the other hand, the no-till (NT) and the till-planting (TP) treatments resulted in the best soil aggregate stability, but for the NT treatment there are some practical difficulties such as sowing, fertilising, weed control, and soil crust cultivation, without which low yield may result. Therefore, some use of tillage implements is unavoidable. Results of this research indicated that the chisel plough plus disc (CD), and the Khishchi tined implement plus disc (KD) treatments were not significantly different from the NT and TP treatments and they can be recommended. In other words, temporal analysis of the non-linear fractal dimension indicated that the values of D_{nl} were increased during the experiment years, particularly, in the mould board plough plus disc (MD), chisel plough plus disc (CD), chisel plough plus rotary tiller (CR), and the twice chisel plough plus disc (2CD), while fractal dimension in the TP and NT treatments, started to increase late in the 4th year. Therefore, the till-planting and NT treatments may be more appropriate tillage treatments in the conservation of soil aggregate stability.

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