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Predicting surface porosity using a fine-scale index of roughness

Porosity of the top soil strongly influences soil water movement, energy exchange, nutrient cycling, and seedlings germination. As there is no adequate method to determine the soil porosity in the field it is proposed to investigate the correlation between soil surface porosity and roughness. The terrain and micro relief was measured by a laser profiler for three different tillage types in a period of 45 days and the correlation with the porosity measured by pycnometer method is presented.

Keywords
Soil roughness, laser profiler, tillage

Abstract
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4 figures, 1 table, 9 references

The porosity of the topsoil strongly influences soil water movement, energy exchange, nutrient cycling, and seedlings germination [1,2]. A common apparatus to determine soil porosity is an air pycnometer, which provides an accurate measurement and is satisfactory for conventional soil investigation. Unfortunately, this method is time-consuming because soil samples need to be oven-dried for 24 h at 105 °C before porosity measurement. Alternatively, for soil roughness determination, the laser profiler is a non-contact and rapid method as the data can be acquired and processed immediately in the field [3,4,5]. Because of this advantage, Sun et al. [6] proposed to investigate the correlation between soil surface porosity and roughness.

In their preliminary attempt, ESD (elevation standard deviation) in 2D space was chosen as an index relating soil roughness to surface porosity. Nevertheless, the value of ESD resulted from contributions of both the soil terrain profile and microrelief. As a miscellaneous consequence, ESD was an indicator of the superposition of surface unevenness regardless of scale-dependent characteristics. This study expands that work with the following objectives:

(1) To develop an index based on fine-scale roughness measurement for characterizing the relationship between soil surface roughness and porosity.
(2) To verify the defined index for different tillage treatments.
(3) To validate the fine-scale index with different grid size.

Materials and methods

The field experiment was performed at the Dikopshof Experimental Field of Bonn University, of which the textural compositions (mg mg^{-1}) of the soil (silt-loam, USDA Standard) were: sand 0.17%, silt 67%, clay 16%, and the organic content was 1.89%. In order to compare the effects of different tillage treatments on the soil surface roughness over time, four plots (30 m length, 3 m width) were cultivated with GN (Cultivator with rigid tines, wing shares and roller), G (Spring tine cultivator), PRP (Moldboard plow+landpacker and ring roller) and KE (Rotary harrow, rigid and segmented roller) respectively. Two measurements were taken in each plot (2 m length, 1 m width) at intervals of 5 days from August 11th to September 25th.

The laser profiler used to take measurements was developed by the Department of Agricultural Engineering, Bonn University, Germany. The height resolution was 1 mm. The measurement ranges and spans along both axes could be adjusted by programming parameters into the computer. For this experiment, we set the Y-axis along the tillage direction. The scan area was fixed to 1.40×0.48 m and each span along the X- or Y-direction was 2 mm.

Several different indices have been presented to compute the surface unevenness in previous studies [7,8,9]. In general, these indices can be categorized into three kinds of data treatments, e.g. ESD, slope-angle (or tortuosity measure) and autocovariance function. The proposed index at a fine-scale in our study, RI (roughness index) consisted of two equations. Firstly we defined a local index γ_{ij} as

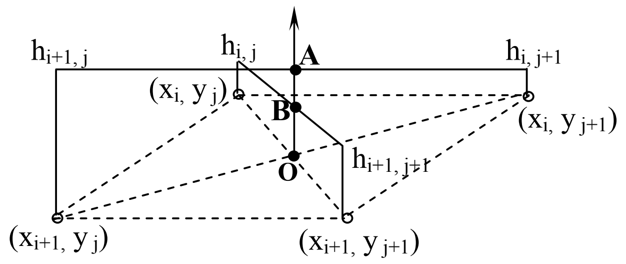
$$\gamma_{ij} = \frac{|h_{AO} - h_{BO}|}{h_{AO} + h_{BO}} \qquad (1)$$

Fig. 1 shows a geometrical dimension of h_{AO} and h_{BO} at any grid of the scanned plot. Then RI is computed by

$$RI = \frac{1}{nm}\sum_{j=0}^{m-1}\sum_{i=0}^{n-1}\gamma_{ij} \qquad (2)$$

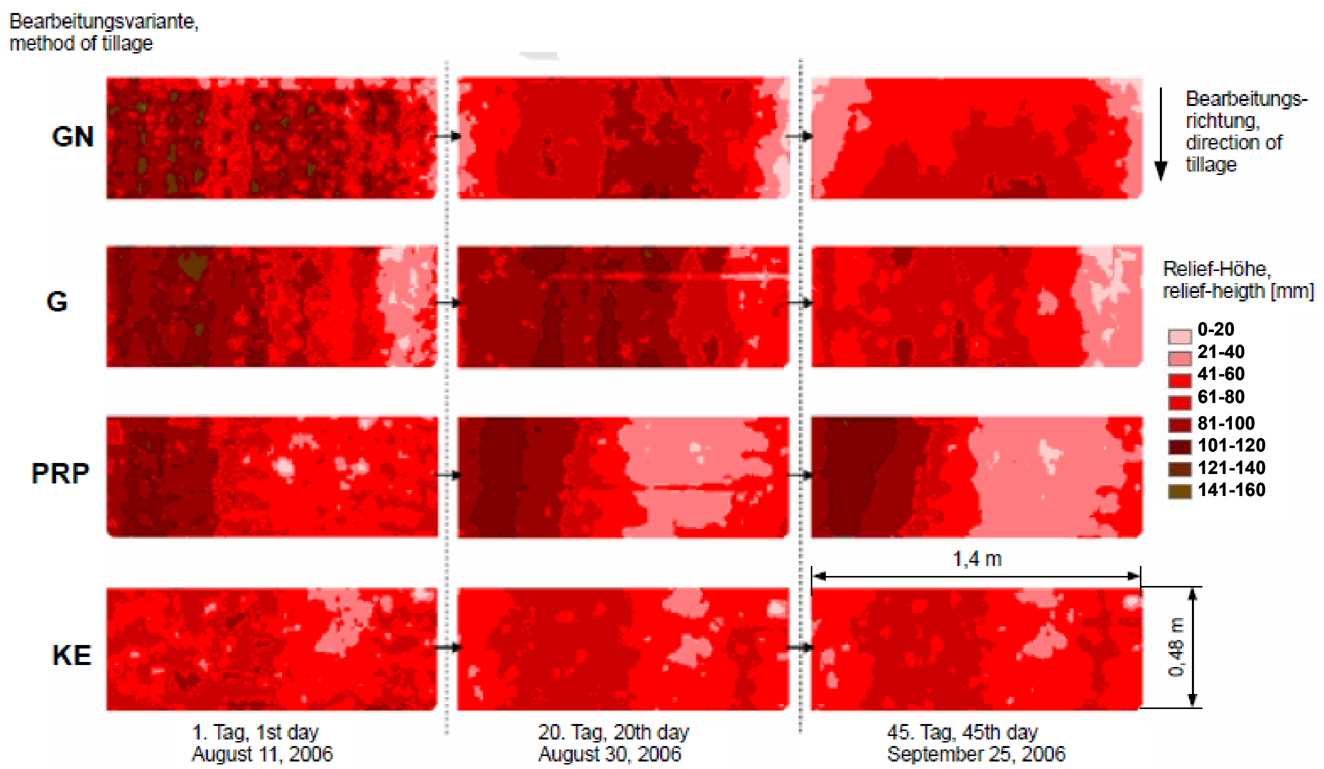
where n is the total observations along X-axis and m is the number of total steps along Y-axis. Obviously, Eq. (1) is a differential function with respect to a grid size, whereas Eq. (2) is a global average value of in the scanned area. The grid size of

Fig. 1



Geometrical representation of RI defined as Eq. (1). "O" = the middle point of the grid, $h_{i,j}$ = the height at any point of x_i and y_i • h_{AO} = the projecting distance of A to O, and A is the middle point between $h_{i+1,j}$ and $h_{i,j+1}$ • h_{BO} = the projecting distance of B to O, and B is the middle point between $h_{i,j}$ and $h_{i+1,j+1}$

Fig. 2



The surface changes of each tilled plot at 1st, 20th and 45th day on four different tillage-treatments GN: chisel plow with wing shares and two rollers, G: spring tine cultivator; PRP: moldboard plow with land packer and rear/front roller tillers; KE: rotary harrow with cage and crusher roller

Eq. (1) is chosen small (2 cm×2 cm) so that the effect of soil surface unevenness at large-scale in a tilled field could be minimized; thereby RI refers to a fine-scale.

Results and discussions

Temporal effects on surface unevenness

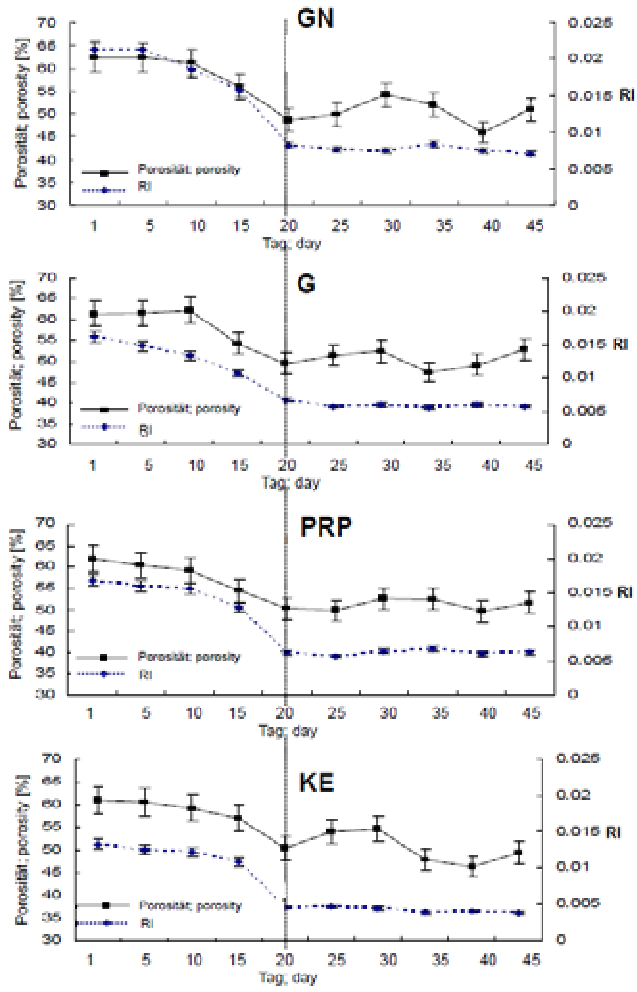
In order to provide an insight into the surface evolution with respect to the different scales and time, four groups of maps were processed and are presented in **Fig. 2**. Here each map or image represents a scanned rectangle area (1.40 m×0.48 m) that included 1680 grids, and the maps in each row referred to the type of tillage treatment employed. As distinguished from the maps in the same row in **Fig. 2**, two significant observations were made. First, the surface roughness corresponding to all tillage types became relatively smooth at the grid-scale (or fine-scale) following the experimental process. Second, comparing the map of 1-day to that of 45-day for each tillage type at large-scale, the residues of plow furrows and ridges were more or less left. From these important observations, one can see that the index defined by Eq. (1) together with Eq. (2) at a fine-scale is reasonable for associating surface roughness with porosity.

Statistical analysis of RI and porosity

The dynamic processes of measured RI and surface porosity with respect to the tilled plots during the whole experiment period are displayed in **Fig. 3**. It is noted that from the beginning of the experiment the RI of each plot declined markedly until the 20th day, but then became flat. As far as the surface porosity was concerned, the initial values of four plots were rather consistent (ca. 62%). At the first stage (1~20 day), the porosity of each plot also rapidly decreased. After 20 days (second stage) the surface porosity fluctuated at certain degree over time unlike the RI.

Certainly, complicated weather factors could accelerate or decelerate the dynamic processes of the surface roughness and porosity, but the correlation between both parameters was independent of the successive time. **Table 1** indicates the regression results of each plot from the acquired data for two stages, respectively. The coefficients of determination (R2) for the linear function under the different tillage treatments in the first stage were quite high (0.889 ~ 0.982). Moreover, the transect value of each linear equation in 1~20 days seemed independent of the tillage styles because these values were relatively consistent (40.064~44.882). Inferentially, this parameter relied on the soil texture, aggregate property and the water content in the field at the time of tillage operation. In addition, **Table 1** also lists the statistical results of each tilled plot from the acquired data within the second stage. Unfortunately, the slope values in the second stage showed inconsistent trends with respect to the different tillage types, regardless of higher or lower R^2 values. Therefore data from the second stage (right of the dashed line in **Fig. 3**) will be omitted in the following discussion.

Fig. 3



Dynamic process of surface porosity and RI (Roughness Index) between 1 and 45 days after tillage for each tillage treatment

Table 1

Parameters of linear regression for "surface porosity" and "RI" for each tillage treatment

Bearbeitungs-form; Tillage type	$y = ax + b$ (y = Oberflächenporosität, porosity; $x = RI$)					
	1. Phase, 1st stage (1~20 Tage, days)			2. Phase, 2nd stage(21~45 Tage, days)		
	a	b	R^2	a	b	R^2
GN	1052.3	40.064	0.98	29.783	50.006	0.001
G	1406.7	40.375	0.8896	-690	54.536	0.017
PRP	1074.9	42.824	0.932	3209.9	31.194	0.753
KE	1201.5	44.882	0.9825	7359.1	19.25	0.625

A general analysis of four tilled plots at fine-scale

To get an overview of the relationship between surface porosity and RI, the data of all tillage treatments in the first stage of the experiment were combined and a linear regression was fit to the entire data set with an R^2 of 0.707. The calculated root mean square error

(RMSE) of the porosity was equal to 2.66%. Furthermore, the dependence of R^2 on varying grid lengths was investigated.

Fig. 4 illustrates that the smaller grid size had a higher R^2 value, and thus one could comprehend the reason why the defined RI referred to the fine-scale. Besides, since the chosen grid length (2.0 cm) of RI was smaller than the diameter (5.7 cm) of the sampling cylinder that was used for porosity measurement and both parameters were apparently smaller than the geometrical size of soil terrain profile, it is also convincing that the present study was based on the fine-scale.

Conclusion

By the aid of a relief laser profiler the surface roughness of plots tilled with 4 different tools were measured. Aim of the study was to determine the correlation between soil surface roughness and surface porosity. To define the roughness a fine scale index was derived from and applied on data of the plots with different tillage types. In the first 20 days of the experiment, which are highly relevant for plant emergence, there was a correlation of $R^2 > 0.89$. Because of the influence of weather the correlation declined in the successive days, in which there is a lower impact of soil porosity on plant development.

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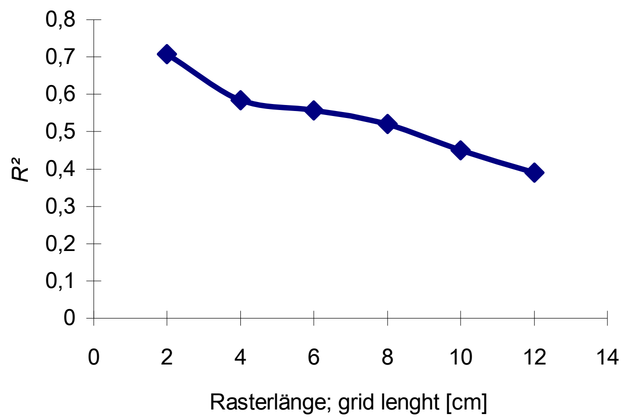
Fig. 4



Dependency of R^2 on grid length