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Changes of pore orientation in soil lessive caused by tillage measures

ABSTRACT. The paper aimed at a description of the direction of pore cross-sections in soil lessivé after different treatments during onion cultivation in the growing season and in changeable weather conditions. The measurements were taken on the basis of opaque soil blocks using computer assisted image analysis. For the statistical evaluation of the obtained results the statistics of two-dimensional vectorial data (circular statistics) was used. In order to compare soil states the Pearson compatibility test χ^2 was carried out. The obtained results showed that the applied methods of the vectorial data statistics allowed defining the distribution type of pore cross-sections considering their direction. The taken measurements proved that the applied cultivation treatments led to the soil material homogenisation, which was supported by a generally random pore cross-sections orientation. The tested soil in most cases showed an isotropic pore distribution. The observed anisotropy resulted mainly from the compaction and intensive or long-lasting rainfall.

KEY WORDS: soil structure, pores, morphometry, image analysis, circular statistics, orientation

The knowledge on the direction and level of soil pore anisotropy, namely cracks and cavities, allows for better understanding of the processes determined by a soil structure. It also allows for modelling these processes [Vogel et al. 1993]. Distribution of soil pores and their continuity determine the water and nutrient transport as well as gas exchange, which influence the life conditions of soil organisms and cultivated plants.

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Therefore, the aim of the paper was to characterise pore cross-sections directions in a non-uniform soil lessive (developed from silt on a siliceous marl) subjected to various tillage operations and changing weather conditions in growing season during onion cultivation. Vectorial data statistics widespread in geological and biological sciences [Capaccioni et al. 1997, Cladouhos 1999, Mann et al. 2003] and poorly applied in agricultural and soil sciences, was used for statistical analysis of the achieved results.

METHODS

Localisation of the experimental object, sampling points and method of opaque soil blocks making for analyses were discussed in the work by Słowińska-Jurkiewicz et al. [2004]. Rules for preparation of the digital photos subsequently used in image analysis were also described in the above-mentioned paper. Measurements were made on the basis of binary pictures of soil block surface, including the sample of 75 mm × 65 mm area. Only pore cross-sections, whose gravity centres were included within the protection frame of 67.1 mm × 58.1 mm, were taken into account for counting when working out the results [Wojnar et al. 2002]. The size was another criterion: pore cross-sections of at least 100 pix^2 area (0.179 mm^2) were selected for orientation analysis due to the difficulty in classification of smaller objects. Then, round pore cross-sections (with elongation index less than 0.11) were eliminated applying the results presented by Kołodziej et al. [2004], because such objects had no distinguished orientation axis. It should also be mentioned that these objects comprised a low per cent of all tested ones (0–2.52 %).

The pore cross-sections direction was characterised by determination of the orientation of the longer side of the smallest rectangle limiting an object, θ_i, within an angle range of 0–180°. The horizontal direction corresponded to 0°, vertical – 90° and angles increased counterclockwise. Circular frequency histograms (rose diagrams) were constructed on the basis of the achieved results.

The statistical analysis was performed in order to find out if the objects in tested samples had random (uniform) orientation or were distributed along selected direction [Baas 2000 after Watson 1966, Mardia 1972 and Batschelet 1981]. Parametric Rayleigh's test was carried out to check if the probability distribution of orientation data for tested population was von Mises's circular-normal frequency distribution (equivalent of Gaussian normal distribution for non-directional data). Von Mises's distribution is characterised with two parameters: direction of mean vector, M, and concentration of vectorial data (strength of mean vector), K. The level of vectorial data concentration may also be characterised using Batschelet's circular variance $s_B{}^2$, or circular standard deviation s_B. The lower dispersion, the larger length of mean vector, R, and the more population differs from the uniform distribution. Variable R is within the range from 0 to 1; 0 represents total data dispersion (large dispersion, uniform distribution) and 1 – total data concentration proving the orientation of all objects along single direction [Mann et al. 2003].

The R value for a sample can be calculated from the formula:

$$R = \frac{1}{N}\sqrt{X_r^2 + Y_r^2} = \frac{1}{N}\sqrt{\left(\sum_{i=1}^{N} X_i\right)^2 + \left(\sum_{i=1}^{N} Y_i\right)^2} = \frac{1}{N}\sqrt{\left(\sum_{i=1}^{N} \cos\theta_i\right)^2 + \left(\sum_{i=1}^{N} \sin\theta_i\right)^2}\ ,$$

where: N – number of objects (pore cross-sections); X_r, Y_r – coordinates of R vector end originating at (0,0) point; i – index denoting the pore cross-sections in a sample; θ_i – orientation of vector originating at (0,0) and ending at (X_r,Y_r) for i-th pore cross-section.

The critical value of Rayleigh's test is given by the formula: $R_\alpha = \sqrt{\frac{3{,}00}{N}}$ for $\alpha = 0.05$ and $N \geq 15$. If R value calculated for a sample is equal or greater than critical one ($R \geq R_\alpha$) at the assumed significance level, the tested distribution is circular-normal, otherwise the distribution is uniform.

For random variables with circular-normal distribution, the direction of mean vector can be then calculated using the following trigonometrical relationship: $M = \mathrm{arc\,tg}\left(\frac{Y_r}{X_r}\right)$ (°). The vectorial concentration (strength of mean vector), K, is directly related to the mean vector length by formulae: $K = \frac{1}{6}R(12 + 6R^2 + 5R^4)$ for $R \leq 0.65$ and $K = [2(1–R) – (1–R)^2 – (1–R)^3]^{-1}$ for $R > 0.65$.

Circular standard deviation s_B, is a vectorial equivalent of standard deviation for common non-vectorial data: $s_B = \frac{180}{\pi}\sqrt{2(1 - bR)}$ (°), where: b – a correction factor ($b \approx 1$). In addition, confidence sector for the mean vector may be calculated: $\pm d° = m_\alpha\,(NRK)^{-2}$ (°); where $m_\alpha = 112$ for a significance level of 5 % and the equation is valid for $NRK \geq 6$. The estimate of a true mean vector of the general population ($\mu°$) is given as $(M – d°) < \mu° < (M + d°)$ at a confidence level of $(100 – \alpha)$ %.

Rayleigh's test and rose diagrams were made using free software designed by Baas [2000] – EZ-ROSE ver. 1.0. The statistical analyses were carried out at a significance level of $\alpha = 0.05$. Furthermore, comparisons of the orientation distributions were made applying χ^2 Pearson's compatibility tests.

RESULTS

Table 1 presents Rayleigh's test results for the consecutive soil states, and in Figure 1 corresponding rose diagrams are shown. The area of each circular sector is proportional to the frequency of particular orientation class. Twelve orientation classes were distinguished: for every 15° from 0° to 180°. Values of θ_i angles for particular pore cross-sections were grouped in left-closed intervals:

Table 1. Results of Rayleigh's test at the significance level $\alpha = 0.05$

State	N	$R_{0.05}$	R	M (°)	s_B (°)	K	$\pm d$°	Distribution type
1	92	0.181	0.345	0.462	32.793	0.735	11.598	von Mises's circular-normal
2	158	0.138	0.223	162.675	35.716	0.457	13.959	von Mises's circular-normal
3	312	0.098	0.076	–	–	–	–	uniform
4	351	0.092	0.079	–	–	–	–	uniform
5	143	0.145	0.116	–	–	–	–	uniform
6	343	0.094	0.063	–	–	–	–	uniform
7	448	0.082	0.031	–	–	–	–	uniform
8	347	0.093	0.053	–	–	–	–	uniform
9	293	0.101	0.088	–	–	–	–	uniform
10	36	0.289	0.169	–	–	–	–	uniform
11	64	0.217	0.439	179.127	30.343	0.976	10.691	von Mises's circular-normal
12	392	0.087	0.135	24.711	37.673	0.273	14.709	von Mises's circular-normal
13	292	0.101	0.040	–	–	–	–	uniform
14	150	0.141	0.162	23.729	37.082	0.329	19.791	von Mises's circular-normal
15	225	0.115	0.148	35.355	37.400	0.299	17.758	von Mises's circular-normal
16	79	0.195	0.193	–	–	–	–	uniform
17	155	0.139	0.061	–	–	–	–	uniform
18	22	0.369	0.588	3.639	26.008	1.438	12.987	von Mises's circular-normal
19	64	0.217	0.105	–	–	–	–	uniform

N – number of pore cross-sections; $R_{0.05}$ – critical value at the significance level $\alpha = 0.05$;
R – value for tested population; M – mean vector orientation; s_B – circular standard deviation; K – mean vector strength; ± d° – confidence sector for the mean vector orientation

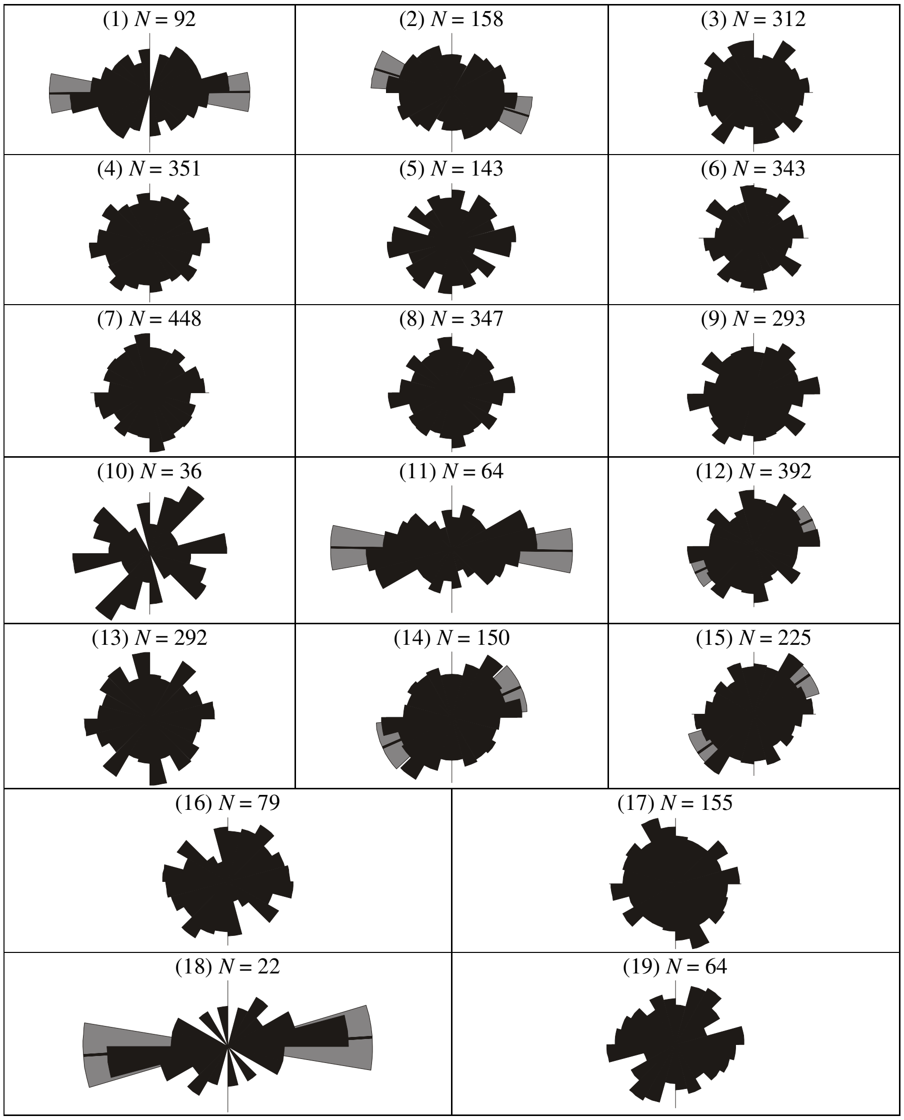

Figure 1. Roses of orientations for subsequent soil states (1) – (19)
N – number of pore cross-sections; description in the text

[0;15), [15;30) *etc*. Results were symmetrically drawn also for the other semicircle – from 180° to 360°. For distributions that fulfilled von Mises's distribution conditions, black line indicated the mean vector orientation, and the corresponding angular confidence sector was marked in grey colour. The rose diagrams allowed easy observation of the changes of pore cross-section orientations due to external conditions.

Non-uniform soil lessive was included in the experiments from 2nd April to 15th November 1990 during onion cultivation. Horizontally oriented pores (i.e. parallel to the soil surface) dominated in the soil at the initial state (state 1 – before cultivation, 2nd April). Harrowing using medium harrow to 5 cm depth (state 2, 4th April) caused the change of soil pores' orientation to skew one, and *M* was almost 163°. Later, several-day rainfalls (state 3, 10th April) as well as subsequent harrowing with active harrow (state 4, 10th April, and state 5, 11th April) up to 15 cm depth aiming at proper preparation of the soil for sowing, did not cause any general changes in pore cross-section direction and the orientation distributions were uniform. The onion sowing ended with rolling (state 6, 12th April) invoke statistically significant changes of pore cross-section orientation distribution as compared to the previous state. Percentage of vertically oriented pores slightly increased and those arranged parallel to the soil surface – decreased. Other external factors, despite their diversity: state 7, 24th April – after spraying made on 16th April and several-day rainfalls, states 8 and 9 – before and after harrowing using light harrow (16th May), state 10 – soil compaction during fertilisation with nitrogen fertiliser by tractor Ursus C-330 (11th June), did not influence the orientation distribution of the soil pore cross-sections. No significant differences were also found between state 10 and state 11 (soil after loosening with a six-raw inter-plant hoe to 5 cm depth, 18th June), probably due to the small number of soil pore cross-sections tested in the samples. However, statistically significant changes of classification of particular pore cross-sections to distinguished orientation groups were recorded after two weeks and heavy rainfalls (state 12, 4th July). Pores arranged horizontally at *M* almost equal to 180° dominated in loosened sample (state 11). Vertically oriented pores, due to which the water and air transport between soil and atmosphere could be realised, comprised a much lower number. The pore direction changed into skew one with *M* of about 25° after heavy rainfalls and soil self-consolidation (state 12); the distribution became much uniform, which was proven by lower *R* value as compared to the previous state. Soil after manual hoeing (state 13, 4th July) was characterised with chaotic distribution of the soil pores. After six-week rainfalls (state 14, 12th July), a slight decrease of number of pores parallel to the soil surface could be observed and pores became more oriented – along the direction of about 24°. Manual hoeing (state 15, 12th July) caused little compensation of the distribution of the soil pores' direction and the increase of the number of vertically oriented pores, undoubtedly associated with the specificity of the device action. A similar situation was observed for state 13. The disappearance of the smallest pores occurred during eight following days and on the 20th July (state 16) the remaining pores were randomly oriented. After loosening using horse hoe (state 17, 20th July), the soil pores did not get a characteristic orientation. Removing the onion out from the field after harvest caused general changes of the soil structure. Even a month later (state 18, 16th October), the pore cross-sections were horizontally oriented and the number of pores perpendicular to the surface was low. The observation confirmed the results achieved by Murphy *et al*. [1977] as well as Słowińska-Jurkiewicz and Domżał [1991]: pores in the soil subjected to strong compaction showed the preferred orientation. Such a state changed after skimming – the pore orientation became random (state 19, 15th November).

CONCLUSIONS

1. Applied methods of vectorial data statistics allowed for classification of the type of pore cross-section distribution depending on their orientation.
2. Measurements revealed that applied tillage operations led to homogenisation of the soil material, which in general was proven by random orientation of pore cross-sections.
3. In most cases, the tested soil was characterised with isotropic pore distribution. Observed anisotropy first of all resulted from soil compacting and intensive or long-term rainfalls.

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