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Effect of tillage on fractal indices describing soil surface microrelief of a Brazilian Alfisol

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Abstract

Soil surface roughness is known to influence water infiltration, runoff and erosion. Soil surface roughness changes with management and weather and its mathematical description still remains an important issue. The main objective of this study was to investigate the effect of tillage on the two fractal indices, fractal dimension, *D*, and crossover length, *l*, currently used in characterizing soil surface microrelief. The statistical index random roughness, RR, was also assessed. Field experiments were done on an Alfisol located at Rio Grande do Sul State (Brazil). Two tillage treatments (conventional versus direct drilling) were tested. The soil surface microrelief was assessed by point elevation measurements in 16 plots for each treatment. The sampling scheme was a square grid with 20 × 20 mm between point spacing and the plot size was 280 × 280 mm, so that each data set consisted of 225 individual elevation points. All indices were calculated after trend removal, both by slope correction, i.e., oriented microrelief, and by slope plus tillage marks correction, i.e., random microrelief. The implemented algorithm for estimating *D* and *l* consisted in evaluating the roughness around the local root mean square deviation (RMS) of the point elevation values. Irrespective of tillage treatment and detrending procedure, fractal behavior extended only over a bounded range of scales, from 40 to 100 mm, due to the experimental setup. In these conditions, assessing fractal indices was not always straightforward. The statistical index RR and the fractal index *l* were significantly different between tillage treatments for oriented and random surface conditions. *D* values of random soil surfaces were not affected by tillage treatment, whereas *D* values of oriented microrelief were significantly lower in the direct drilled plots. Removal of tillage marks trend resulted in a significant increase in *D* values. Within each tillage treatment, *l* and *D* were significantly correlated.

Keywords: Soil roughness; Fractal indices; Tillage; Root mean square; Alfisol

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1. Introduction

The concept of soil surface roughness is central in the scientific description of runoff generation and sediment production (Kamphorst et al., 2000; Merril et al., 2001; Vidal Vázquez, 2002; Darboux and Huang, 2005). Soil surface roughness has been demonstrated to influence water infiltration, splash amount, overland flow and runoff routing (Govers et al., 2000; Römkens et al., 2001; Gómez and Nearing, 2005). Furthermore, the most relevant parameters used as inputs of erosion prediction models, as for example water retention by surface depression, flow concentration and flow networking indices, are commonly assessed from soil surface roughness.

On agricultural fields, one may expect disordered roughness created by the random disposition of structural units, aggregates and clods, which is superimposed by periodic effects induced by cultivation. In turn, both types of microrelief features, disordered or random roughness and oriented or periodic roughness, may be superimposed to the natural landscape area at larger scales. Thus, roughness measurement is scale sensitive. Therefore, the difficulty remains in drawing a mathematical description of the microrelief of agricultural fields (Kamphorst et al., 2000; Vidal Vázquez et al., 2005).

The characterization of soil surface microrelief requires time-consuming measurements, irrespective of the equipment used for acquisition of point elevation data. Pin meters were the former dominant field-practical devices used since the 1960s (Allmaras et al., 1966; Currence and Lovely, 1970). Later, since the 1980s, the use of higher technological means, mainly laser scanner devices (Huang and Bradford, 1990; Darboux and Huang, 2003), allowed more scale-sensitive and scale-continuous roughness measurements.

Various statistical and geostatistical indices of roughness have been proposed and tested for their ability to characterize soil surface microrelief (Allmaras et al., 1966, Linden and van Doren, 1986; Hansen et al., 1999). The use of fractals as descriptors of soil roughness has already been proposed (Armstrong, 1986; Huang and Bradford, 1992; Huang, 1998; Miranda, 2000; Vidal Vázquez et al., 2005). Fractal indices have been considered as a type of representation that better fit actual field microrelief data to account for the multiscale effects or for the fluctuations of local statistics (Eltz and Norton, 1997; Vidal Vázquez et al., 2005). The use of fractal indices for roughness characterization has also been object of some criticism (Kamphorst et al., 2000). A review of the applications of fractals to soil surface microrelief characterization is found in Vidal Vázquez et al. (2005).

According to Römkens and Wang (1986), different hierarchical surface roughness types may be recognised, such as random roughness, oriented roughness and topography roughness. Dominant devices used to measure soil roughness are scale-sensitive and scale-continuous over the scale 1 mm (laser scanner) or 1 cm (pin meter) to 1 m, allowing characterization of random and oriented roughness. Therefore, roughness features at higher scales, considered to be relevant for erosion studies, currently are not assessed. However, for many applications, the experimental set up over a limited area of about 1 m^2 should be satisfactory (Hansen et al., 1999; Kamphorst et al., 2000; Vidal Vázquez, 2002). Huang (1998) stated that attempts to quantifying soil surface roughness had been limited by the quality of the data sets obtained by pin meter type devices, indicating a grid resolution in the order of 1 mm or less as the most appropriate. Merril et al. (2001) suggested that devices for soil microrelief measurements should be designed to take advantage of increases in scale. This could be achieved by using instruments with higher resolution or devices providing point elevation data over larger areas.

In spite of the advantages of soil surface microrelief characterization by laser scanner, Merril et al. (2001) indicated that low technology field-practical devices can give effective prediction of roughness parameters. Previous studies on the performance of different models to describe roughness fractal indices from data sets measured from laser scanner and pin meter (Miranda, 2000; Vidal Vázquez, 2002; Vidal Vázquez et al., 2005) showed that, while laser scanning allowed to better characterize microtopographic features, both types were adequate for a relevant assessment of microrelief using fractal dimension, D, and crossover length, l.

Several soil properties, such as clay and organic matter content, and other properties influencing soil structure stability may affect the roughness produced by different implements. Moreover, soil moisture during tillage also has a great influence on the roughness created by different tools. Furthermore, most inherent soil properties and soil-use induced properties are intercorrelated to some extent. This complicates the analysis of the influence of one single property on soil surface roughness. Therefore, experiments on different sites should cover a wide variety of arable soils and farming conditions (Vidal Vázquez, 2002).

However, research on the characterization of soil surface roughness is scarce and most studies have bee carried out in temperate climates, i.e., U.SA. (Allmaras et al., 1966; Römkens and Wang, 1986; Eltz and Norton, 1997; Merril et al., 2001) and Europe (Hansen et al., 1999; Kamphorst et al., 2000, Vidal Vázquez et al., 2005). In despite of this trend, Magunda et al. (1997) compared changes in microrelief during simulated rainfall in soil from Minnesota (USA) and Uganda, and Vidal Vázquez (2002) presented results of field microrelief measurements in Spain and São Paulo state (Brazil).

Acid, nutrient poor oxisols, ultisols and alfisols are the dominant soil types in the humid and subhumid tropics and subtropics. In Brazil, they are the most extensive soil orders. Pin meters and profile meters were the former dominant means for measuring soil roughness and still are the only ones available. The main purpose of this paper was to present the results of field research on soil microrelief of a Brazilian Alfisol characterized by a low technology device and to analyze the relevancy of the fractal approach for this type of roughness data sets.

2. Materials and methods

2.1. Site, soil and tillage operations

The study was conducted at the agricultural research station of Federal University of Rio Grande do Sul in Guaíba, near Porto Alegre, Brazil, latitude 30°06′50S and longitude 51°19′30″W. The study field is about 35 m above sea level in an undulating area with rolling topography. The field itself is gently sloping (5.6%). The mean annual rainfall at the study site is approximately 1400 mm, with a more or less uniform distribution throughout the seasons.

The deep, well-drained acid soil studied here has developed from granite and is classified as a dystrophic brown-yellowish Latossolo in the current Brazilian Soil Classification System (EMBRAPA, 1999) and as a dusky red Podzol in the former version (EMBRAPA, 1982). This is equivalent to an Alfisol in the U.S. Soil Classification System (Soil Survey Staff Division, 1993). It has an argillic horizon, upper boundary at 40–42 cm depth, with substantial clay content (37–47%). The topsoil (0–20 cm depth) has sandy clay loam texture, 47% sand, 22% silt, 31% clay, acid pH ($\mathrm{pH_{H_20}}$ 4.5 and $\mathrm{pH_{KCl}}$ 3.5) and the organic carbon content was 1.16 g dm^{-3} (Alves and Cabeda, 1999).

In our study, two different soil tillage treatments were analyzed, conventional tillage and direct drilling. All experimental plots of both treatments were continuous cultivated for 3 years when the microrelief was assessed, but the experimental site had never been cultivated before. Soil use prior to cultivation was grazing the native vegetation. The native vegetation, called native pasture (campo nativo) in Brazil, consisted of abundant grass, low shrubs and sparse trees, and could be considered as a degraded savannah. Plots were cropped to soybean (Glycine max) in summer and oats (Avena strigosa) in winter during the three years after natural vegetation removal. Conventional tilled and direct drilled plots randomly located across the site were maintained with the same treatment once established. Thus, the history of crop succession and tillage system in the last 3 years prior to the roughness measurements was uniform in space and time.

Conventional tillage included three tillage operations per season. In summer and in winter, first, the field was disc-ploughed and then harrowed twice using a disc harrow. Disc ploughing was always performed to a depth of about 20 cm using tools with four discs and a separation of 55 cm between them. The shearing depth of harrowing was 12 cm, the used tool had 20 discs and the space between discs was 17 cm. A field cultivator was used for drilling to a depth of 5 cm and the sowed rows were 50 cm apart.

Soil microrelief measurements were made in November, just after the last tillage, and drilling operations following the summer soybean crop in the succession.

Soil moisture during microrelief measurements under conventional tillage was 14.0±0.1 and 15.0±0.1 g 100 g^{-1} at depths of 0–10 cm and 10–20 cm, respectively, whereas under direct drilling these values were 13.0±0.1 and 15.0±0.15 g 100 g^{-1}, respectively. Soil infiltration tests were conducted under simulated rainfall at the time of our experiments, just after soil surface microrelief measurements, and the resulting infiltration rate varied between 17.3 and 27.5 mm/h under conventional tillage and between 46.6 and 47.2 mm/h under direct drilling. The study site and the management history are described more in detail elsewhere (Alves and Cabeda, 1999).

2.2. Field data set

The study data set acquired during the field experiments included 32 roughness surfaces, 16 for the conventional tillage and 16 for the direct drilling treatment. Elevation data sets were taken with a low technology pin board device. The pin meter used for collecting point elevation measurements was capable of measuring with a horizontal resolution of 20 mm, a vertical resolution of 0.1 mm and a vertical range of approximately 300 mm. The sample scheme was a square grid of 20 × 20 mm. Each 280 mm profile consisted of 15 points and 15 profiles per plot were measured. Hence, each data set consisted of 225 individual elevation points.

Trends due to oriented roughness, i.e., the effect of slope, or both slope and tillage marks, were removed by the standard procedure proposed by Currence and Lovely (1970), which allows to distinguish between oriented and random roughness. Oriented roughness condition was obtained following correction for slope using the plane of best fit for each plot. Random roughness surfaces resulted from removing of row and column trend effects. The residual elevation values given as a function of the horizontal coordinate system provide a standard numerical representation of the surface and constitute a digital elevation model (DEM) of the surface. For each experimental surface, two DEMs were analyzed. The first one was obtained after slope trend removal and represents oriented roughness due to both tillage marks and aggregation. The second one resulted from both slope and tillage marks detrending that is thought to represent the surface configuration due to aggregates and clods randomly located on the soil surface. DEM examples for residual surfaces of the two study treatments, conventional and direct drilling, before and after tillage trend removal are shown in Figs. 1 and 2, respectively.

2.3. Determination of statistical and fractal microrelief parameters

Three roughness indicators, random roughness (RR), a classical index describing vertical statistics and two fractal indices, namely fractal dimension, *D*,

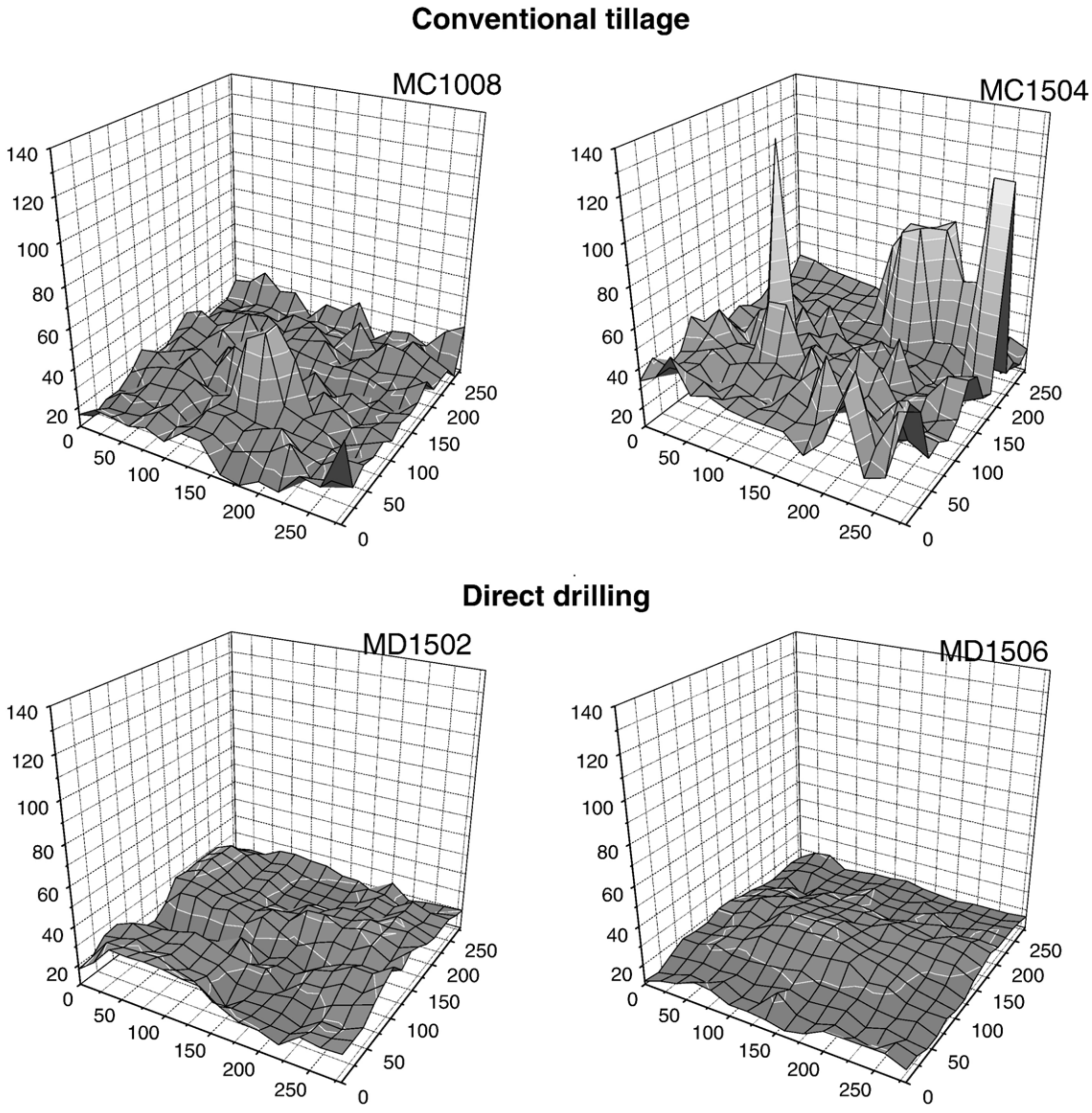

Fig. 1. Examples of oriented microrelief for conventional tillage and direct drilling (units in mm).

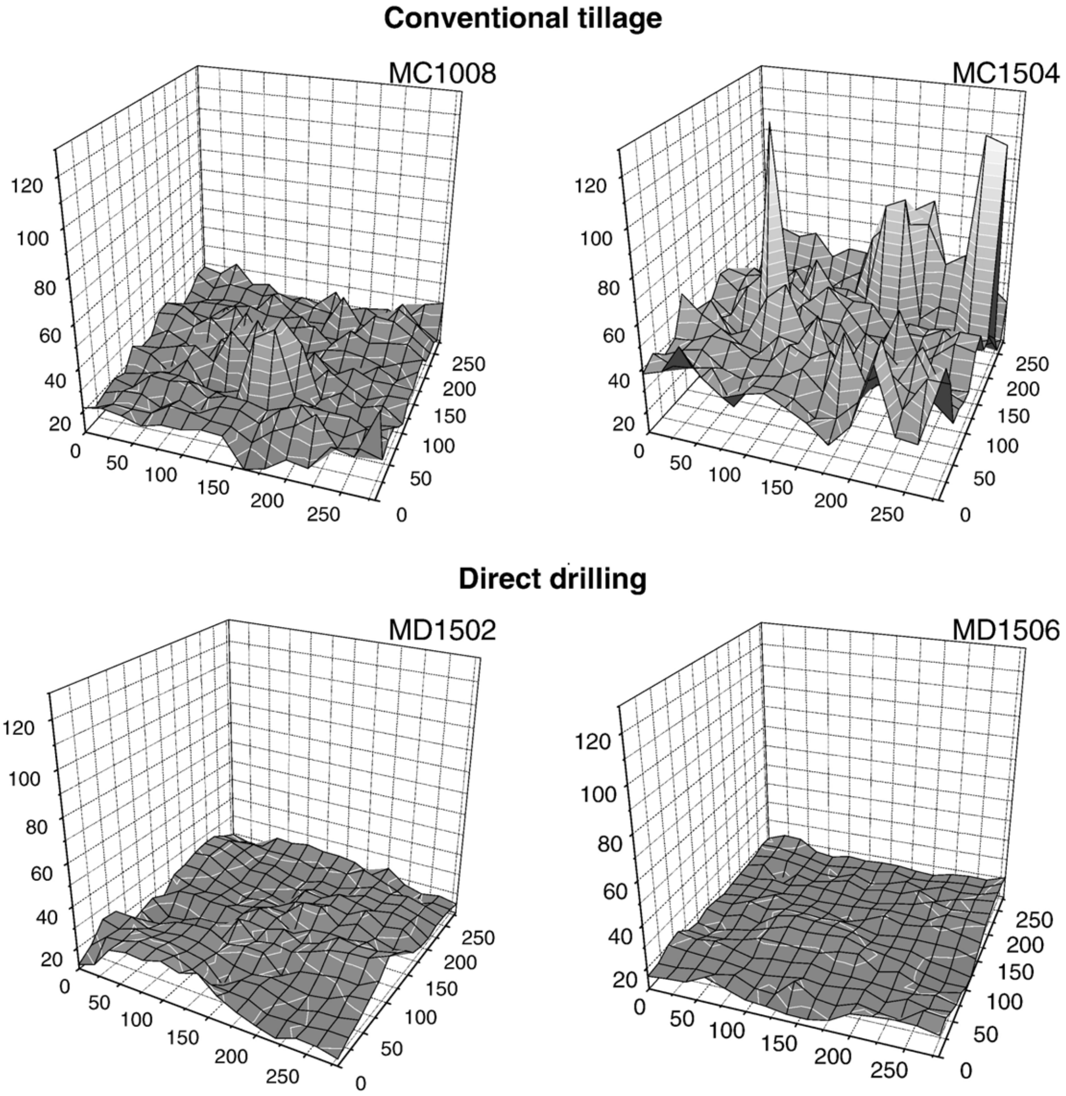

Fig. 2. Examples of random microrelief for conventional tillage and direct drilling (units in mm).

and crossover length, *l*, were assessed after slope and slope plus tillage trends effects were removed.

Random roughness, the microrelief descriptor which is most often referred to in the literature, is calculated simply as the standard deviation of the point elevation measurement from the DEMs, after correction for slope and tillage marks (random microrelief) according to Currence and Lovely (1970). Calculations were performed also after single correction for slope (oriented microrelief).

Different methods have been proposed to estimate fractal indices, *D* and *l*, from soil surface microrelief transects or surfaces (Miranda and Paz González, 2002). Values of the fractal dimension, *D*, for soil microtopographic profiles or surfaces may vary with the model used and the assumptions made in formulating the model and the resulting algorithms. The advantages and drawbacks of these techniques have been discussed elsewhere (Vidal Vázquez et al., 2005). Two methods are applied to estimate fractal indices: non-variational methods (tortuosity, Richardson number, box counting) and variational methods (semivariogram, root mean square (RMS) or roughness length). Non-variational techniques assume implicitly that there is self-similarity in the soil surface along a range of scales and aim to characterize soil microrelief features by calculating a single index. Because microrelief fractal behavior is better modeled by a self-affine or by a prefractal surface, the use of non-variational methods has been strongly criticized (Miranda, 2000; Vidal Vázquez et al., 2005).

Variational techniques are considered to allow a better description of soil microrelief. The more commonly used variational approaches estimate the fractal indices of soil profiles or surfaces from semivariance or local root mean square. Both methods are based on the calculation of the Hurst exponent, H, from which the fractal dimension, D, is assessed; moreover, an additional parameter, the so-called crossover length, l, is obtained when variational methods are used. Fractal dimension, D, is a descriptor of horizontal variations of soil roughness, whereas crossover length, l, is related to vertical differences in point elevation data.

Mathematical derivations of the available approaches for determining fractal indices of soil surface microrelief have been summarized in other reviews (Malinverno, 1990; Huang and Bradford, 1992; Gallant et al., 1994; Moreira and Da Silva, 1994; Perfect and Kay, 1995; Huang, 1998; Vidal Vázquez et al., 2005).

The RMS method was chosen for assessing D and l in the study data set, the reason being that this method allows a more efficient fractal analysis than the semivariogram (Vidal Vázquez et al., 2005), as expected, given the limited size of the experimental data sets in this study.

Thus, fractal indices were calculated from the average deviation around the mean elevation value (RMS) of all points located inside a square window with size h (Moreira and Da Silva, 1994). Average values of RMS, denoted as $\bar{W}(h)$, for different scale ranges, h, are computed according to the equation:

$$\bar{W}(h)=\frac{1}{N_h}\sum_{u=1}^{N_x-h}\sum_{v=1}^{N_y-h}\left\{\frac{1}{m_h}\sum_{i=u}^{u+h}\sum_{j=v}^{v+h}\left[Z_{i,j}-\bar{Z}_h\right]^2\right\}^{\frac{1}{2}} \qquad (1)$$

where N_h is the total number of windows of size h, the pair (u,v) represents the initial position of the window in the surface, N_x and N_y are the total number of points in x and y directions, respectively, m_h is the number of points in a window of size h, $Z_{i,j}$ are data point elevations regularly spaced over the surface, and $\bar{z}_h$ represents the average elevation value for all points in the window located in (u,v) with size h.

Windows of the same size are situated all over the surface, the RMS for each one is calculated and then the average value of all obtained. This procedure is then repeated with windows of different sizes. Assuming fractal behavior, the slope of the log–log plot of the structural function, $W(h)$, versus distance, h, gives an estimation of the Hurst exponent, H.

Using a fractal Brownian motion model (fMB), the crossover length was defined by Huang and Bradford (1992) based on the semivariogram structural function, $\gamma(h)$. In a similar way, in accordance with Malinverno (1990) and Miranda (2000), the straight line portion of the function $W(h)$ versus distance, h, near the origin may be described by the crossover length and the fractal dimension as:

$$\bar{W}(h)=l^{1-H}h^{H} \qquad (2)$$

Following Huang and Bradford (1992) and Korvin (1992), the fractal dimension, D_{RMS}, of the soil surface is obtained from the Hurst exponent and the Euclidean dimension $d=3$, according to:

$$D_{\mathrm{RMS}}=3-H \qquad (3)$$

Finally, as described by Huang and Bradford (1992), the crossover length, l_{RMS}, may be estimated by:

$$l_{\mathrm{RMS}}=\exp[a/(1-H)] \qquad (4)$$

where a is the intercept of the straight line portion of the structural function $W(h)$ at the y axis.

Next, for simplicity, D and l will be used instead of D_{RMS} and l_{RMS}.

Fractal analysis was performed by means of double logarithm plots of root mean square function $W(h)$ against scale, h. Selected examples are shown in Figs. 3 and 4 for random and oriented surfaces, respectively. In these examples, results for the steepest and the shallowest slopes for both tillage treatments are drawn.

Two segments were present at every plot in Figs. 3 and 4. All plots of the structural function $W(h)$ against h in this figures show a general trend of a sloping straight line, near the origin, followed by a further

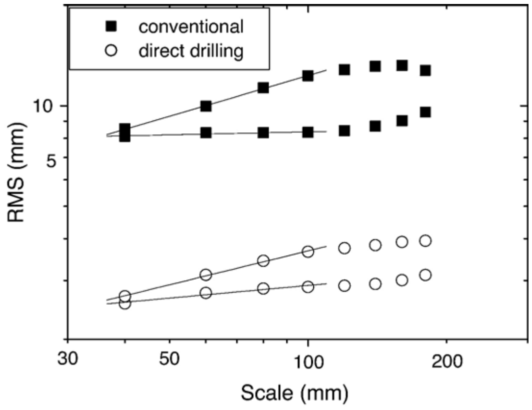

Fig. 3. Relationship between RMS function and scale for selected surfaces (random microrelief).

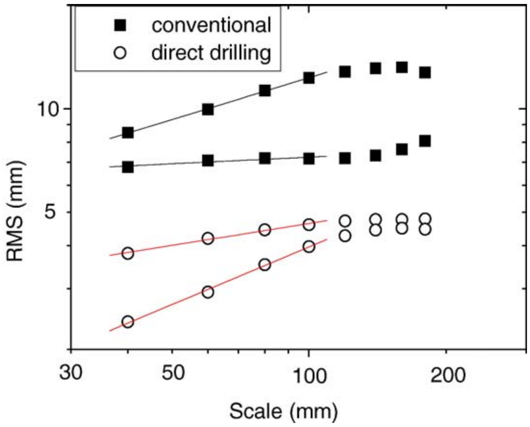

Fig. 4. Relationship between RMS function and scale for selected surfaces (oriented microrelief).

region where the slope breaks and it is no longer constant, varying towards an asymptote.

Fractal dimensions were estimated from the first straight line segment, before this scale break. The cutoff distance was obtained following least squares adjustment. However, in our study, the data were insufficient to statistically estimate the upper cutoff length. Thus, the scale break was assumed to be 100 mm for the 32 study data sets.

The accuracy of the fractal dimension assessment depends on the accuracy in delimiting the straight line segment for the roughness functions. In our study, only the first four experimental points in the scale range from 40 to 100 mm were used to estimate the fractal parameters *D* and *l*.

Statistical analyses, i.e., linear regression analysis between roughness indices, variance analysis by ANOVA test following the model: tillage treatment, detrending procedure and their interactions (tillage treatment × detrending procedure), and covariance analysis were performed using the SAS package, version 8.0 (SAS Institute, 1999).

3. Results and discussion

Soil surface conditions were visibly different between tillage treatments. Conventional tillage had a wide range of aggregate and clod sizes, more or less evenly distributed over the study field. After direct drilling, rough rows of disturbed soil were separated by smooth undisturbed between-row areas; in this case, the study plots included both row and between-row patches. In conventional tillage, microrelief was created by disc fragmentation and inversion so that the height amplitude of aggregates and clods was similar than length and width. In contrast, direct drilling fragmented a small portion of the soil surface without inversion and, as a result, the microrelief units in the disturbed surface area exhibit a reduced height (Figs. 1 and 2).

3.1. Scaling regions of soil microrelief

All the RMS functions obtained were linear from approximately 40 to 100 mm, as in the examples shown in Figs. 3 and 4. A surface roughness whose fractal spectrum will be limited at low frequencies is an expected result, since the break in scale is mainly related to the size of the structural units at the soil surface. Conventional tillage with disc ploughing and disc harrowing and direct drilling with field cultivator produced surface microreliefs that were clearly scale variant.

Mathematical fractals are scale invariant, i.e., a fractal look exactly the same at any resolution. However, soil surface microrelief, like most soil physical properties, are mostly statistical fractals in which fractal scaling is usually restricted to a limited range of scales (Perfect and Kay, 1995). On a log–log scale, the initial straight line of the structural function *W* (*h*) may be modeled by a power law. However, the break in steepness observed in Figs. 3 and 4 for random and oriented surfaces, respectively, is an indication of the prefractal nature of the roughness spectrum. Thus, the microrelief defined by point data fits a prefractal model, rather than a self-similar one.

As a rule of thumb, relations covering at least two orders of magnitude are required to infer fractality. On the other hand, theoretically, the ratio between the upper (100 mm) and the lower cutoff (40 mm) must not be less than $2^{1/D}$.

The orders of magnitude of the study surfaces range from 20 mm (acquisition length) to 280 mm (surface side). Moreover, the relevant range of scales for fractal analysis is only from 40 to 100 mm. These thresholds imposed by the experimental setup obviously do not account for all the structural features involved in microrelief. Thus, fractal properties will be investigated only on the scale extent imposed by the pin meter device used, meaning on a limited spatial frequency spectrum. The small number of data points for each surface constituted also a limitation for fractal analysis.

Assuming a fractional Brownian model, in soil surface microrelief patterns, two parameters are required for quantifying different degrees of soil roughness, fractal dimension, *D*, and crossover length, *l*.

The fractal dimension, *D*, can be considered as a relative measure of the distribution of different-sized elements on the surface. A steeper slope on the structural function, $W(h)$, indicates more contrast on the surface elevation size distribution. D describes how roughness changes with the scale of observation. It gives a measure of the irregularity of a set of data points independent of the numeric value involved, which is not the case for the indices based on the standard deviation, and provides a tool for examining the horizontal pattern of spatial organization of the soil surface microrelief.

The crossover length, l, puts the actual size scale into the proportional size distribution on the surface. It is important to note that only prefractal curves have a crossover dimension (Huang and Bradford, 1992). For prefractal profiles or surfaces, the crossover dimension is a valuable scaling parameter. This parameter specifies the variance or the standard deviation at a reference scale. Thus, like RR, l describes the vertical statistics of each surface.

The scale at which the straight line breaks, i.e., fractal dimensions change, has been referred to as the correlation length and is an interesting parameter to consider for describing soil microrelief (Vidal Vázquez et al., 2005). It gives an indication of the characteristic size of the large structural units, i.e., larger clods for the conventional tilled and larger fragments for the direct drilled surfaces. In this work, the upper cutoff was assumed to be constant (100 mm); however, this does not indicate that the main structural units of both tillage treatments are of the same order of magnitude, but may be attributed to the limited size of the experimental plot.

3.2. Effect of management on statistical and fractal indices of random microrelief

The standard procedure for detrending point elevation measurements includes slope and tillage marks removal, which should allow comparison of data sets with different grid spacing and sizes. Thus, fractal parameters for random microrelief were first addressed. The statistical (RR) and fractal indices (l, D) of the 32 soil surfaces corrected for slope and tillage marks are listed in Table 1.

Random roughness (RR) values for the conventional treatment ranged from 6.20 to 15.16 mm with a mean of 8.84 mm and those for direct drilling were from 2.48 to 4.19, with a mean of 3.18 mm. DEMs of the random surfaces with the largest and the smallest RR values are shown in Fig. 1 for conventional and direct drilling treatments.

Random roughness was significantly different between treatments according to an F test ($P<0.01$). Random roughness statistics allows discrimination of the two classes of surfaces under study, conventional and direct drilling. As expected, conventional tillage was very effective in increasing surface roughness, so that RR clearly indicates a decreasing trend from ploughed soil to the direct drilled one. However, RR does not describe horizontal variations of soil roughness.

Table 1
Calculated values of statistical and fractal indices for the study surfaces corrected for slope and tillage marks (random microrelief)

Plot	RR (mm)	D	Standard error	l (mm)	Standard error	r
Conventional tillage						
1	8.23	2.91	0.011	5.17	0.370	0.976
2	8.30	2.73	0.019	3.18	0.450	0.992
3	6.84	2.86	0.005	4.54	0.144	0.998
4	8.51	2.77	0.018	4.93	0.682	0.990
5	8.61	2.85	0.008	5.49	0.291	0.996
6	10.59	2.85	0.014	4.89	0.481	0.986
7	6.63	2.81	0.022	3.41	0.514	0.980
8	6.20	2.61	0.012	1.34	0.120	0.999
9	10.64	2.94	0.015	7.98	0.819	0.908
10	8.73	2.92	0.014	6.88	0.644	0.957
11	6.74	2.89	0.005	3.57	0.100	0.998
12	15.16	2.69	0.021	5.71	1.040	0.993
13	8.33	2.90	0.023	6.21	0.969	0.931
14	10.48	2.97	0.009	7.75	0.448	0.882
15	10.48	2.60	0.008	2.98	0.201	0.999
16	7.06	2.93	0.010	5.83	0.360	0.972
Direct drilling						
17	2.78	2.83	0.001	0.83	0.006	1.000
18	3.23	2.77	0.017	0.99	0.090	0.993
19	3.07	2.77	0.005	0.77	0.022	0.999
20	3.97	2.80	0.003	1.49	0.025	1.000
21	3.60	2.76	0.004	1.06	0.021	1.000
22	3.25	2.67	0.009	0.81	0.051	0.999
23	3.06	2.77	0.009	0.88	0.046	0.998
24	3.09	2.78	0.008	1.18	0.051	0.998
25	3.35	2.87	0.016	1.74	0.152	0.977
26	4.19	2.66	0.010	0.69	0.048	0.999
27	2.98	2.84	0.019	1.16	0.116	0.979
28	2.33	2.75	0.008	0.51	0.027	0.998
29	3.16	2.78	0.008	0.85	0.036	0.998
30	2.48	2.73	0.010	0.54	0.037	0.998
31	3.12	2.78	0.006	0.90	0.028	0.999
32	3.21	2.84	0.007	1.42	0.057	0.997

Values and errors of the fractal parameters, fractal dimension, D, and crossover length, l, assessed by the root mean square method for each of the 32 plots of the study data sets are shown in Table 1, together with those of random roughness. The coefficients of determination for the straight line portion of the structural function, $W(h)$, were between 0.882 and 0.999 in the conventional tilled treatment and between 0.977 and 1.000 in the direct drilled one. As stated before, these fractal indices were calculated from a linear regression obtained from only four data pairs of the structural function values, W

(h), versus the scale. Moreover, the upper cut off value was not the result of a statistical determination, but subjectively estimated. The fractal dimension, D, value may vary depending on the range of scale. As a consequence, estimations of this parameter could only be compared if this influence is excluded.

The standard errors in estimating D varied between 0.005 and 0.023 in the conventional tilled and between 0.003 and 0.019 in the direct drilled treatment. Likewise, absolute errors in l were larger in the conventional tilled surfaces (ranging from 0.100 to 1.040) than in the direct drilled ones (0.006 to 0.152). When taking into account relative values, the magnitude of errors in estimating l for the conventional tilled surfaces may result higher than 10% of the absolute value, but they were lower than this threshold in the direct drilled surfaces.

Like RR, the crossover length, l, also characterizes vertical variations of soil roughness. Index l was obtained assuming the stationarity of the roughness surfaces and the power-like behavior of the RMS function near the origin. The mean crossover length of the conventional tilled plots was 4.99 mm and the minimum and maximum were 1.34 and 7.98 mm, respectively. In the direct drilled plots, these values were mean 0.980 mm, minimum 0.51 mm and maximum 1.49 mm. There were significant differences between the two study treatments ($P<0.01$). These results reinforce the relevancy of the crossover length parameter as a discriminator of vertical differences in roughness.

As expected, the parameter l was significantly correlated with RR, as indicated by the coefficient of correlation ($r^2=0.72$) between both parameters. However, the scatter of the plot RR versus l remains important, which may be due to the non-stationarity of the experimental soil surfaces. Using either the statistical index random roughness, RR, or the fractal crossover length, l, permits to distinguish the two classes of microrelief without ambiguity. Nevertheless, they do not describe the horizontal irregularities of the study surface.

Unlike RR and l, the fractal dimension, D, is a descriptor of horizontal variations of soil roughness, which implies that it has to be considered in connection with an index describing differences in roughness height.

If soil surface structural units and the point elevation data sets used in their description were randomly distributed, this could be best modeled by Brownian motion and a fractal dimension of $D=2.5$ would be obtained. Soil microrelief data sets with $D<2.5$ are referred to as persistent and those with $D>2.5$ as anti-persistent. Persistent surfaces or profiles display spatial correlation between neighboring points. Anti-persistent surfaces or profiles show negative correlation between elevations, i.e., a height change in one direction is likely to be followed by the next height in the other direction. Moreover, within the anti-persistent range, lower numbers represent smoother curves.

For the whole data set of 32 random soil microrelief surfaces, the fractal dimensions extracted ranged from 2.60 to 2.97. Thus, the 32 data study sets show anti-persistent features. Surfaces from conventional tilled plots were characterized by higher mean values of fractal dimension ($D=2.85$) than those from direct drilled fields ($D=2.78$), but mean values were not significantly different ($P<0.05$). However, the ranges of fractal dimension values of the direct drilled surfaces (2.67–2.87) were narrower than those of the conventional tilled ones (2.50–2.97). As a matter of fact, fractal dimension statistics poorly discriminate the two kinds of random field surfaces in this study and D values were not significantly different between treatments ($P<0.01$).

The larger range of D values obtained for data sets acquired under conventional tillage indicates a highly horizontal variation of soil roughness conditions for this treatment. The narrower range of D values of the data set from the direct drilled plots suggests more homogeneous surface roughness conditions. These results are coherent with the visual observations of both tillage treatments.

When dealing with conventional tilled surfaces, one may expect an important horizontal anisotropy of the soil surface conditions, even after tillage marks have been removed. The cultivation process itself may initiate relatively homogeneous patches sized with an order of magnitude close to that of the experimental plot, 28 cm × 28 cm, from which small D values may result. Then, it should be taken into account that conventional tilled plots look more rugged, simply because of differences in elevation. However, when they are normalized, they may or may not appear smoother than the direct drilled ones.

Crossover length, l, and fractal dimension values estimated for the two different tillage treatments were not independent of each other. By linear regression analysis, the following relationships were obtained:

$$\text{Conventional}: \; l = 11.73D - 28.17, \; r^2 = 0.57 \tag{5}$$

$$\text{Direct drilling}: \; l = 4.13D - 10.48, \; r^2 = 0.48 \tag{6}$$

The above relationships between l and D are significant for both tillage treatments ($P<0.05$). Thus, within each treatment, as the surface roughness increases, the fractal dimension, D, i.e., the contrast in point elevation distribution, also tends to increase. Note that these significant correlations are an expected result from Eqs. (2) and (4) relating crossover length, l, with structural RMS function, $W(h)$, and the Hurst exponent, H.

Given the above correlation between l and D, an analysis of covariance was performed. Using the crossover length, l, as a secondary variable, D values of the study treatments were significantly different ($P<0.01$). Using two fractal indices conjointly, fractal dimension, D, and crossover length, l, reduces the ambiguity observed when characterizing soil surface roughness only by a single index related to the altitude differences.

3.3. Comparison of indices for oriented and random surface conditions

Tillage treatment influences not only random roughness but also oriented roughness. Indicators calculated from slope corrected point elevation data sets are also adequate descriptors of soil microtopography. The statistical (RR) and fractal indices (l, D) of the 32 soil surfaces corrected for slope (oriented microrelief), together with standard errors in D and l, are listed in Table 2. In this table are also shown coefficients of determination for the straight line portion of the structural function, $W(h)$, varying between 0.921 and 0.999 in the conventional tilled treatment and between 0.995 and 0.999 in the direct drilled one.

Table 3 lists the mean values of the statistical index RR and the fractal indices l and D for both tillage treatments, with and without correction for tillage marks. Again, for oriented conditions, the statistical index RR was significantly higher ($P<0.01$) in the conventional tilled than in the direct drilled. Likewise, the increase of the fractal crossover length, l, in the oriented conventional tilled surfaces was significant ($P<0.01$).

Oriented surfaces from conventional tilled plots exhibits higher mean values of fractal dimension ($D=2.792$) than those from direct drilled plots ($D=2.660$) and mean values were significantly different ($P<0.01$). Thus, fractal dimension values, D, of oriented microrelief, allow discrimination between conventional tillage and direct drilling, which was not the case for random microrelief.

Table 2
Calculated values of statistical and fractal indices for the study surfaces corrected for slope (oriented roughness)

Plot	RR (mm)	D	Standard error	l (mm)	Standard error	r
Conventional tillage						
1	9.29	2.94	0.016	6.05	0.604	0.921
2	9.54	2.69	0.022	3.12	0.532	0.992
3	8.15	2.81	0.008	4.79	0.261	0.997
4	10.32	2.78	0.019	6.21	0.909	0.989
5	9.87	2.84	0.002	6.02	0.088	0.999
6	12.07	2.80	0.006	4.99	0.214	0.998
7	8.48	2.84	0.019	4.18	0.529	0.980
8	7.07	2.59	0.014	1.39	0.145	0.998
9	11.51	2.92	0.015	8.10	0.811	0.951
10	10.04	2.91	0.011	7.81	0.608	0.976
11	7.65	2.79	0.006	2.95	0.120	0.998
12	16.41	2.62	0.018	4.41	0.736	0.996
13	9.38	2.87	0.023	6.47	1.023	0.960
14	11.56	2.93	0.011	7.24	0.521	0.968
15	12.17	2.49	0.012	1.91	0.229	0.999
16	8.09	2.89	0.010	5.70	0.396	0.989
Direct drilling						
17	4.05	2.71	0.007	0.79	0.033	0.999
18	4.71	2.70	0.008	1.01	0.049	0.998
19	4.41	2.72	0.008	0.94	0.046	0.998
20	5.26	2.79	0.011	2.03	0.141	0.995
21	5.85	2.57	0.013	0.56	0.062	0.998
22	4.58	2.63	0.006	0.92	0.036	0.999
23	3.93	2.74	0.003	1.11	0.022	0.999
24	3.84	2.75	0.008	1.44	0.070	0.998
25	5.06	2.78	0.021	1.71	0.223	0.986
26	5.48	2.62	0.007	0.83	0.044	0.999
27	3.69	2.71	0.024	0.88	0.128	0.989
28	3.21	2.63	0.011	0.32	0.031	0.998
29	4.25	2.68	0.007	0.66	0.030	0.999
30	4.31	2.44	0.018	0.07	0.019	0.998
31	5.75	2.61	0.003	0.55	0.014	0.999
32	7.57	2.49	0.007	0.45	0.033	0.999

Again, as expected, for oriented microrelief crossover length, l, and fractal dimension, D, values estimated for the two different tillage treatments were not independent of each other. By linear regression analysis, the following relationships were obtained:

$$\text{Conventional}: \; l = 12.59D - 30.1, \; r^2 = 0.69 \qquad (7)$$

$$\text{Direct drilling}: \; l = 4.27D - 10.49, \; r^2 = 0.70 \qquad (8)$$

Also, the above relationships between l and D are significant for both tillage treatments ($P<0.05$).

Mean RR values of the oriented soil microrelief surfaces are significantly higher ($P<0.01$) than those of random soil surfaces, corrected for tillage marks in both treatments. This increase was larger in the direct drilled (from 3.18 to 4.74 mm) than in the conventional tilled

Table 3
Mean values of statistical (RR) and fractal indices (l, D) after slope + tillage mark correction (random microrelief) and after slope correction (oriented microrelief)

	Random microrelief			Oriented microrelief		
	RR (mm)	l (mm)	D	RR (mm)	l (mm)	D
Conventional	8.84 A	4.99 A	2.826 A	10.1 A	5.08 A	2.792 A
Direct drilling	3.18 B	0.98 B	2.775 A	4.74 B	0.89 B	2.660 B

(8.84 to 10.10 mm) surfaces. Thus, there is a statistical indication of the importance of the oriented roughness, induced by the used field cultivator, in the direct drilled plots.

However, mean l values of the conventional tilled treatment were not significantly different ($P<0.05$) before and after correction for tillage marks. Mean l values of the conventional tilled surface showed a trend to increase after tillage marks removing, whereas mean l values of direct drilled surfaces slightly decreased for oriented microrelief conditions.

It is also apparent from the results in Table 3 that mean D values were lower before removing tillage features, both in the conventional and direct drilled treatments. Differences in fractal dimension, D, between the two detrending procedures were also significantly different ($P<0.01$). All the D values calculated after tillage trend removal indicate anti-persistence. However, if only slope but not tillage trend was removed, D values varied between 2.491 and 2.936 in the conventional tillage treatment and between 2.444 and 2.777 for direct drilled. Thus, before tillage trend removal, D values in the range of persistence may be found. The absolute values of D after tillage trend removal estimated in the present work were of the same order of magnitude as those reported previously from both laser scanned and pin meter assessed soil surface microrelief (Vidal Vázquez et al., 2005).

Fractal dimension values calculated using data acquired by laser devices and only corrected for slope were reported by Huang and Bradford (1992) and Eltz and Norton (1997). Absolute D values obtained by Huang and Bradford (1992) in plots of about 1 m^2 varied between 2.5 and 2.7. Eltz and Norton (1997), in a small experimental area, 24.8 by 39.8 cm, found that 70% of the estimated D values varied between 2.5 and 2.7, but some of the surfaces in this study were persistent, with D values lower than 2.5. Our results of fractal dimension, D, estimated from data sets obtained with a low technology experimental device are consistent with those previously reported by other authors. In spite of this, there is a need to collect high quality microtopography data sets over a wide range of soils.

4. Conclusions

The structural function $W(h)$, i.e., local root mean square versus distance calculated from point elevation data sets obtained with a low technology device, thus, a broad interval of measure, was fitted by a power law function in a restricted range of scales. Assuming self-affine fractal behavior, the cutoff between two fractal intervals was set at 100 mm. The estimated fractal dimension of soil microrelief after corrections for slope and tillage marks was between 2.60 and 2.97 for conventional tillage and between 2.66 and 2.87 for direct drilling.

The statistical index random roughness, RR, and the fractal index crossover length, l, clearly discriminate between the two tillage treatments studied. In surfaces with oriented roughness a variance analysis indicates that fractal dimension, D, was significantly different between tillage treatments, whereas in random surfaces there was no tillage effect on D values. A covariance analysis using crossover length, l, as a secondary variable showed that the fractal dimension, D, was also a function of tillage for random microrelief conditions.

Further research is needed to examine the sensitivity of the fractal parameters D and l to the choice of an upper cutoff value of the RMS structural function in small point elevation data sets, to allow statistical determination of this limit.

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