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Determination of the influence of tillage on the soil structure by fractal analysis[1,2]

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A b s t r a c t. This contribution deals with an evaluation of soil structure by the unconventional method of fractal analysis. The soil is represented as a pore medium with statistically self-similar structure which represents a fractal structure. The fractal dimension is presented as decisive representative of the structural properties of soil. The fractal dimension is a non-integer number which expresses degradation of soil structure which was caused by pores. This number includes comprehensively the modification of structural properties of soil induced by arbitrary influence. The fractal dimension of clay-loam and sandy-clay soil was related to the activity of factors which represented the influence of exactly defined tillage practices (conventional, reduced and direct seeding) in the depths of 0-3 and 6-9 cm. The intensity and statistical significance of individual factors were determined by analysis of variance. The effects of tillage practices on the modification of surface soil structure represented by fractal dimension and the influence of the tillage depth and the locality were confirmed.

K e y w o r d s: fractal analysis, soil structure, tillage

INTRODUCTION

The purpose of the study was the determination of the influence of tillage on the soil structure by the method of fractal analysis and analysis of variance. Numerous authors have been interested in the study of fractal properties of soil. Fractal representation of soil structure seems to be especially suitable to describe soil porosity, fragmentation and water properties (Rieu and Sposito, 1991). Fractal parameters become also important in understanding and quantifying soil degradation and its dynamics. The pore capacity fractal dimension along the lines and across the areas depends on the soil and sediment genesis, geographic localisation and applied management. Fractal dimensions of soil solid and pore sets along the lines and across the areas seem to be useful parameters for monitoring the influence of tillage on soil physical properties and also for estimation of the degree of soil compaction (Oleschko, 1998). Turcotte (1986, 1992) and Khron (1988) reviewed the applications of fractal geometry in geological sciences. Perfect and Kay (1995) introduced a review about fractals and theirs application in soil science and research of processing of soil. Giménez *et al.* (1998) introduced the concept that structural units of freshly tilled soil are mainly fragments produced by the tillage.

The study is aimed at testing the suitability of the fractal models for mass and numeric distributions and the surface roughness of the fragments generated by tillage.

MATERIALS

The influence of tillage operations on the structure of soil was observed at four sites. The soil samples were taken from a research site Hausweid belonging to the Research Institute for Agriculture and Technology (FAT) – Tänikon (longitude 8.906°E, latitude 47.481°N) in Switzerland, from the Mendel Agriculture and Forestry University in Brno, Institute of Common Vegetal Production, Research Station in Žabčice (longitude 16.617° E, latitude 49.002° N), Czech Republic, and from the District Research Institute of Agroecology in Michalovce, Research Stations Milhostov (longitude 21.717°E, latitude 48.650°N) and Vysoká (longitude 22.100°E, latitude 48.618°N), Slovak Republic. The characteristics of the soil, the cultivation practices and the duration of tillage are shown in Table 1. The practices

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Table 1. Characteristics of soil localities and tillage

Localities	Tänikon			Žabčice		Vysoká		Milhostov	
Type of soil	Psefitic Cambisol			Gley Fluvisol		Typical Fluvisol		Gley Fluvisol	
Soil class	Sandy - clay			Loamy - clay almost clay		Sandy - clay		Loamy - clay almost clay	
Applied technology	C*	R	DS	C	R	C	DS	C	DS
Duration of tillage (years)	13	13	13	30	30	20	3	30	3

*C – conventional, R – reduced, DS – direct seeding.

have been described in detail by Kubík and Nozdrovický (2004). The sites were chosen on the grounds of long-time tillage by individual technologies, which ensured greater probability of the modification of the soil structure. The soil samples were obtained by means of the method of Kopecky's rolls (diameter 6.5 cm, height 3 cm, volume 33 cm^3) from the depth of tillage 0-3 and 6-9 cm.

The density, ρ_s, bulk density, ρ_b, and porosity, ε, of these soils were measured by means of the classic methods. The density, ρ_s, of the soil was determined by the pycnometric method as specious density of the solid particles of soil. This density is defined as the relation of the mass of solid particles of soil dried at the temperature 110°C to the fixed mass, m_s, to the volume, V_s, of these particles and the cavities not wetted by the measuring liquid are included:

$$\rho_s = \frac{m_s}{V_s}, \tag{1}$$

The density was determined from the equation (Brož, 1983):

$$\rho_s = \frac{(m_2 - m_1)\rho_k}{V_p \rho_k + m_2 - m_3}, \tag{2}$$

where: V_p – volume of the pycnometer, m_1 – mass of the empty pycnometer, m_2 – mass of the pycnometer with dry sample, m_3 – mass of the pycnometer with sample and auxiliary liquid, ρ_k – density of auxiliary liquid.

Benzene with the density $\rho_k = 870.622$ kg m^{-3} was used as auxiliary liquid at the temperature of 27°C. The benzene density was determined by Mohr scales. The volume of the pycnometer $V_p = 2.485 . 10^{-5}$ m^3 was determined from the equation:

$$V_p = \frac{m_4 - m_1}{996.567}, \tag{3}$$

where: m_4 – mass of the pycnometer with water, 996.567 – density of water at the temperature of 27°C in kg m^{-3}.

The bulk density ρ_b was determined from the equation:

$$\rho_b = \frac{m}{V}, \tag{4}$$

where: m – mass of the soil sample from Kopecky's ring determined by weighting, with uncertainity of 10^{-4} g, V – volume of soil samples given by the geometrical dimensions of the Kopecky's ring.

The porosity, ε, was given by the equation:

$$\varepsilon = \left(1 - \frac{\rho_b}{\rho_s}\right)100, \tag{5}$$

where: ρ_b – bulk density of soil, ρ_s – density of soil.

The samples from Tänicon were obtained in the summer, in the year 2000, and from the localities Žabčice, Milhostov and Vysoká in the autumn, in the year 2001.

The arrangement for determination of the fractal analysis parameters of the soil samples is shown in the Fig. 1. The soil samples were taken by Kopecky's rings. The surface of soil was cleaned from the plant residuals and was ranged. The roll was pushed to the depth of tillage 3 cm (with its bottom border) and after removing the top layer of the soil of the thickness 6 cm to the depth 9 cm. Always two samples of soil were taken from the depths of tillage 0-3 and 6-9 cm. The sample had the form of a cylinder with diameter of 6.5 cm, and height of 3 cm.

The soil samples located in the Kopecky's rings were dried in the laboratory by natural drying on the air during 3 days and then impregnated with a 1:2:10 mixture of hardening

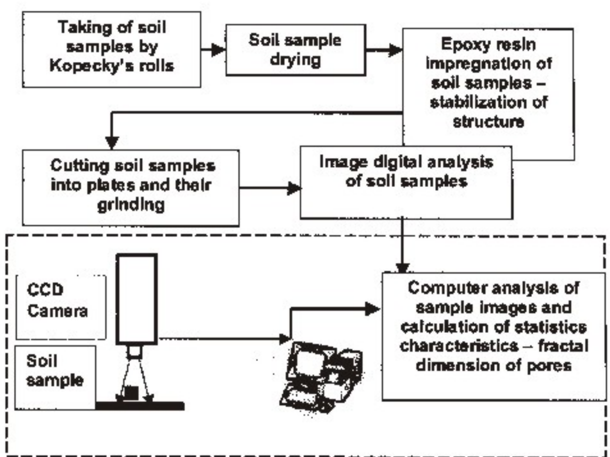


Fig. 1. Arrangement for determination of the fractal analysis parameters of the soil samples.

agent P-11(Sindat, Plzeň), diluent S-6006 (Elastic, Šelpice) and polyester resin CHS Epoxy 1200 (Sindat, Plzeň). We needed 1 ml of P11, 2 ml of diluent S-6006 and 10 ml of CHS Epoxy 1200 per one soil sample. The soil samples had the shape of the cylinder given by the Kopecky's rings (volume of the sample was 33 cm^3). The impregnation was realized under vacuum conditions under air pressure of several hundres pascals provided by vacuum pump in a glass container with the volume of 3000 cm^3, where the soil sample was freely located on the plate. The impregnating liquid was dosed from the burette, located in the top part of the glass container, for a period of 2 h. The soil samples were hardened for 24 h under natural conditions. After the resin had sufficiently hardened, samples were cut into several sections of the size of 20x30 mm and grinded with an average thickness of 5 mm. The black and white camera SONY CB-2801 with the array of 768x576 pixels was used to digitize the surface of the soil samples, and a frame-grabber which provided collaboration with a PC (Pentium 200 MHz). The control software IMPOR'99 (Kvant, Bratislava) was used for the camera to provide pre-processing of the snapshots. The snapshots had the size of 768x576 pixels. The digitized samples were adjusted to the size of 512x512 pixels with the resolution of 38 pixels cm^{-1}, giving 0.26 mm $pixel^{-1}$. The size of these snapshots was 13.3x13.3 cm and the photo of the size 13.3x13.3 cm corresponded to the size of 3.3x3.3 mm on the original soil samples. The forty times magnification of the CCD camera was provided by using distance rings. The adaptation was needed for using the software KARL2 (Observatory, Hlohovec) to process the digitized snapshots. Good contrast between black and white colour was achieved by graphic filtering of the digitized sample snapshots. The white colour represented the pores and the black colour the solid partitions of the soil. The program KARL2 was sensitive to white colour. The digitized samples were covered by raster of the side size square R (pixel). The raster was changed through different sizes (Table 2) and the occupation of the squares was always determined. The number of pores was always determined and so the fractal dimension was established from Eq. (6). The pores and the solid particles of soil were substituted by the squares of side R. Snapshots of thirty surfaces of each tillage technology and depth were used for the determination of fractal dimension statistical sets.

The fractal analysis method of 'box' counting was used for the determination of empirical fractal capacity dimensions (Oleschko *et al.*, 1998). Double logarithmic plots of N(R) against R were used for the estimation of fractal dimension from the slope of equation:

$$\ln N(R) = \ln A - D \ln R, \tag{6}$$

where: N(R) is the number of squares occupied by pores, R is the side of the pore square, A is the side of the soil sample and D is fractal dimension.

Statistical and not ideal self-similarity of the soil surfaces was observed, and so the statistical method of one-way and multifactor analysis of variance was used for determination of the influence of tillage, depth of tillage and locality on the structure of soil by using the fractal dimension as statistical parameter. The statistical program STATGRAPHIC ver.5.0 (StatSoft) was used for statistical evaluation.

Table 2. Side size of square R of the raster (the size of the pore)

R (pixel)	2	4	6	8	10	12	14	16	18	20
R (mm)	0.013333	0.026	0.039	0.052	0.065	0.078	0.091	0.104	0.117	0.130

Table 3. The result values of density, bulk density and porosity of the studied soil

Site		Tänikon			Žabčice			Vysoká			Milhostov		
Depth (cm)	Tillage	ρ_s	ρ_b	ε	ρ_s	ρ_b	ε	ρ_s	ρ_b	ε	ρ_s	ρ_b	ε
		(kg m^{-3})		(%)	(kg m^{-3})		(%)	(kg m^{-3})		(%)	(kg m^{-3})		(%)
0-3	C	2532.1	1091.0	56.91	2549.7	1496.8	41.29	2629.9	1348.9	48.71	2480.6	1672.8	32.56
	R	2532.1	1010.0	60.10	2549.7	1587.5	37.74	–	–	–	–	–	–
	DS	2531.1	872.5	65.54	–	–	–	2629.9	1355.7	48.48	2480.6	1641.6	33.82
6-9	C	2531.1	–	–	2549.7	1740.6	31.73	2629.9	1438.0	45.32	2480.6	1735.9	30.02
	R	2531.1	–	–	2549.7	1465.9	42.51	–	–	–	–	–	–
	DS	2531.1	–	–	–	–	–	2629.9	1497.0	43.08	2480.6	1919.0	22.63

RESULTS AND DISCUSION

The result values of density, bulk density and porosity of the studied soil are shown in Table 3. The values were determined from Eqs (2), (4), and (5), respectively.

A digital image of the surface of the sandy-loam soil from the locality of Tánikon, exposed after direct seeding, after digital filtration (filter KARL2) and after the application of the raster R=64 pixels (0.416 mm in reality) is presented in the Fig. 2. The average values of the fractal dimensions and their standard deviations for all the sites, depths and tillage practices are shown in Table 4. Every average value of the fractal dimension was evaluated as arithmetic average from 30 values. The influence of technogen factors, depth of tillage and locality, on the variability of the fractal dimension and consequently on the structure of the soil was studied.

The files used for statistical processing contained 30 values of fractal dimensions for each technology, depth and tillage practices. 450 values of the fractal dimension were tested together. The tillage practices were marked by the number: 1 – conventional tillage, 2 – reduced tillage, 3 – direct seeding. The analysis of the tillage influence was realized for two depth of 0-3 and 6-9 cm.

The multifactor analysis of variance without interactions and multiple range analysis (Scheffe's method) for multiple comparison was used. At first, we found out if the statistical differences in the average values of the fractal dimension influenced by tillage, depth of tillage or locality were statistically significant. From the values shown in Table 5 it follows that with reliability better than 95%, at the significance level of α=0.05 (calculated significance level was α=0.0024) we were able to state that average values of the fractal dimensions influenced by the factor, with the exception of tillage. We can also state, at the significant level of 0.05, that the average values of the fractal dimensions influenced by the factors: depth of tillage and locality are statistically significantly different at a significance level less than 0.5 (0.0171 and 0.0000). The highest average variability of the fractal dimension was influenced by the effect of

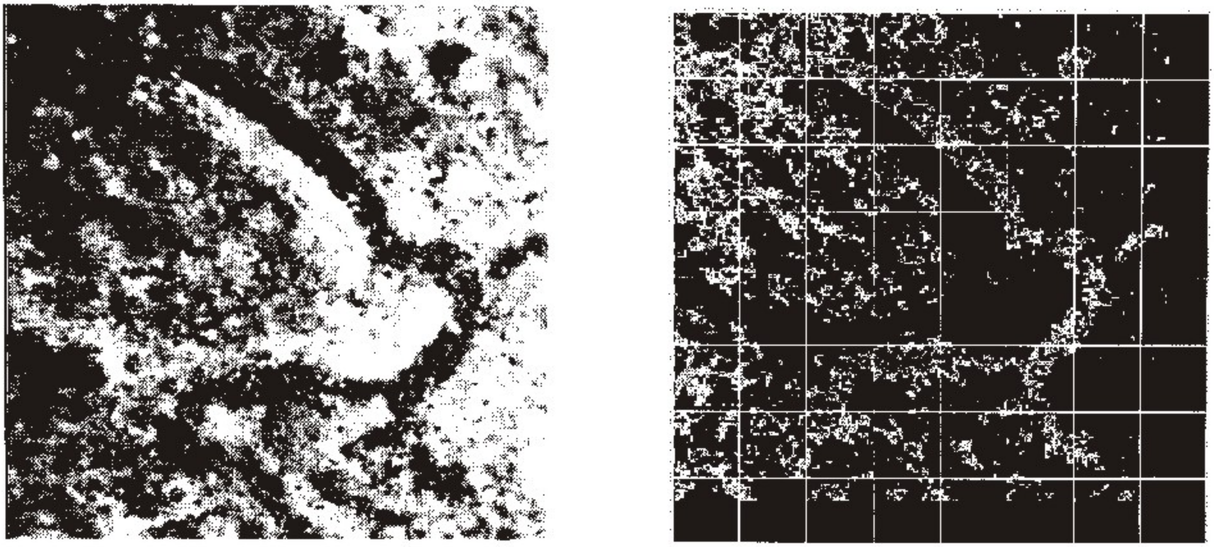


Fig. 2. Digital image of the surface of sandy-loam soil from the locality Tánikon exposed after direct seeding, after digital filtration (filter KARL2) and after application of the raster R=64 pixels (0.416 mm in reality).

Table 4. Area fractal dimensions, D, for pores of soil for different tillage systems and depths and their standard deviations, SD (%)

Site		Tänikon		Žabčice		Vysoká		Milhostov	
Depth (cm)	Tillage	D	SD	D	SD	D	SD	D	SD
0-3	C	1.4994	13.4	1.5787	10.1	1.5379	10.8	1.3972	13.2
6-9		–	–	1.4273	10.1	1.4618	8.5	1.4244	10.3
0-3	R	1.6214	11.0	1.5568	11.7	–	–	–	–
6-9		–	–	1.5438	13.3		–	–	–
0-3	DS	1.5579	10.0	–	–	1.5322	11.8	1.3509	11.6
6-9		–	–	–	–	1.4604	10.5	1.4354	7.9

Table 5. Multifactor analysis of variance of fractal dimension, D, at the significance level $\alpha = 0.05$

Source of variance	Sum of squares	Degrees of freedom	Mean square	F statistic	Significant level
			Main effects		
Tillage	0.2144979	2	0.1072489	6.102	0.0024
Depth of tillage	0.1006477	1	0.1006477	5.726	0.0171
Locality	0.8154685	3	0.2718228	15.465	0.0000
Residual	7.7864941	443	0.0175767	–	–
Total	9.6324857	449	–	–	–

locality (mean square was 0.2718). The second highest effect had the variability influenced by the factor of the tillage practice (0.1073). The average variability of the fractal dimension influenced by the factor of the depth of tillage was the lowest (0.1007), but its influence had the same level as the influence of the factor of the tillage practice. The influence of the tillage practice and the depth of tillage was two times smaller than the influence of the factor of locality. The average variabilities influenced by other sources were ten times lower than other influences (0.0176).

Then, we studied which files of the fractal dimensions, from the point of view of the average values, were statistically significantly different at the significance level less than 0.05, by means of multiple range analysis method, with the use of the Scheffe test. This method enabled us to find out if the factors significantly influenced the fractal dimension which represents the structural properties of the soil. The influence of the factor of the tillage practice created two homogeneous groups of average values of the fractal dimensions. Table 6 presents them by the capitals X placed one bellow another. The average values of the fractal dimensions whose variability was statistically significantly influenced by the effect of the conventional tillage and the direct seeding are contained in the first group. In the second one, the dimensions influenced by the reduced tillage are contained. A statistically significant difference, with probability of 95%, was found between the average values of the fractal dimensions whose variability was influenced by the conventional tillage (1) against reduced tillage (2). A statistically significant difference was also found among the average values of the fractal dimensions, the variability of which was influenced by the direct seeding (3) against the reduced tillage (denoted by the asteriks in the Table 6). The fractal dimension influenced by the conventional tillage and by the direct seeding had almost the same values: 1.4785 and 1.4789. The reason of the event was apparently unbalanced files. The average value of the fractal dimension influenced by the effect of the reduced tillage was 1.5443. Figure 3 presents a box and whisker plot which enables the comparison of the influence of the tillage practices on the fractal dimension. The top and bottom sides of the box represent the upper and lower quartil, the horizontal line inside the rectangle represents the median. The whiskers tending up and down represent the maximal and minimal values.

We also present, in Table 7, multiple range comparison with the use of the Scheffe method for the factor depth of tillage. A statistically significant difference was detected between the fractal dimensions whose variability was influenced by the depth of tillage at the level of 0.05. From Table 7 we can see that two homogeneous groups were created which are denoted by the capitals X. The differences in the average values of the fractal dimensions influenced by the factor of the depth of tillage were significantly different (denoted by the asterisk). The average value of the fractal dimension for the factor of the 6-9 cm depth of tillage was lower (1.4839) than the value for the depth of 0-6 cm

Table 6. Multiple range analysis by means of Scheffe method on the significance level $\alpha = 0.05$ for the factor of technology

Tillage	Number of samples	Dimension	Homogeneous groups	
1: C	210	1.4789230	X[1]	
2: R	90	1.5443347		X
3: DS	150	1.4785030	X	
Contrast		Difference	Limit	
1-2		-0.06541	0.04679 *	
1-3		0.00042	0.03699	
2-3		0.06583	0.05487 *	

[1]X in the same column represents one homogeneous group, *denotes statistically significant difference.

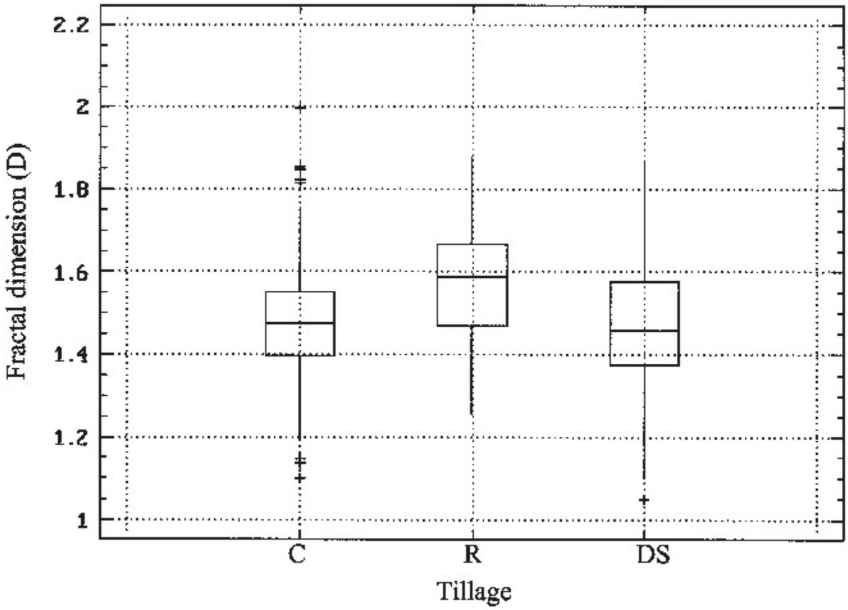
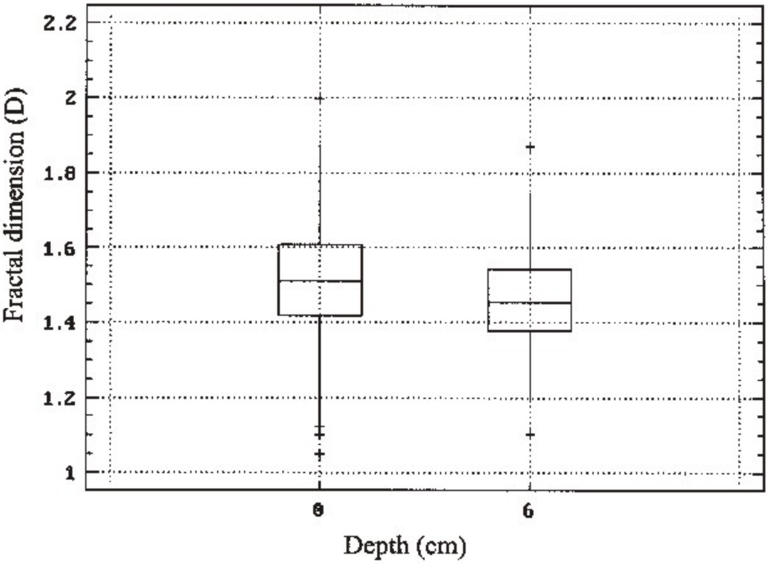


Fig. 3. Mutual comparison of technology factor effect on fractal dimension, D, by means of box and whisker plot.

Table 7. Multiple range analysis by means of Scheffe method on the significance level $\alpha = 0.05$ for the factor of depth

Depth of tillage (cm)	Number of samples	Dimension	Homogeneous groups
0-3	270	1.5173074	X[1]
6-9	180	1.4838663	X
Contrast		Difference	Limit
(0-3) – (6-9)		0.03344	0.02747*

[1]X in the same column represents one homogeneous group, *denotes statistically significant difference.



(1.5173). This result corresponds with the fact that the higher value of the fractal dimension is connected with higher value of the area porosity. Figure 4 presents the mutual comparison of the influence of the factor of the depth of tillage on the fractal dimension for all the localities.

Table 8 presents multiple range comparison with the use of the Scheffe method for the factor of locality. A statistically significant difference was observed between the fractal dimensions whose variability was influenced by locality, regardless of the influence of the other factors, at the significance level of 0.05. A statistically significant difference between the soil structure and soil class follows from this analysis.

Two homogeneous groups of average values of the fractal dimensions, denoted by the capital X placed one bellow another, were created as followes from Table 8. The value of the fractal dimension from the locality of Milhostov (1.4239) is in the first group, and the values of the fractal dimensions from the localities of Žabčice, Vysoká and Tänikon are in the second group. The asterisks in Table 8 denote the statistically significant difference between average values of the fractal dimensions from studied localities. It means that the differences among the average values of the fractal dimensions influenced by the factor of locality were not significantly different between the sites Tänikon-Žabčice and Tänikon-Vysoká. The influence of the Milhostov soil from the first homogeneous group was significantly different from the second homogeneous group of the soil type at the significant level 0.05. Figure 5 presents a box and whisker plot which enables the comparison of the influence of the localities on the fractal dimension. The Milhostov soil with the loam-clay almost clay soil showed

Table 8. Multiple range analysis by means of Scheffe method on the significance level $\alpha = 0.05$ for the factor of locality

Sites	Number of samples	Dimension	Homogeneous groups
Milhostov	120	1.4239047	X[1]
Žabčice	120	1.5156156	X
Vysoká	120	1.5199722	X
Tänikon	90	1.5428550	X
Contrasts		Difference	Limit
Tänikon	Žabčice	0.02724	0.05760
Tänikon	Vysoká	0.02288	0.05836
Tänikon	Milhostov	0.11895	0.05836*
Žabčice	Vysoká	-0.00436	0.05734
Žabčice	Milhostov	0.09171	0.05734*
Vysoká	Milhostov	0.09607	0.04807*

[1]X in the same column represents one homogeneous group, *denotes statistically significant difference.

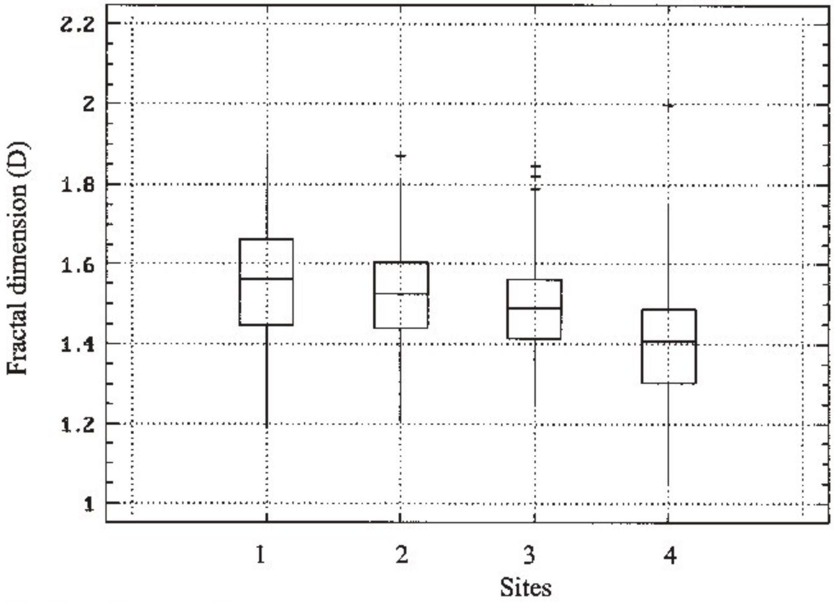


Fig. 5. Mutual comparison of the influence of the factor of locality on fractal dimension, D, by means of box and whisker plot; 1 – Tänikon, 2 – Žabčice, 3 – Vysoká, 4 – Milhostov.

lower values of the fractal dimension (1.4239). The value of the fractal dimension of the Žabčice soil was markedly higher (1.5156) than the values of the soil of Vysoká (1.5200) and than the soil of Tänikon (1.5429).

CONCLUSIONS

1. The fractal dimension is a parameter which is connected with the area porosity of the soil, because it is determined by counting the number of the pores of the soil sample and so expresses the structural properties of the soil.

2. The fractal dimension expresses the degradation of the soil structure caused by the pores if we suppose that the ideal geometrical structure is without pores.

3. It is possible to determine the different states of the structure of the soil as influenced by conventional tillage, reduced tillage and direct seeding by means of the fractal analysis and analysis of variance.

4. The strongest influence on the fractal dimension was observed for the factor of locality. The influence of the factors of tillage practice and depth of tillage was two times smaller.

5. The possibilities of the evaluation of the differencies in the soil structure (characterized by the fractal dimension) influenced by the tillage practice were documented. A significant difference was proved between the influence of conventional tillage and reduced tillage and between the influence of reduced tillage and direct seeding,

6. The possibilities of the evaluation of differences in the soil structure (characterized by the fractal dimension) influenced by the depth of tillage were documented. A significant difference in the soil structure was proved between the influence of the depth of tillage 0-3 cm and that of 6-9 cm.

7. The possibilities of the evaluation of the differences in the soil structure (characterized by the fractal dimension) influenced by the locality were documented. Significant differences in the soil structure were proved between the influence of localities under investigation.

8. The advantages of the presented method consist in the information that only one parameter - fractal dimension - evaluated the specific structure of the soil. The presented method enables faster evaluation of the changed properties of the soil in comparison with the classic methods, because one parameter is enough. The classic methods require several parameters (density, bulk density, porosity, granularity).

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