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FIELD SCALE HETEROGENEITY OF SOIL STRUCTURAL PROPERTIES IN A MORAINE LANDSCAPE OF NORTH-EASTERN GERMANY

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Abstract. Spatial variability of soil structure complicates interpretation of investigations on soil physical properties and their influence on crop growth. Especially, for pleistocene sandy and sandy-loamy soils, small scale heterogeneity and the range over which observations give reliable estimates on the state of soil properties have to be considered. The aim of this study was to investigate the variability structure of various soil physical and morphological parameters in a field soil. In an Albic Luvisol under conventional tillage located in Müncheberg, Germany, numbers and pore area fraction of macropores >200 μm were determined for samples taken from the topsoil layer (15 cm average soil depth), a layer compacted by wheel traffic (30 cm) and the subsoil (55 cm). For macropore determinations polished blocks of soil samples were used, stabilized with polyester resin (stained by fluoresceine). In the same layers, soil texture, saturated hydraulic conductivity, air permeability, dry bulk density and rootability were investigated for samples from 25 profiles in a 4 ha block within a 60 ha field. In the subsoil, clay content, total carbon content, dry bulk density and rootability were autocorrelated over a distance of about 25 to 50 m. Whereas soil structural parameters, such as numbers and area of macropores as well as permeability properties varied randomly even over the shortest distance sampled (10 cm). For the topsoil and the plough pan, variability appeared to be unstructured in case of hydraulic conductivity, air permeability, dry bulk density, rootability and number and area of macropores. Considering the short distances between the sample cores (10 cm) taken in the same soil profile, structural variation was identified in the topsoil.

Keywords: spatial variability, soil structure, soil physical properties

INTRODUCTION

Farmers in the moraine landscape of north-eastern Germany are confronted with a high spatial variability of soil structural properties affecting crop growth. For improving the basis for management decisions, soil scientists try to identify the relation between crop production and various soil properties. For determining effects of different soil structural conditions affecting rootability and crop yield, the soil physical parameters dry bulk density [14] and penetrometer resistance [13] are often employed. Nevertheless, with these properties highly relevant functions of the pore system are neglected, such as water and gas transport and rootability [6,11,12,20]. Especially in diluvial sandy and sandy-loamy soils, soil structure varies extremely over short distances [9,10]. Therefore, parameters may be preferred for evaluation of soil structural state on one hand reflecting the shape of pore system such as hydraulic and pneumatic permeability [8,20] and on the other hand morphometrical description of pore space [1,4,7]. Lack of knowledge exists concerning the quantitative identification, description and handling of soil structural heterogeneity. Sampling strategies have to be evaluated with respect to their representativity of observations in time and especially in space [17,18]. Only if a spatial continuum of observations can be determined, the underlying field processes mainly affecting spatial variability of crop production can be identified [19]. This study is an approach to investigate the spatial structure of various soil physical and morphological parameters and to give information for designing sampling schemes for local field scale soil quality mapping in a north-eastern German agricultural landscape.

MATERIALS

The sample site is an Albic Luvisol on boulder clay in a pleistocene ground moraine [15] under conventional tillage of a former agricultural production cooperative in Müncheberg.

Field soil samples were taken at 15 sites from 25 profiles distributed across an area of about 400 x 100 m between 1986 and 1988 (Fig. 1). In order to judge and to compare the soil structural state in the 'regularly' trafficked field with an extremely loaded zone affected by numerous machinery passes, one site was investigated within the headland. Except for the profile scale in this site, no variability pattern across the headland was investigated in this study.

Soil samples were taken in spring from the top soil (15 cm), the plough pan layer (30 cm) and the subsoil (55 cm). Physical parameters determined were: soil texture (Table 1), dry bulk density, saturated hydraulic conductivity [2] and air permeability [8]. Six samples were taken per depth interval in each profile.

Soil morphology was studied by using horizontal polished soil blocks stabilized with polyester resin (UPAN 24-23; Buna Ltd.) and stained by fluoresceine [3]. After visualization under ultra-violet light the number and pore area fraction of macropores >200 μm (determined in 3 different size classes, i.e., 200-630, 630-2000, >2000 μm) were quantified by DENSITRON 2 (former Scientific Apparatus Construction of the Academy of Agricultural Sciences of the G.D.R.) using black and white photographs of soil blocks with 49 x 34 mm^2 area. The preparation of such slices is time consuming so that 3 micromorphological samples per depth interval were taken but only in 19 profiles (marked by 'o' in Fig. 1).

T a b l e 1. Soil texture and total carbon content at different soil depths

Soil depth (cm) Variance σ^2	Sandy	Silt	Clay	Total carbon
		(g g^{-1})		(g 100 g^{-1})
10 - 15	0.64	0.28	0.08	0.81
σ^2	$2.5\ 10^{-4}$	$2.4\ 10^{-4}$	$0.5\ 10^{-4}$	0.7
30 - 35	0.62	0.28	0.10	0.38
σ^2	$2.30\ 10^{-5}$	$5.5\ 10^{-4}$	$2.1\ 10^{-5}$	0.06
55 - 60	0.58	0.26	0.16	0.19
σ^2	$2.0\ 10^{-3}$	$1.1\ 10^{-3}$	$2.2\ 10^{-3}$	$0.70\ 10^{-4}$

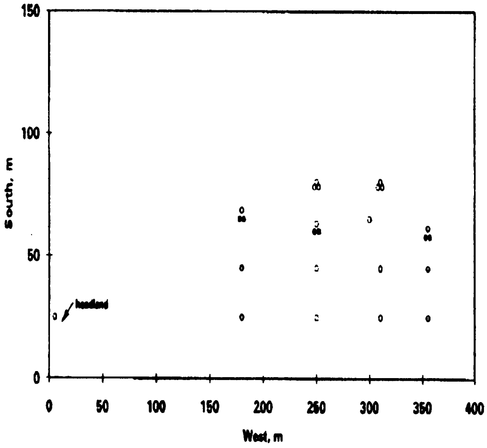

Fig. 1. Position of the sample sites and profiles in the field (the sign '↓' marks the extremely compacted turning zone), in profiles marked by '•' also micromorphological samples were taken, whereas in profiles marked by 'o' only physical parameters were determined.

The rootability (number of roots penetrating the soil core sample (i.d. - 5.6 cm, h - 6.1 cm per time unit) of the different soil layers was examined by a lab experiment under controlled moisture, temperature and light conditions [5].

Spatial variability of parameters was analyzed by semivariograms. This method gives basic information about heterogeneity structure of the soil as a function of spatial (and/or temporal) coordinates [16-18]. Ideally, the semivariance increases from zero at zero distance between neighbouring observations to some sort of plateau, the sill. The sill is approximately equal to the variance of the sample set (σ^2) if stationarity is met. The distance within the semivariance approaching the sill, is called the range. The range shows the distance over which the variables are correlated. If the semivariance reaches the sill at the smallest sampling distances, this is a so called pure nugget effect [16].

RESULTS AND DISCUSSION

Visual, morphometrical and physical assessment of the soil

The sandy top soil is mostly a granular, single-grained and fine perforated structure. Spatial arrangement of void patterns differs between discrete pores and vughs irregularly connected with other voids. These changes can be observed over short distances, within 2-3 cm (Fig. 2).

The plough pan, compacted by wheel traffic within the furrow, shows a coherent, massive structure with hardly any aggregates observable in the soil matrix. The pores are mainly of a discrete, different shape, and their number is low compared to topsoil and subsoil. Some fissures and cracks can be observed (Fig. 3).

The pore system in the loamy subsoil is characterised by numerous voids of biological origin (rounded, nearly circular or elongated pores with smooth walls), channels and other cavities of irregular shape and size. The soil matrix is not aggregated but coherent (Fig. 4).

The visual differences in soil structure can be analysed and described quantitatively. Some results of this quantitative analysis are presented in Table 2. Although a higher bulk density occurs in the subsoil, conductivity and rootability results are in the same order of magnitude as those in the topsoil (Table 2). This may be due to the number and pore area fraction of macropores. The total number of pores >200 μm in the subsoil is lower than in the topsoil, but there exist more pores >2000 μm in the subsoil. Regarding pore area fraction a significant difference exists between top- and subsoil on one hand and the plough pan layer on the other hand, where lower conductivity and pore portions occur.

In order to evaluate the effects of compaction results not only from different soil depth, but also from regular field site profiles were compared with those from the headland. Significantly higher dry bulk density, reduced number and percentage area of pores and lower conductivity values have to be considered for the headland zone. All variables measured in headland reflect the extremely compacted and disturbed structure, but even more in the topsoil as compared to the subsoil. The number of macropores >200 μm in the field sites is approximately twice as much as in the headland topsoil, and the same in the subsoil.

Spatial analysis

At first profile averaged data were analysed by semivariance analysis. In the topsoil observations varied randomly in space. Area fraction of pores 630-2000 μm is shown in Fig. 5a. At distances larger than 20 m, pore area fraction varies randomly whereas at the shortest distance considered, semivariance seems to indicate structured variability (Fig. 5b). Semivariograms for the other parameters in this soil depth show pure nugget effects. Though the

T a b l e 2. Soil physical and root parameters from regular field sites (fs, average of 14 sites with 6 samples per depth) and from the highly compacted headland at the field border (hl, 1 site, average of 6 samples per depth) in three soil depths

Soil depth (cm) Variance σ^2	Dry bulk density (g cm^{-3})		Pore area fraction >200 μm (%)		Number of pores >200 μm		Number of pores >2000 μm		Saturated hydraulic conductivity (m d^{-1})		Pneumatic permeability (m d^{-1})		Number of roots	
	fs	hl	fs	hl	fs	hl	fs	hl	fs	hl	fs	hl	fs	hl
10-15	1.58	1.73	8.22	5.80	348	222.0	4.00	3.00	0.25	0.0230	1.33	0.110	27.0	1.00
σ^2	0.006	4.50	11.02	5.95	40305	74.3	10.20	2.30	0.032	0.0007	0.96	0.006	83.9	2.56
30-35	1.78	1.77	5.46	2.10	209	169.0	3.00	3.00	0.140	0.0002	0.45	0.076	22.0	18.0
σ^2	0.002	4.01	11.00	0.53	20132	2178.0	5.99	1.00	0.003	0.0000	0.06	0.002	62.8	60.7
55-60	1.68	1.70	7.32	5.90	245	202.0	5.00	6.00	0.180	0.0310	1.54	1.29	28.0	23.0
σ^2	0.001	3.03	11.10	27.20	8716	3960.0	7.86	1.59	0.012	0.0013	2.07	0.83	30.4	21.9

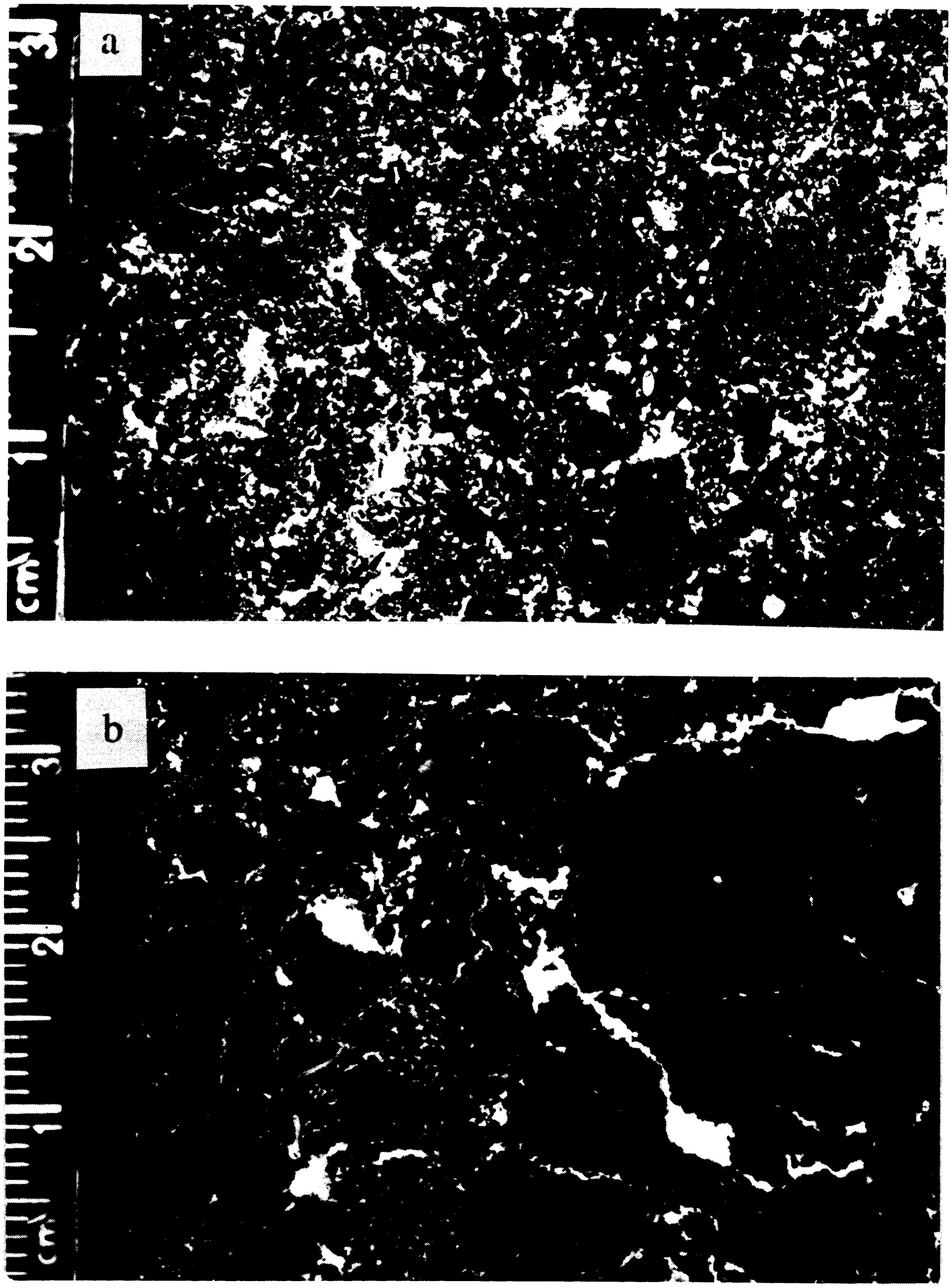

Fig. 2. Photographs of soil structure in the topsoil with continuous pore system (Fig. 2a: dry bulk density 1.50 g cm^{-3}) and more discrete individual pores (Fig. 2b: dry bulk density 1.55 g cm^{-3}) changing over short distances.

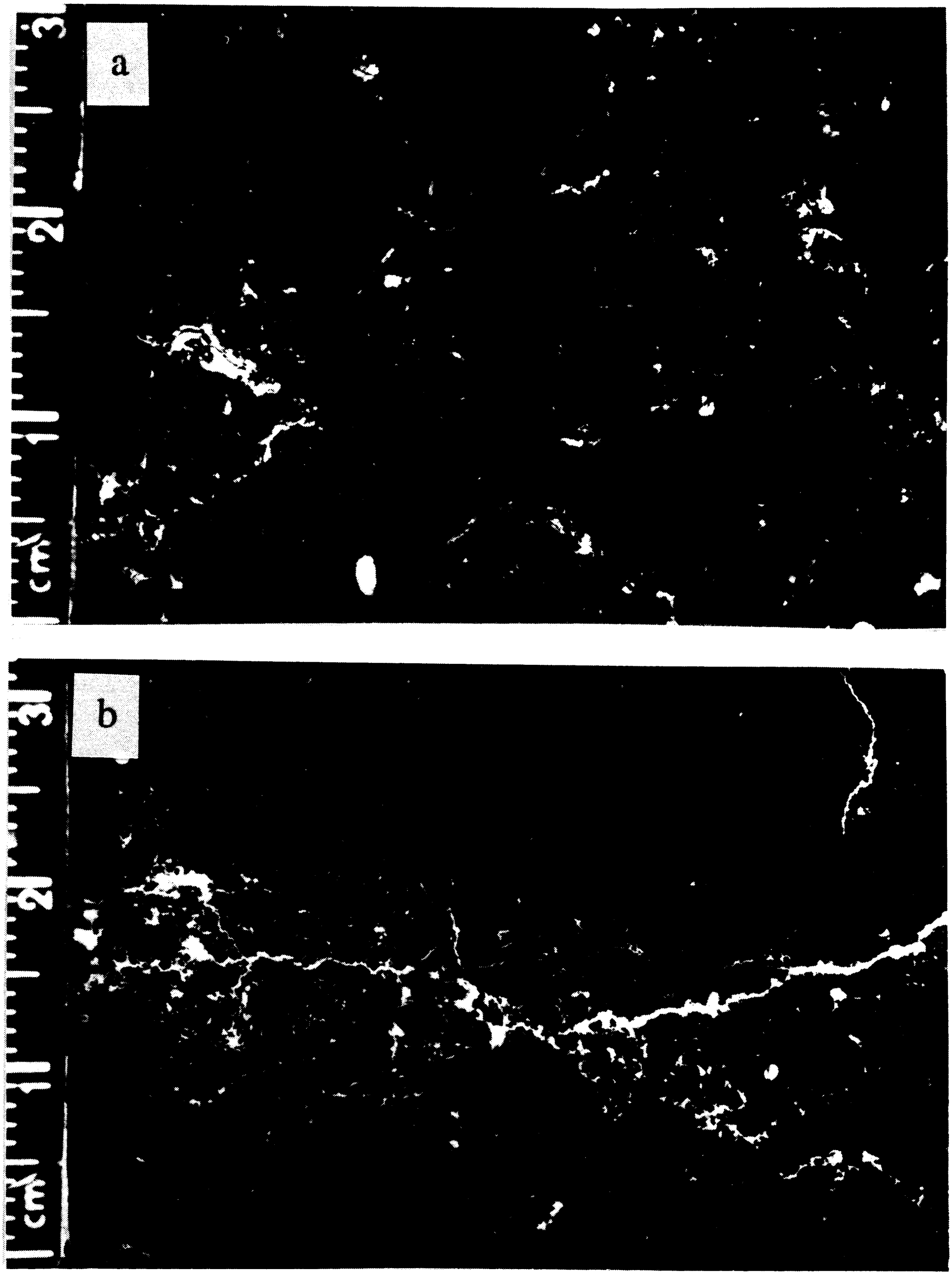

Fig. 3. Coherent, massive structure in the plough pan layer with discrete pores (Fig. 3a: dry bulk density 1.65 g cm^{-3}) and fissures as result of high compaction (Fig. 3b: dry bulk density 1.76 g cm^{-3}).

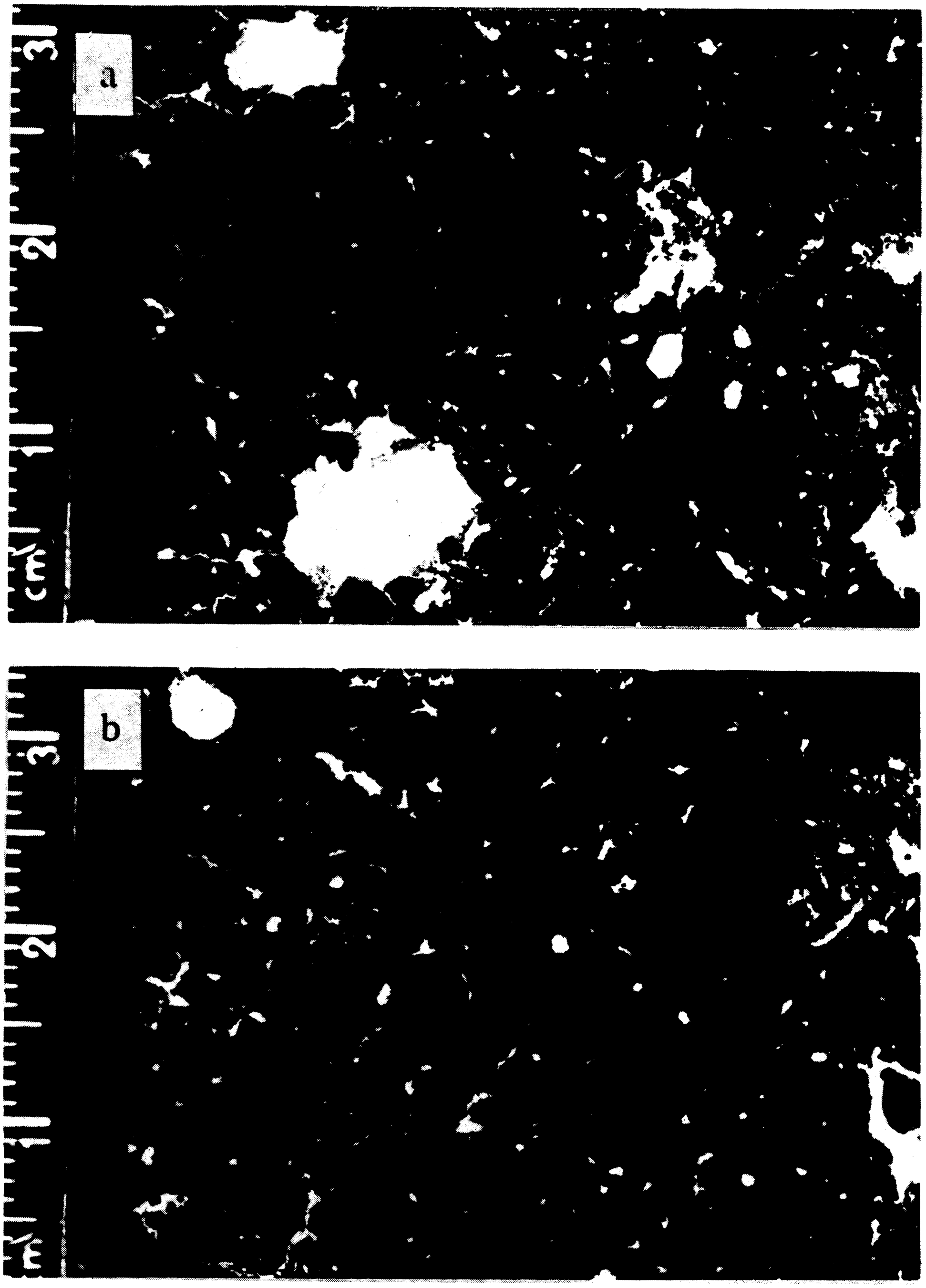

Fig. 4. No aggregated subsoil structure, but with many voids of biological origin and other cavities of irregular shape and size (Fig. 4a: dry bulk density 1.56 g cm^{-3}; Fig. 4b: bulk density 1.63 g cm^{-3}).

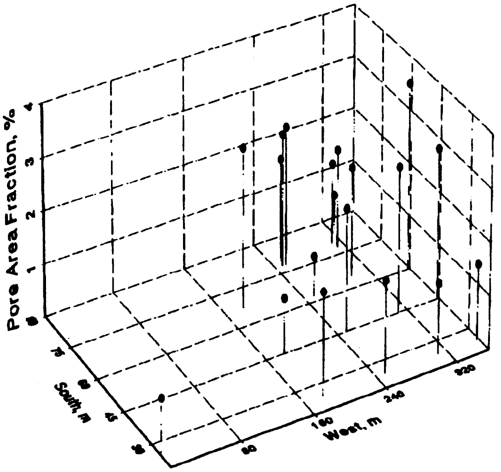

Fig. 5a. Pore area fraction 630-2000 μm in the topsoil for sample sites investigated.

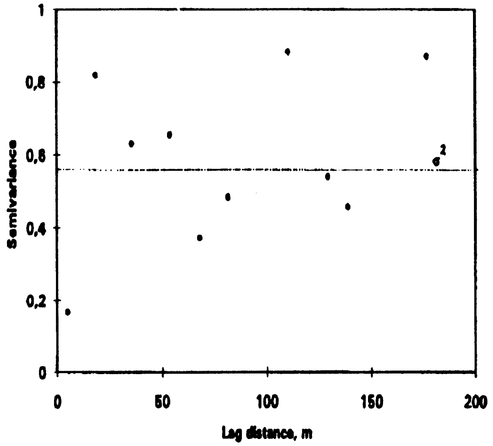

Fig. 5b. Semivariogram for pore area fraction of pores 630-2000 μm in the topsoil.

parameters may then be described commonly by the mean and variance, one has no idea about the range of spatial representativity of the parameter observed. Hence, no information can be derived about the spatial continuum of soil structure which would have been necessary for spatial interpolation. In our case, it would be necessary to reduce the sampling distance or, may be, to increase the volume of soil samples for characterising structure of spatial variability of properties investigated in this study.

In the compacted plough pan, variability is non-structured. In Fig. 6, a pure nugget-effect for the pneumatic permeability is shown as an example. Semivariograms for all parameters investigated in this depth show such a pure nugget-effect.

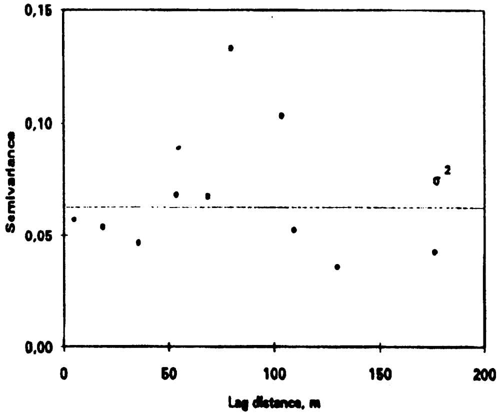

Fig. 6. Semivariogram for pneumatic permeability in the plough pan layer.

In the subsoil there seems to exist a structured variability of some parameters. In Fig. 7a, total carbon content is shown for the profiles investigated. The semivariogram for this parameter shows a range of about 50 m (Fig. 7b).

Bulk density and number of roots seem to be autocorrelated up to a distance of 25 m, and 40 m, respectively.

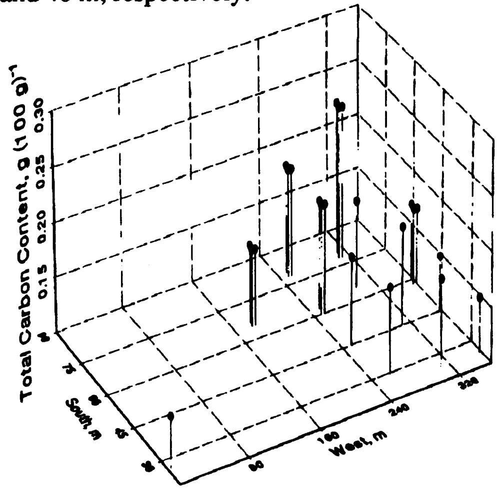

Fig. 7a. Distribution of total carbon content in the subsoil for different sample sites.

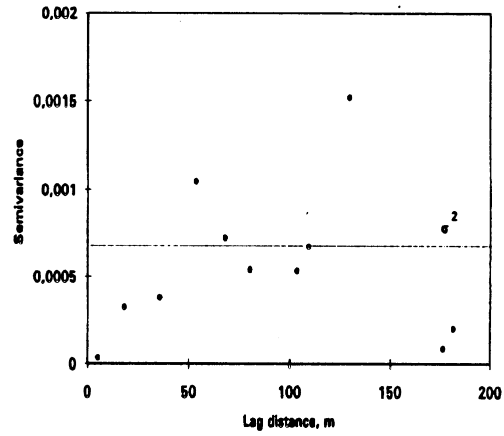

Fig. 7b. Semivariogram for total carbon content in the subsoil.

Moreover, spatial variation for smaller sampling distances was determined using individual morphological samples within the same layer in the profile. The analysis of these data shows an autocorrelation length of about 10 m for pore size distribution in the top soil (one example is given for pore area fraction >2000 μm in Fig. 8). For short distances (up to 3 m) semivariance was lower than σ^2, indicating structured variation.

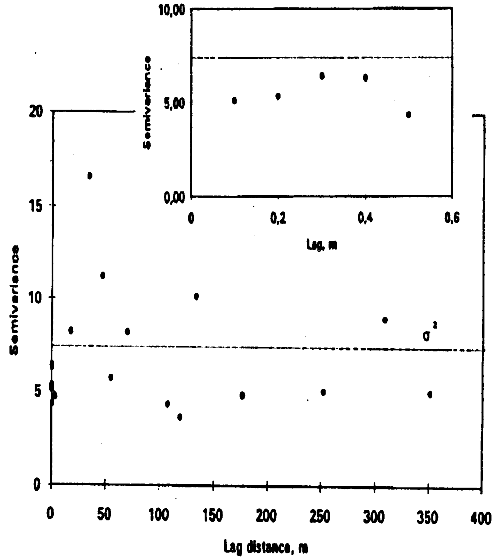

Fig. 8. Semivariogram for pore area fraction >2000 μm in the topsoil calculated from smallest sampling distances.

The semivariogram for number of pores >2000 μm (Fig. 9) indicates random variation even over short distances.

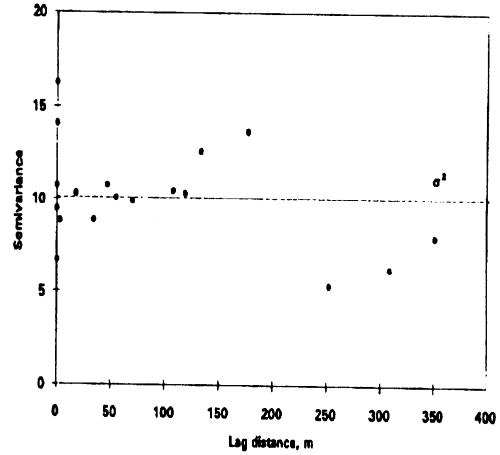

Fig. 9. Semivariogram for number of pores >2000 μm in the topsoil.

These latter two results mentioned show once more that the area of pore fraction especially in the class of the largest macropores has no relation to the number of pores in this class. A few wide pores may determine a greater pore area fraction than a lot of smaller pores do (compare Table 2). It is important to know both: area and number of pores, because both parameters can help to interpret other physical properties.

In the plough pan layer we could not observe structured variability, similar to results from profile averaged data. A reason therefore may be that the variance of this data set is lower than in the other soil layers investigated (about half as much of that for pore size parameters in the topsoil), caused by more homogeneous and compacted soil matrix with less pores.

Different parameters show structured variability in the subsoil (pore area fraction and number of pores in the classes 200-630 and 630-2000 μm). These parameters are correlated stronger to physical properties such as dry bulk density and soil texture, for which structured variability is detected in this soil depth also (compare Fig. 7). Pores >2000 μm influencing soil functional properties occur randomly in space in the subsoil (Figs 10,11). These macropores are of great importance for water transport processes through soils. The strong variation in this pore size class is mainly caused by complexity of biological, chemical and physical processes [1,12,20].

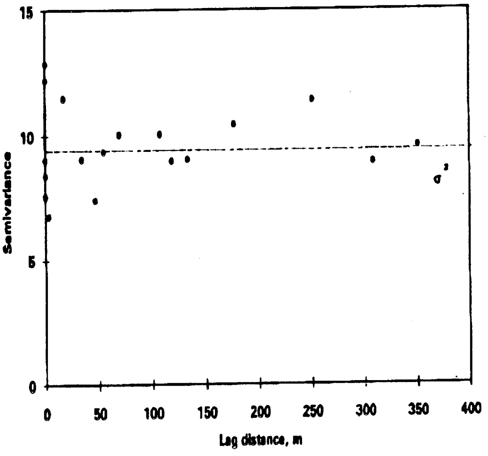

Fig. 10. Semivariogram for pore area fraction >2000 μm in the subsoil.

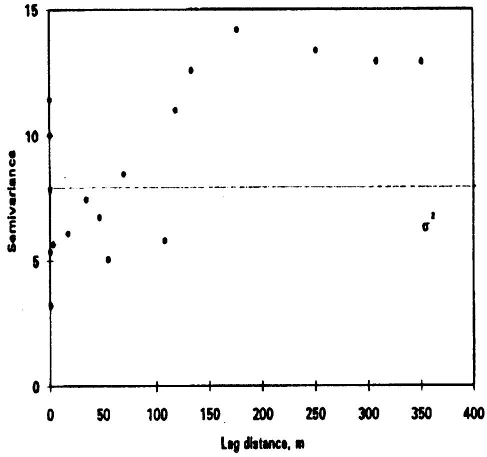

Fig. 11. Semivariogram for number of pores >2000 μm in the subsoil.

CONCLUSIONS

The apparent variability of soil structure has to be quantified by measuring several physical properties. Most of those parameters investigated in this study concerning functional properties of the soil show random variability especially in the topsoil and plough pan layer even over short sampling distances of 10 cm. Soil textural properties and amount of total carbon content show structured variability in the subsoil. Dry bulk density observations are correlated up to 25 m distance, number of roots up to 40 m and total carbon content up to about 50 m. This information can be considered for spatial interpolation.

In order to investigate parameters highly dependent on biological and other soil structure affecting causes (pore area fraction and number of pores, permeability for air and water), it may be necessary to use special nested sampling strategies on the basis of the analysis of spatial variance of properties temporally more stable (soil texture, bulk density, content of organic material, soil-genetic aspects). Detection of causal connections between different variables measured with parallel samples with a random variation even over short distances seems impossible because of missing spatial representativity of observations. Further investigation is necessary to develop effective sampling strategies for field studies of structural state and transport coefficients in a heterogeneous agricultural landscape.

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REFERENCES

1. **Altemüller H.J., Sommer C.:** Korngrößenverteilung und Bodenverdichtung in gefügekundlicher Sicht. Mitteilgn. Dtsch. Bodenkundl. Gesellsch., 34, 153-156, 1982.
2. **Birecki M., Kullmann A., Revut M.:** Untersuchungsmethoden des Bodenstrukturzustandes. Dtsch. Landwirt., Berlin, 1968.
3. **Bober M.:** Mikromorphologische und bodenphysikalische Charakterisierung von Verdichtungszonen in der Krumenbasis auf Moränenstandorten. Dissertation, AdL der DDR, FZB Müncheberg, 1986.
4. **Bouma J., Kooistra M.J.:** Soil morphology and soil water movement. In: Soil Micromorphology (Eds N. Fedoroff, L.M. Bresson, M.A. Courty). Proc. VIIth Int. Working Meeting, Paris, 507-512, 1987.

5. **Dannowski M.**: Die Kennzeichnung von Schadverdichtungen in Krumenböden mit Hilfe von Durchwurzelungsversuchen unter Laborbedingungen. Arch. Acker- Pflanzenbau Bodenkd., 33/5, 277-284, 1989.
6. **Ehlers W., Köpke U., Hesse F., Böhm W.**: Penetration resistance and root growth of oats in tilled and untilled loess soil. Soil Tillage Res., 3, 261-275, 1983.
7. **Feldhaus D.**: Kennzeichnung des Grobporenraumes von Böden mittels Mikromorphologie. Tag. Stoffkreislauf und Bodennutzung, Halle, AdL der DDR, 1981.
8. **Gätke C.R.**: Zum Einfluß des Bodenwassergehaltes auf die pneumatische Leitfähigkeit eines Sandbodens. Arch. Acker- Pflanzenbau Bodenkd. 33/8, 437-443, Berlin 1989.
9. **Kooistra M.J.**: The effects of compaction and deep tillage on soil structure in dutch sandy loam soil. In: Soil micromorphology (Eds N. Fedoroff, L.M. Bresson, M.A. Courty). Proc. VIIth Int. Working Meeting, Paris, 445-450, 1987.
10. **Lehfeldt J., Bober M., Kullmann A.**: Mikromorphologische Charakterisierung des Porensystems sandiger und lehmiger Bodensubstrate der Krumenbasis auf Moränenstandorten. Arch. Acker- Pflanzenbau Bodenkd., 32/10, 629-635, 1988.
11. **Lehfeldt J., Kullmann A., Bober M.**: Wirksamkeit kontinuierlicher Vertikalporen in Bodensubstraten der Moränenstandorte. Arch. Acker- Pflanzenbau Bodenkd., 30/9, 539-547, 1987.
12. **Menning P.**: Charakterisierung und Bewertung der Struktur landwirtschaftlich genutzter Böden. Tag. der AdL der DDR, 215, 5-15, 1983.
13. **Morstein K.H.**: Einsatzrichtlinie zur Krumenbasisbearbeitung auf D-, Lö- und V-Standorten. FZB Müncheberg, AdL der DDR, 1984.
14. **Petelkau H.**: Nachweis und ackerbauliche Bewertung raddruckbedingter Schadverdichtungen. FZB-Report Müncheberg, 14-24, 1987.
15. **Schmidt R.**: Die Struktur der Bodendecke der Grundmoränengebiete der DDR. Petermanns Geograph. Mitt., 126/3, 153-170, 1982.
16. **Usowicz B. Walczak R.**: Investigations and analyses of spatial variability of soil temperature. Int. Agrophysics, 6(1-2), 43-53, 1992.
17. **Warrick A.W., Myers D.E., Nielsen D.R.**: Geostatistical methods applied to soil science. In: Methods of Soil Analysis, Part I. (Ed. A. Klute). Agron. Monograph Series No. 9 (2nd edition), ASA and SSSA, WI. Madison, 53-82, 1986.
18. **Weitz A., Bunte D., Hersemann H.**: Application of nested sampling technique to determine the scale of variation in soil physical and chemical properties. CATENA, 20, 207-214, 1993.
19. **Wendroth O., Al-Omran A.M., Kirda C., Reichardt K., Nielsen D.R.**: State-space approach to spatial variability of crop yield. Soil Sci. Soc. Am. J., 56(3), 801-807, 1992.
20. **Werner D.**: Wirkung von Verdichtungsprozessen auf Struktur- und Leitfähigkeitseigenschaften des Unterbodens bindiger Substrate und Möglichkeiten ihrer meliorativen Beeinflussung. Tag. der AdL der DDR, 215, 17-38, 1983.