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MULTIDIMENSIONAL STATISTICAL METHODS FOR CLASSIFICATION AND DIAGNOSTICS OF THE PORE SPACE IN MICROMORPHOLOGICAL THIN SECTIONS

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The methods of multidimensional statistics and claster analysis were used to create an automatized classification and diagnostics of the pore space in 200 micromorphological vertically oriented thin sections prepared from podzolic soils (the Republic of Komi, Russia), soddy-podzolic soils in the Moscow region, gray forest soils (Tula region) and chernozems (Kursk and Voronezh regions in Russia, Odessa region in Ukraine). The computer image analysis permitted to study fine macrovoids (d = 0.2–2 mm) in the field of vision 2 × 2 cm. Every void in the field of vision was measured to determine its section area (S), perimeter (P), diametrical (D) and longitudinal (L) sections, orientation of the long section axe in the thin section and the form factor $F = (4pS/P^2 + D/L)/2$. 100–150 voids were taken for measurements in every thin section. To characterize the pore space in thin sections, under use were also the empiric distribution of voids according to the form factor and orientation as well as the average length of voids in the field of vision. The discrimination analysis made it possible to elaborate an automated system and to give the morphometric characteristics of the pore space in the studied soils with varying structures so specific for loamy soils at the territory of European Russia including crumbly, granular, nutty, platy, massive-platy, fissure-like and massive structures. The results of the automated diagnostics have a rather high similarity with the expert visual assessment of the pore space in thin sections (75–90%).

Keywords: the pore space in soil, classification, diagnostics, multidimensional statistic methods, claster analysis

INTRODUCTION

For today it becomes more and more evident that the methods to present initial data and the methods to formalize the processing of visual objects at all the levels of the soil megasystem organization: from micromorphological thin sections to small-scale soil maps are becoming increasingly common [8]. The unity of principles for the image analysis permits to perform the methods of multidimensional statistics and claster analysis in soil micromorphology. It is also possible to automatize the classification and diagnostics of the pore space fabric in thin sections.

The total amount of voids in thin sections should be considered as a visual image of the pore space in aggregates, morphones and soil horizons on the whole. As the micromorphotypes so specific for horizons and soils are distinguished among the abundant variants of the fabric, a great diversity of the pore space allows distinguishing the types of its fabric (geometrical types) characteristic of different soil structures [3]. With development of the automated image analysis it became possible to classify the fabric of the pore space taking into complete account all the components of its voids [1–5].

This study is aimed to perform available methods of multidimensional statistics and claster analysis for the automatized classification and diagnostics of the pore space in thin sections. The objectives of the present study are oriented:

to make the computer image analysis of voids in 200 thin sections prepared from different horizons of virgin and arable loamy soils within the forest, forest-steppe and steppe bioclimatic zones of European Russia and Ukraine;

to apply the claster analysis of the obtained micromorphometric data about the fabric of the pore space in thin sections;

to use discriminatory equations for elaborating a program of automatized morphometric diagnostics (recognition) of the pore space in soil;

to compare the results of automatized diagnostics of the pore space in thin sections with those obtained by the expert visual assessment.

OBJECTS OF RESEARCH AND METHODS

The pore space was studied in thin sections of vertical orientation prepared from podzolic soil (Republic of Komi, Russia), soddy-podzolic soil (Moscow region), gray forest soil (Tula region) and chernozems (Kursk, Voronezh regions in Russia and Odessa region in Ukraine). The thin sections of 3 × 4 cm in size displayed all the main genetic horizons of the studied virgin soils and a set of plough horizons with the soil structure from crumby to massive one. More than 200 thin sections with different soil structural organization have been analyzed.

The method of computer image analysis was performed to study fine macrovoids (d = 0.2–2 mm) in the field of vision (2 × 2 cm). The section area (S), its perimeter (P), diametrical (D) and longitudinal (L) sections, orientation of the long section axe were measured for every void in the thin section. The orientation was determined as a deviation angle of the long axe from the vertical. The amount of voids measured in each field of vision and those in the thin section made up 100-150 voids. Special attention was paid to studying the form of voids. Under measurement were also the index $R = 4\pi S/P^2$ to show the difference of the void contour and the index $I=D/L$ characterizing the isometric contour of the void. Besides, the form factor $F = (4pS/P^2 + D/L)/2$ was calculated for every void as well. This index has advantage to characterize the void forms and permits to distinguish the voids with different sections from fissured to around ones [6].

The following data have been used to give a complex assessment of the pore space fabric in thin sections:

1. Distribution of voids according to their form including fissured ($0<F\leq0.2$), stretched broken ($0.2<F\leq0.4$), isometric broken ($0.4<F\leq0.6$) isometric weakly broken ($o.6<F\leq0.8$) and around ($0.8<F\leq1.0$) macrovoids in per cent from the total amount of the measured voids.

2. Distribution of voids according to their orientation, including the content of voids with vertical (and subvertical), inclined and horizontal (subhorizontal) orientation in per cent from the total amount of the measured voids in thin sections. They were grouped in the following intervals: the first group – within the 0^o–30^o interval, the second group – 30^o–60^o and the third group – 60^o–90^o.

3. An average arithmetical value of the void length in fields of vision (averaged for the whole thin section).

Thus, the fabric of the pore space was described by using a set of 9 parameters including 5 parameters for the form, 3 parameters for the orientation and one parameter for the void length.

The methods of claster analysis and digital classification according to a number of quantitative features were used to formalize the processing of the obtained micromorphological data [3, 4].

DISCUSSION

The claster analysis allowed identifying 8 groups (types) of the macrovoid fabric, the similarity of which is not less than 70% in every group: massive (without aggregates), fissured-massive, massive-fissured, crumby, crumby-microblocky (granular), angular-isometric-blocky (nutty), platy and massive-platy (Table 1). These 8 types were taken from larger groups, in which the similarity level is rather low. For all this, a set of informative morphometric indices seemed unequal at different levels of automatized grouping of thin sections. In case of distinguishing two great parts (isometric and planar) the index of the form proved to be most informative: the isometric pore space reveals a higher content of isometric voids in thin sections ($F>6$), whereas in the planar pore space the content of stretched anisometric voids and fissures ($F<4$) is increased. At the next stage of automatized grouping the thin sections with isometric voids display a leading role of the form but in the thin sections with anisometric voids the orientation of voids is dominant.

Let us give a brief characteristic of fabric types in the macrovoids. The averaged morphometric parameters of these types are presented in Table 2.

1. The around fabric of the pore space is typical for massive soil structure, in which the aggregates are absent. The macrovoids are separated, the content of voids with the form factor $0.6<F<0.8$ and $0.8<F<1.0$ is increased and makes up 30% and 20% respectively. This void fabric is observed in the interped mass of large structural particles in mantle loams, in disaggregated plough horizons and in soils compacted by heavy agricultural machines.

2. The fissured-around fabric of the pore space is characteristic of the fissured-massive soil structure with single fissured voids in the non-aggregated soil mass. Thanks to the fissured voids in the pore space the content of around voids with $0.8<F<1.0$ is decreased but the content of voids with $F<0.4$ shows an increase.

Table 1. Classification scheme of the pre space in loamy soils

Pore space in thin sections	Isometric pore space, isometric sections of voids prevail				Planary pore space, anisometric sections of voids prevail			
Space, kind of the contour	Weakly broken, the void contours have a weakly broken form			Higher broken, the void contours have a higher broken form	Non-oriented, the void orientations is not expressed		Horizontal-oriented, dominant ate horizontal voids	
Type No.	1	2	3	4	5	6	7	8
Type of the pore space	Around pore space	Fissure-around pore space	Around-fissure pore space	Tracery	Net	Lattice	Horizontal--fissured	Orizontal-fine fissured
Characteristics	Dominant voids with around and sub-around sections	Among around and subaround sections there are single fissure-like voids	Among around and subaround sections rare fissure-like voids are met	Dominant isometric voids with broken contours	Dominant stretched broken voids and planars of different orientation	Dominant highly stretched planars of different orientation	Abundant large horizontal planars	Abundant fine horizontal planars
Soil structure	Massive	Fissure-massive	Massive-fissured	Crumby	Crumby-microblocky (granular)	Angular-blocky (nutty)	Platy	Massive-platy

Table 2. The average morphometric indices for types of the pore space in soil

Soil structure	Type of the pore space	The void content, % of the total content of voids in thin section								Average arithmetic length of voids. mm
		Form factor *F*					Orientation			
		<0.2	0.21–0.4	0.41–0.6	0.61–0.8	0.81–1.0	vertical	inclined	Horizontal	
Masive (non-aggregated)	Around pore space	1	12	33	33	21	33	34	33	0.69
Fissured-massive	Fisured-around	5	19	35	29	12	36	34	30	0.81
Massive-fissured	Around-fissured	14	20	29	24	13	30	34	36	1.08
Crumby	Tracery	2	29	44	20	5	38	33	29	1.30
Crumby-microblocky (granular)	Net	13	45	29	11	2	33	34	33	1.64
Angle-blocky (nutty)	Lattice	34	35	22	6	3	30	34	36	1.68
Platy	Horizontal-fissured	31	27	22	14	6	22	23	55	1.67
Massive-platy	Horizontal- fine fissured	30	28	24	13	5	15	20	65	1.27

3. The around-fissured fabric of the pore space is inherent to the massive-fissured soil structure, where the amount of fissures increases but the voids with $F<0.4$ are not dominant. This fabric type reveals 5 groups of the void form from fissured to around ones. The macrovoids are evenly distributed according to the form although the maximum is observed in the $0.4<F<0.6$ interval. This fabric of the pore space is widely distributed in lower horizons of texture-differentiated soils, in degraded plough horizons and transitional horizons (AB) of chernozems.

4. The tracery fabric of the pore space is typical for the crumby structure of soils characterizing by the presence of isolated aggregates, the surface of which has a wavy-around form without flat edges. The isometric or weakly stretched voids are dominant, whose linear size is higher than that in the massive soil structure. In distribution of voids according to the form the maximum is found to be in central $0.4<F<0.6$ interval, the minimum is distributed between the low and high F factor. This fabric of the pore space is observed in plough soil horizons as well as in humus horizons of virgin soils with intensive zoogenic transformation.

5. The net fabric of the pore space takes place in the crumby-microblocky (granular) structure of soils, in which the aggregates are presented not only by around aggregates but also angular microblocks with subparallel edges. The voids between such microblocks are relatively stretched in length, thus increasing the content of voids characterized by the anisotropic form (to 45%). Distribution of macrovoids according to the form is maximal in $0.2<F<0.4$ interval being minimal when $F>0.8$. This fabric of the pore space is inherent to the soil horizons with granular structure (typical chernozem, etc.). It can be also observed in the crumby-nutty structure of the soil mass.

6. The lattice fabric of the pore space is characteristic of the angular-isometric-blocky (nutty) structure. Dominant are isometric or weakly stretched angular structural particles with flat edges and the lattice of fissured voids between them. The amount of fissured voids makes up more than 30%. The average length of voids is higher as compared to that in the other types. The voids are distributed according to the form with maximum in intervals of $F<0.2$ and $0.2<F<0.4$. The

given fabric of the pore space is met in horizons with the nutty and finely prismatic structure.

7. The horizontal-fissured fabric of the pore space is typical for the soil with a clearly expressed platy structure. The distribution of voids according to the form is the same as in the lattice fabric. Specific is the prevailed amount of macrovoids with horizontal and subhorizontal orientation. This fabric of the pore space takes place in podzolic horizons, in the upper part of the Bt horizon, in excessively compacted plough horizons with the platy structure.

8. The horizontal-fine fissured fabric of the pore space is observed in the massive-platy structure of soils, where isolated structural particles are slightly expressed or absent at all. The non-aggregated soil mass is penetrated by fine horizontal fissured voids. The voids are distributed according to the form and orientation in the same way as in the horizontal-fissured fabric. The specific feature is that the average length of voids is decreased.

The results of multidimensional statistical analysis showed that the projections of the above pore space types disagree with each other, being isolated within the framework of a definite set of features (Table 3).

The types of the pore space fabric are distinguished by similarity degree. In Fig. 1 it is possible to see their mutual arrangement determined by the method of basic components [3]. The first two components reveal 70.3% of total dispersion. The displacement of the first component to the right speaks about the increased amount of fissures. The second component displaced upwards reflects the linear length of voids and changes in their spatial orientation. The around fabric of the pore space is found in the lower left part of coordinates. This fabric type is isolated to a considerable extent and differs from the other types by its form. The fissured-around and around-fissured types well agree according to the second component but reveal a difference according to the first one. Being so specific the tracery fabric can sometimes coincide with the other types and the net one in particular. Thanks to abundant horizontal and subhorizontal fissured voids the horizontal-fissured type of the fabric is sharply differed from the other fabrics of the pore space.

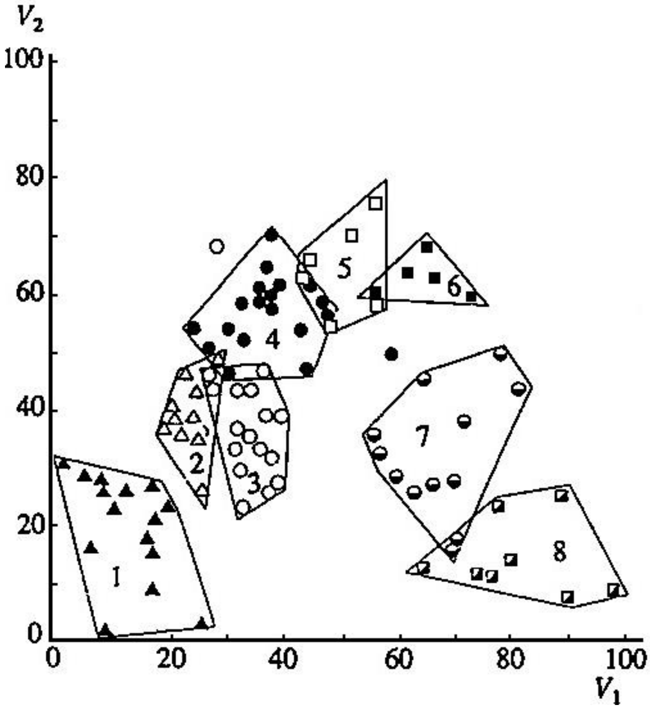
The discrimination analysis allowed determining the classification coefficients to create a program of the automatized morphometric

Table 3. Results of multidimensional statistical analysis (f_1=9)

No. types under comparison*		D^2	F	f_2	Projections of objects in classes			
class					class *i*		class *i*	
i	*j*				min	min	min	max
1	2	14.88	5.8	13	–261	–244	–274	–264
1	3	40.75	15.8	13	1803	1831	1756	1778
1	4	61.28	23.8	13	–765	–732	–822	–799
1	5	94.49	36.7	13	40	76	–55	–18
1	6	232.40	90.4	13	–76	–24	–294	–241
1	7	99.32	38.6	13	–407	–380	–538	–495
1	8	292.39	58.7	8	8	51	–299	–245
2	3	25.52	7.9	10	–199	–183	–228	–209
2	4	68.48	21.1	10	–1060	–1039	–1145	–1109
2	5	49.10	15.2	10	38	55	–18	4
2	6	108.33	33.4	10	–693	–662	–801	–760
2	7	63.26	19.5	10	–330	–308	–423	–395
2	8	566.67	80.7	5	–1523	–1466	–2123	–2040
3	4	134.64	41.6	10	–5675	–5619	–5806	–5781
3	5	17.03	5.3	10	–444	–432	–461	–447
3	6	38.06	11.7	10	2175	2196	2142	2165
3	7	39.68	12.2	10	–643	–627	–695	–670
3	8	177.00	25.2	5	–6178	–6116	–6355	–6338
4	5	114.90	35.5	10	586	608	460	503
4	6	252.76	78.0	10	1950	1987	1688	1757
4	7	76.40	23.6	10	–318	–295	–410	–373
4	8	712.92	101.6	5	1012	1064	256	361
5	6	54.12	16.7	10	–343	–321	–396	–370
5	7	32.33	10.0	10	–3215	–3200	–3262	–3238
5	8	294.59	42.0	5	3924	3983	3636	3672
6	7	36.84	11.4	10	326	347	286	310
6	8	221.92	31.6	5	829	882	612	649
7	8	7.19	1.0	5	241	252	229	236

* No. of types under comparison and their characteristics (see Table 1).

diagnostics of the pore space fabric (Table 4). Based upon this program the studied thin section represented by 9 parameters of the pore space fabric is automatically regarded to the close type of void fabric. Having known the void distribution according to the form and orientation as well as the average arithmetical length of voids in the thin section, it is feasible to diagnose the fabric of the pore space within



Types of structure macro pore space (1 – okrugloporovoe 2 – fractured okrugloporovoe 3 – okrugloporovo fractured 4 – openwork, 5 – net 6 – grating 7 – horizontal fracturing; 8 – horizontal melkotreschinovatoe) in the coordinates of principal components; *V*1 represents the first component of 53.9%, the second component of *V*2 – 16.4% of the total variance.

the 8 distinguished types. To assess the quality of this system, the results of automatized diagnostics were compared with its expert visual valuation (Table 5). On the average, they are coincided in 10 thin sections. It is worthy of note that the most specific types of the pore space in massive, crumby, platy and massive-platy structures reveal the coincidence of visual and morphometric assessments exceeding 90%. The similarity of results is expressed to a lesser extent in fissured-massive, crumby-microblocky (granular) and angular-isometric-blocky (nutty) structures of soil. The automatized morphometric diagnostics has a number of advantages: it is independent on the expert-subjective

Table 4. Linear discriminatory functions $y = a_0 + \sum_{k=1}^{9} a_k X_k$

No. types under comparison		Setting functions									
class		a_0	a_1	a_2	a_3	a_4	a_5	a_6	a_7	a_8	a_9
i	*j*										
1	2	–7.8	–0.9	–0.5	0.1	–0.4	0.8	0.0	–0.2	0.2	–1.9
1	3	678.9	5.1	6.4	7.0	7.1	7.6	0.5	–0.4	–0.1	–7.8
1	4	–226.7	–0.6	–0.8	–0.8	–0.2	1.8	–1.6	–2.5	–1.4	–11.8
1	5	–41.7	–3.1	–1.1	–0.1	0.6	0.6	–0.2	0.0	0.2	–10.4
1	6	–107.2	–4.9	–1.4	0.1	0.5	0.8	–1.1	–0.1	1.2	–9.9
1	7	–71.8	–1.6	–0.5	–0.4	0.0	0.8	0.9	–0.8	–0.1	–28.9
1	8	–157.9	–7.2	–1.0	0.1	–0.6	1.6	1.5	–0.6	–0.9	–10.2
2	3	461.6	3.1	4.5	4.7	5.3	4.4	0.4	0.4	–0.8	0.1
2	4	–369.0	1.4	1.1	–2.9	–0.1	1.8	–4.4	–2.5	–1.0	–21.6
2	5	–47.0	–2.3	–0.8	–0.2	0.2	0.8	0.2	0.5	–0.6	–9.9
2	6	–88.8	–3.2	–0.6	–0.1	–0.3	1.0	–0.3	–0.0	0.4	–7.1
2	7	–53.5	–0.1	–0.3	–0.1	0.5	–0.1	0.4	0.1	–0.5	–32.8
2	8	–269.2	–9.2	–3.1	3.1	–1.3	1.3	3.9	1.7	–5.6	19.3
3	4	–1246.7	–5.7	–9.1	–11.3	–10.1	–4.9	–3.2	–3.1	–1.7	–21.8
3	5	–48.5	–0.5	–0.9	–0.6	–0.2	0.4	0.1	0.0	–0.1	1.9
3	6	153.9	0.6	1.6	2.1	2.2	2.0	0.0	–0.1	0.1	–4.4
3	7	95.0	1.4	1.2	1.0	1.9	2.0	0.3	0.1	–0.5	–24.4
3	8	–1446.0	–15.6	–13.6	–13.8	–13.2	–11.9	0.3	2.6	–2.9	9.6
4	5	179.2	–3.5	–1.7	2.4	1.3	–2.0	2.0	2.0	0.3	4.7
4	6	136.0	–4.8	–0.1	2.4	2.7	–5.1	1.2	1.2	0.8	15.1
4	7	–4.7	–0.4	–0.1	1.2	0.5	–1.6	0.9	–0.6	–0.3	–20.2
4	8	382.5	–11.7	–3.4	5.3	0.7	–2.7	9.3	5.8	1.2	15.4
5	6	–52.1	–2.2	–0.1	0.4	1.0	–1.3	–0.2	–0.1	0.4	–5.3
5	7	–31.4	–0.3	0.4	0.1	–0.4	–0.1	0.3	–0.0	–0.3	–18.5
5	8	–327.8	–6.2	–1.4	–2.4	–2.2	6.0	–1.28	6.0	–4.8	14.2
6	7	10.0	1.2	0.6	–0.1	0.2	–0.7	0.5	0.4	–0.9	–16.9
6	8	97.0	3.9	1.3	0.8	–0.3	–1.8	2.3	1.8	–4.0	16.6
7	8	10.3	–0.1	–0.1	–0.4	–0.0	0.5	–0.2	0.2	–0.0	15.0

Note: the content of macrovoids (%) with *F*: X_1 – < 0.2; X_2 – 0.21–04; X_3 – 0.41–0.6; X_4 – 0.61–0.8; X_5 – 0.81–1.0; X_6 – the content of vertical and subvertical macrovoids, %; X_7 – the content of inclined macrovoids, %; X_8 – horizontal and subhorizontal macrovoids; X_9 – average length of voids in thin section, mm; the type number in Tables1 and 3.

Table 5. Visual and automated morphometric assessments of the pore space in soil

Visual assessment		Morphometric assessment	
Type of the pore space	Amount of thin sections	Type of the pore space	Amount of thin sections
Around-pore	10	Around-pore	10
Fissure-around-pore	10	Fissure-around-pore	6
		Around-pore-fissured	4
Around-pore- fissured	10	Around-pore-fissured	8
		Lattice	1
		Net	1
Tracery	10	Tracery	10
Net	10	Net	6
		Tracery	3
		Around-pore-fissured	1
Lattice	10	Lattice	6
		Net	2
		Around-pore-fissured	2
Horizontal-fissured	10	Horizontal-fissured	9
		Horizontal fine-fissured	1
Horizontal-fine-fissured	10	Horizontal fine-fissured	10

assessment; its reliability is determined by a complex use of the main geometric indices (form, orientation, size) and objective selection of the measured voids. It is also important to indicate that instead of total or average values the empiric distribution of voids according to the above indices is taken as the main diagnostic criteria. Thanks to this fact the morphometric diagnostics of the pore space may be more reliable as compared to the method widely adopted to calculate the visually distinguished aggregated, spongy and non-aggregated microzones in thin sections.

CONCLUSION

The given studies showed that the use of multidimensional statistic methods permits to achieve a new level of theoretical and practical decisions in classification and diagnostics of the pore space in thin sections. The claster analysis allowed identifying 8 types of the macrovoids fabric (d = 0.2–2.0) in thin sections of loamy soils at the territory of European Russia. They differ in distribution of macrovoids according to form factor F, orientation and their average length. These types of the pore space fabric are specific for such soil structures as massive (without aggregates), fissured-massive, massive-fissured, crumby, granular, nutty, platy and massive-platy. A formalized system for soil recognition elaborated by using the discrimination analysis makes it possible to carry out the morphometric diagnostics of the pore space based upon the parameters of form, orientation and length of voids in thin sections. The results of the automatized diagnostics proved to be similar to those obtained by expert visual assessment of the pore space fabric (75-90%).

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