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Multiscaling analysis of soil roughness variability

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ABSTRACT

Soil surface roughness (SSR) is a parameter highly suited for the study of soil susceptibility to wind and water erosion. The development of a methodology for quantifying SSR has typically been based on field techniques to obtain data, rather than on the indexes used for interpreting soil roughness variability. One of the most used indexes to evaluate SSR is the random roughness (RR), easily calculated from the heights obtained with a pin meter. The RR index was obtained from soil elevation measurements collected at the intersections of a 2×2-cm^2 grid in a 100×400-cm^2 plot from three different types of soil. SSR values for all soil types were obtained after passing three different tillage tools (chisel, tiller, and roller) through three types of soils at field conditions. The RR index was calculated using the standard deviation (SD) of the lines parallel to the direction of tillage. Lines were 20 mm apart.

Since RR assumes vertical random roughness without correlation, the variability of SSR was assessed using structure function (SF) to complement the study. Therefore, the main objective of this analysis was to better illustrate the variability of SSR in relation to spatial distribution. The SF was highly sensitive to soil roughness variability and depended on the tillage tool treatments and soil types, thereby illustrating the origin of the soil roughness variability, either from the soil itself or from the tillage tool used. We also demonstrate that the concept of a generalised Hurst exponent derived from the SF improves our ability to differentiate among the cases.

1. Introduction

Soil surface roughness (SSR), which describes the microvariation in soil elevations across a field resulting primarily from tillage practices and soil texture, is one of the major factors in wind and water erosion (Porta Casanellas et al., 2003). SSR and the complementary soil micro-relief depression pattern determine water infiltration and drainage network development (Vidal Vázquez et al., 2006). Most studies on SSR have focused on the mathematical description of the variations appearing after rainfall, wind events or tillage activities to predict water infiltration and runoff, and demonstrate excellent correlations between these parameters and water storage capacity (Linden and Van Doren, 1986; Kamphorst et al., 2000; Darboux and Huang, 2003). In this sense, different authors have used a variety of indexes to describe SSR as a function of soil erodibility and water storage capacity.

The quantification of SSR first requires the use of field techniques capable of accurately measuring the soil micro-relief from cm to mm. Among the different techniques, the pin meter and profile meter (Burkwell et al., 1963; Roömkens et al., 1986) offer simple and reliable methods that can be used in extreme field situations.

The pin meter is simple, consisting of a row of equally spaced probes lowered onto the ground surface. The pin position is registered either electronically or photographically and later digitalised (Burkwell et al., 1963; Podmore and Huggins, 1980; Wagner and Yiming, 1991). The main disadvantage to this method is the potentially destructive effect of the pins, preventing any further measurements.

The second challenge in measuring SSR is the analysis of the data and the presentation of the results. Mathematically, SSR is defined as the standard deviation of surface elevation readings.

After tillage, soil micro-topography exhibits randomly and oriented tillage roughness marks of different sizes and clods (Allmaras et al., 1966; Zobeck and Onstad, 1987; Huang, 1998). Each specific tillage tool creates its own oriented roughness pattern, which could be quantified using a geometric model. However, the challenge consists of quantifying the spatial distribution of randomly oriented SSR (Huang, 1998). For that reason, most of the studies in SSR interpretation have focused on random roughness (RR), trying to relate different parameters to soil micro-relief variability. For that reason, the most used statistical index is RR, and it is defined as the standard deviation in height after eliminating oriented roughness, such as tillage marks and land slope (Allmaras et al., 1966; Currence and Lovely, 1970).

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In this sense, the RR index can be measured with the pin meter easily because it represents the standard deviation of lines parallel to the tillage direction. This index assumes vertical random roughness without spatial correlation.

Because of the lack of spatial correlation when using RR, even if it provides great reliability, current SSR analysis has focused on developing a unified conceptual framework to describe the geometric complexity of the data with the aid of fractal parameters. To better illustrate SSR variations, a number of methods have been proposed to estimate the fractal dimensions of soil micro-topography as the result of tillage management (Linden and Van Doren, 1986; Malinverno, 1990; Perfect and Kay, 1995; Vidal Vázquez et al., 2005, 2006). However, most of these studies have been compared to the initial RR because it represents a more realistic approach to SSR.

The fractal techniques used can be divided into two groups: non-variational and variational. Non-variational techniques implicitly assume soil surface self-similarity across a range of scales and aim to characterise soil micro-relief features by calculating a single index. The group includes tortuosity (Boiffin, 1984) and the Richardson number (Gallart and Pardini, 1996; Pardini and Gallart, 1998). Because micro-relief fractal behaviour is better modelled on the basis of either self-similar or pre-fractal surfaces, the use of non-variational techniques has been highly criticised, which, in turn, has encouraged the use of variational methods (Vivas Miranda, 2000; Vidal Vázquez et al., 2005). In this group of methods, we found semivariogram interpretation (Armstrong, 1986; Huang and Bradford, 1992; Eltz and Norton, 1997; Vivas Miranda, 2000; Vivas Miranda and Paz González, 2002), spectral analysis (Burg, 1967), and several versions of the root mean square method (Malinverno, 1990; Gallant et al., 1994; Vivas Miranda, 2000; Vivas Miranda and Paz González, 2002).

Variational techniques can provide a better description of SSR (Vidal Vázquez et al., 2006, 2007). Thus, semivariance and local root mean squares are the most commonly used fractal descriptors of soil profiles or surfaces.

Multifractal models have been used to analyse the scale-invariant properties of objects in very different domains, from turbulent flows to financial data. Scale invariance is becoming increasingly important for understanding the complexity of natural phenomena. For that reason, multifractal analysis (MFA) has been used intensively in geomorphometry or digital terrain heights (digital elevation models) (Pike, 2000), but only recently has it been used in studies of agricultural soils. Manninen (2003) showed that bare soil exhibits multiscale behaviour, and Roisin (2007) proved that MFA can effectively analyse the variability in the inner-heterogeneity of tilled soils from soil strength measurements.

The semivariogram method has been largely used to quantify self-similar SSR by extracting a fractal dimension (D) based on the Hurst Index. Even though this index is one aspect of the known structure function (SF) and is widely used in the turbulence context, it has not been used to evaluate soil properties (Pozdnyakova et al., 2005). SF focuses on the absolute values of the differences that occur in arbitrarily large or small data, and it represents an excellent tool to illustrate soil roughness variability, as explained in the Materials and methods section of this study.

Therefore, the main objective of the present work was to illustrate the SF applications for determining soil roughness variability, while simplifying the method of field data assessment, and to assess the spatial variability related to SSR when measured for different scenarios. To this end, several soil height readings were collected for different soil types and tillage tools (García Moreno, 2006; García Moreno et al., 2008a,b) to study heterogeneity based on the SF. The structure function and the associated parameters were then applied to extract a generalised Hurst Index depending on soil type and tillage tool to use a more direct method of data interpretation in terms of variability.

2. Materials and methods

2.1. Experimental sites

The field experiments were conducted on different soil types at three sites in semi-arid central Spain. The first experimental plot was located in the province of Madrid, in fields belonging to the Polytechnic University of Madrid's School of Agricultural Engineering (the E.T.S.I.A. Madrid site). The other two sites were located at La Higueruela (Santa Olalla, province of Toledo), in the Spanish National Research Council's Experimental Station for Environmental Science (La Higueruela site). The main soil characteristics, tested according to ISRIC/FAO (Merrill et al., 1995) and the Soil Science Society of America (1996) methodologies are given in Table 1.

The three types of tools used to till each soil type (chisel, tiller, and roller) are the three most commonly used in the central regions of Spain. All measurements were taken immediately after tillage to preclude the effects of other factors. In other words, SSR was analysed in a total of nine scenarios. Tillage was performed using the following John Deere equipment: a Model 2810 moldboard plow, a Model 610 integral chisel plow, and a roller level.

The field data were gathered in 2005, one of the driest years on record at the experimental sites, with no rainfall in either spring or summer. In fact, accumulated rainfall was 114 l/m^2 in central Spain during the period from November 2004 until August 2005 (Instituto Nacional de Meteorologia, 2005).

2.2. Soil surface roughness data

Field micro-topography measurements were obtained with a full-scale pin meter shown in Fig. 1. This instrument consisted of a row of 35-cm-high pins, placed in a frame where they could slide up or down to conform to surface irregularities. The pin heads were marked with a blue band to better visualise their respective positions when in contact with the soil. The frame, 85 cm-high, was designed in such a way that the pins were elevated when the instrument was moved, creating minimum disturbance in the area being measured. The instrument was made of lightweight aluminium for ease of handling. With rows containing 50 pins spaced at 20-mm intervals, one full meter could be measured along the x-axis with each reading. The y-axis readings were taken by sliding the instrument on tracks across the plot, stopping at 20-mm intervals. As the cells on the resulting grid (20 by 20 mm) were measured, a total of 2500 readings were taken per 1.0 m^2 of area. An earlier study (García Moreno, 2006) showed this spacing to be sufficient to measure surface roughness of the three types of soil.

Each corner of the instrument was marked with a red dot and Visual Basic software was developed that would detect these marks as vertical and horizontal references for shifts in row position.

A Kodak DC 4800 digital camera, set on a tripod, was used to capture pin positions. The lens was focused on a point at the centre of the pin meter (i.e., at the average height of the red marks) to ensure that the image would not be distorted. After comparing several models, a Silk tripod was found to be best suited to the 40-cm camera

Table 1
Properties of selected soils (values in parentheses are the standard deviations of 12 samples for each type, three per subplot).

Site	Conductivity (dS/m)	Organic matter (%)	pH	USDA textural analysis (%)			USDA textural class
				Sand	Silt	Clay	
E.T.S.I.A. Madrid	1.90 (0.34)	1.8 (0.4)	7.8 (0.2)	57 (1)	17 (2)	26 (1)	Sandy clay loam
La Higueruela	0.21 (0.05)	2.6 (0.1)	6.2 (0.2)	53 (2)	23 (3)	24 (1)	Sandy clay loam
La Higueruela	0.68 (0.55)	1.5 (0.2)	5.7 (0.1)	63 (2)	19 (2)	18 (1)	Sandy loam