Assessment of soil structure parameters and functions in agricultural soils

N. Rampazzo, W. E. H. Blum and B. Wimmer

Bestimmung von Bodenstruktur-Parametern und -Funktionen in landwirtschaftlichen Böden

Zusammenfassung

Eine internationale Forschergruppe aus Österreich, Deutschland, Tschechien, Slowakei, Ungarn und Polen arbeitete in den vergangenen 5 Jahren im Bereich der Bodenstrukturforschung zusammen mit dem Ziel, die Bedeutung einzelner bodenphysikalischer Parameter und Prozesse für die landwirtschaftliche Bodennutzung zu erfassen.

Dieses multilaterale Forschungsprojekt bestand aus zwei Teilprojekten:

Ziel des 1. Projektes (1992–1993) war die Erstellung eines Konzeptes für die Ansprache und Bestimmung der Bodenstruktur in landwirtschaftlichen Böden mittels standardisierbarer allgemeiner und spezifischer Methoden. Es zeigte sich, daß bei der Beschreibung des Bodenstrukturzustandes die Aussagekraft des jeweiligen Parameters von der zu evaluierenden Bodenfunktion abhängt. Deshalb wurden die wichtigsten Bodenstruktur-Parameter bestimmten Bodenfunktionen zugeordnet. Die Praxisrelevanz sowie die Anwendbarkeit der jeweils verwendeten Methoden wurden für bestimmte Böden und Feldbedingungen im einzelnen geprüft und diskutiert.

Auf der Basis dieser Ergebnisse startete ein 2. Teilprojekt (1994–1996) mit dem Ziel, die Transportfunktion landwirtschaftlicher Böden qualitativ und quantitativ zu bestimmen. Dazu wurden Pflanzenwachstums-, Wasserhaushalts- und Grundwassermodelle getestet, die mit landwirtschaftlichen, meteorologischen, hydrologischen und bodenkundlichen Parametern arbeiten, um den speziellen Einfluß der Bodenstruktur auf die Transportfunktion landwirtschaftlicher Böden zu qualifizieren und zu quantifizieren.

Im allgemeinen berücksichtigen Pflanzenwachstums-Modelle zwei Gruppen von Parametern: Boden- und Pflanzenparameter. Aus der Modellanalyse zeigte sich, daß zumindest Entwicklungsstadium und -tiefe der Pflanzenwurzel erfaßt werden müssen, um den Einfluß der Bodenstruktur auf das Pflanzenwachstum bestimmen zu können. Die innerhalb der Projektgruppe durchgeführte Modellierung zeigte, daß z. B. allein die Messung von Lagerungsdichte und gesättigter Wasserleitfähigkeit den Pflanzenertrag oft nicht erklären konnte. Erst nach Berücksichtigung der Wurzelverteilung wurde der Einfluß des Bodenstrukturzustandes auf das Pflanzenwachstum im Modell deutlich.

Diese Kooperation bestätigte einmal mehr, daß bezüglich der Bestimmung bodenphysikalischer Parameter große methodologische Probleme bestehen, die darauf zurückzuführen sind, daß für die meisten Bodenstruktur-Parameter Proben in ungestörter Lagerung (z. B. Stechzylinder) zu verwenden sind, und daher die notwendige Anzahl von Wiederholungen den Aufwand enorm erhöht. Um einen breiten Überblick über Wassertransportvorgänge im Boden zu bekommen, empfiehlt es sich daher, verschiedene Feld- und Labormethoden zu kombinieren, insbesondere wenn das Bodenfeuchteregime sehr stark variiert.

Diese Arbeiten zeigten darüber hinaus, daß mikromorphologische Untersuchungen (vom Licht- bis zum Elektronenmikroskop) bei der Bodenstrukturforschung äußerst wichtig sind, insbesondere um die Zusammensetzung und Verteilung von Bodenkomponenten zu verstehen. Die Interpretation von mikromorphologisch erfaßbaren pedogenen Merkmalen (pedofeatures) als Indikatoren bestimmter Prozesse innerhalb eines Bodens oder einer Landschaft ist zusätzlich hilfreich, um die Funktionen der Bodenstruktur und deren zeitlicher Variabilität besser zu verstehen.

Schlagworte: Bodenstruktur, Bodenfunktionen, Pflanzenwachstumsmodelle.

Summary

Scientists from six countries worked together during the past 5 years in the field of soil structure assessment, focussing on the importance of physical soil characteristics for agricultural landuse.

This multilateral cooperation consisted of 2 projects:

The first one (1992–1993) aimed at elaborating a comprehensive concept for the assessment of soil structure in agricultural soils, using standardized methods. For this purpose, representative soils from the different countries, ranging from light to very heavy textured, were investigated by all partners using the same methodology. It was found that the diagnostic value of single methods or parameters for describing the soil structure depends on the specific soil function which has to be evaluated. The applicability of all methods for particular soils or specific field conditions was examined. Moreover, in the frame of this first project, new and innovative equipments were developed and tested by the different research groups.

Based on the obtained results, a second project was started in 1994 aiming at testing and evaluating suitable crop-, soil moisture- and ground water models, in which agricultural, meteorological, hydrological and soil parameters were used in order to describe and to quantify *transport functions* of soil structure as a basis for agricultural plant production.

Generally, models for agricultural plant production include two groups of parameters: soil parameters and plant parameters. Time and rooting depth are necessary plant parameters if crop growth should be coupled with soil structure effects. A test of different models showed for instance that the effect of the saturated water conductivity and bulk density alone on crop yield was not significant. But, as soon as root distribution was introduced as a plant parameter, a strong relation to plant growth could be detected as an overall influence of the soil structural status.

Moreover, in order to get a complete overview about water transport phenomena, a combination of different field and laboratory methods was found to be useful, especially within a wide range of soil moisture from water saturation to dry conditions.

Microscopic studies contributed considerably to the understanding of the spatial organization of soil constituents, their distribution, forms and shapes in the matrix. By interpreting soil features as reflection of processes within the pedon and in the landscape, it becomes possible to understand the type and stability of soil structure and its functionality.

Key words: Soil structure, soil functions, crop modelling.

1. Introduction

One of the most influential factors for agricultural production is soil structure. This was underestimated for a long time, because soil chemical parameters were considered as more important and, in fact, easier to investigate. Nevertheless, this view has changed within the last decades.

Generally, soil scientists describe soil structure in the field only morphologically, describing various types of aggregates or peds. The concept and the definition of soil structure, which can be investigated by different methodological approaches, actually shows several aspects and reflects the soil as a porous system and biological habitat in which specific transport and transformation processes occur and where the scale of investigation is defined by the specific methodological approach (BLUM and RAMPAZZO, 1993).

A comprehensive definition of soil structure was given for example by BREWER (1976), defining soil structure as "the physical constitution of solid soil materials as expressed by the size, shape and arrangements of soil particles and voids and its associated properties" .This and similar general definitions may lead to the conclusion that soil structure should be a "physical" soil property, but almost all soil parameters (e.g. chemical, mineralogical, biological, micromorphological) play an important role in the genesis and variability of soil structure and can therefore be considered as "structural" parameters.

Figure 1 shows as an example how soil structural parameters can be divided into different groups. Many of these parameters are unstable and susceptible to changes. Therefore, since all parameters influence each other leading to a typical structural status, changes of specific parameters may cause to changes of the soil structure.

There are many well known methods for determining soil structure parameters and individual laboratories have adapted those in response to particular needs, depending on

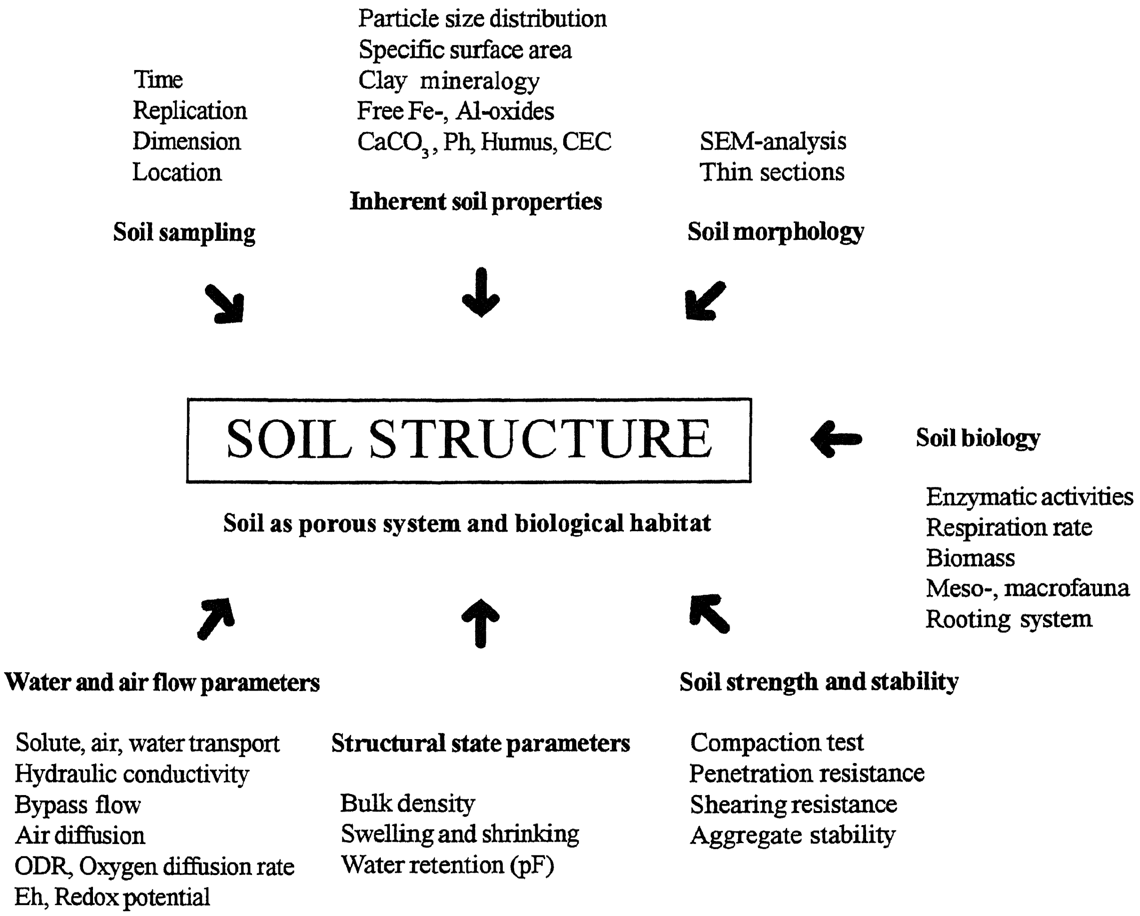

Figure 1: Classification of soil structural parameters, according to BURKE et al. (1986)
Abbildung 1: Einteilung von Bodenstrukturparametern nach BURKE et al. (1986)

circumstances and requirements. Because soil structure is never static, methods suitable for specific conditions may be without result when applied elsewhere. It seems to be impossible to define a single or unique set of methodological procedures for all soils. A broad range of soil structure studies reveals a large number of very different methodological approaches, because most scientists only measure those parameters which they consider relevant for their particular targets. Therefore, numerous publications focussing on soil structure exist, but still no internationally standardized and comprehensive set of methods for its qualitative and quantitative assessment is available. One reason for this is the enormous variability of soil physical parameters, especially in heterogeneous soils.

Moreover, the soil acts as a porous system between atmosphere and lithosphere with different functions (transportation, transformation, fixation, buffering of solids, liquids and gases, biological processes, etc.). The soil structure plays a central role in all of these functions. Therefore it was the aim of this cooperation to investigate the relevance of single soil parameters on specific soil structure functions at an international level. A further aim was to assess the role of soil structure in models for the prediction of crop yields in agricultural plant production.

Based on such ideas, the following institutions worked together during the past 5 years:

- Institute of Soil Science, University of Agricultural Sciences, Vienna, Austria;
- Institute of Soil Science, University of Technology Hanover, Germany;
- Department of Irrigation and Drainage, Faculty of Civil Engeneering, Czech Technical University, Prague, Czech Republic;
- Research Institute for Soil and Water Conservation, Prague, Czech Republic;
- Research Institute of Soil Science and Agricultural Chem-

istry, Hungarian Academy of Sciences, Budapest, Hungary;
- Research Institute of Karcag, Hungary;
- Institute of Agrophysics, Polish Academy of Sciences, Lublin, Poland;
- Soil Fertility Research Institute, Bratislava, Slovak Republic.

2. Material and methods

2.1 Investigated soils

The investigations were carried out on selected soils of each cooperating country within a wide spectrum of texture, ranging from very light textured to very heavy textured soils, in order to give a broad impression on how soil structure parameters may vary under different site and soil conditions. The chemical and physical characteristics of the soils used for the experiments are described by GLINSKI (1993). The soil profiles, classified according to the FAO classification system, were described as follows:

Austria

Cambisol (cultivated arable soil):

Ap (0–20 cm): dark brown (10YR/4/3), silty loam, 1 % skeleton, free of carbonates, medium humus content, crumby structure, plastic consistence, free of concretions, abrupt boundary.

AB (20–40 cm): brown (10YR/5/3), loamy silt/silty loam, 1 % skeleton free of carbonates, medium humus content, moderate fine prismatic structure, plastic consistence, free of concretions, gradual boundary.

Bv (40–80 cm): yellowish brown (10YR/5/4), loamy silt, 1 % skeleton, free of carbonates, medium humus content, fine prismatic structure, plastic consistence, free of concretions, gradual boundary.

BC (80–95 cm): yellowish brown (10YR/5/4), silt, 1 % skeleton, high content of carbonates, low humus content, free of concretions, gradual boundary.

C (95 + cm): yellowish brown (10YR/5/6), silt, <1 % skeleton, high content of carbonates, free of humus, coherent structure.

Chernozem (cultivated arable soil):

Ap (0–15 cm): very dark gray (10YR/3/1), loam, 1 % skeleton, high content of carbonates, medium humus content, crumby structure, abrupt boundary.

Ah (15–23 cm): very dark gray (10YR/3/1), sandy loam, 1 % skeleton, high content of carbonates, medium humus content, crumby structure, abrupt boundary.

AC (23–40 cm): grayish brown (10YR/5/2), sandy loam, 1 % skeleton, high content of carbonates, low humus content, single grain structure, gradual boundary.

C1 (40–70 cm): olive (5Y/5/4), loamy sand, 1 % skeleton, high content of carbonates, free of humus, single grain structure, abrupt boundary.

C2 (70 + cm): light yellowish brown (2,5Y/6/4), silty sand, 1 % skeleton, high content of carbonates, free of humus, single grain structure.

Czech Republic

Arenic Chernozem (experimental plot, pit No. 1):

Ap (0–30 cm): dark grayish brown(10YR/4/2), sandy loam, calcic-like, humic, weak crumby-granular structure, strongly compacted, small sporadic patches of secondary carbonate, diffuse boundary.

A/Ck (30–50 cm): grayish brown to pale brown (10YR/6/3), sandy loam, single grain structure, strongly compacted, moist, small patches of secondary carbonate, gradual boundary.

Ck (50–65 cm): brown (10YR/4/3) loamy sand, single grain structure, increasing amount of coarse sand, dry, small concretions of secondary carbonate, gradual boundary.

C (65–100 cm): sand, single grain structure partly coated by clay films, increasing amount of fine gravel.

Arenic Chernozem (experimental plot, pit No. 2):

Apk (0–22 cm): dark grayish brown (10YR/4/2), sandy loam, humic, weak angular blocky structure, individual concretions of secondary carbonate, diffuse boundary.

Ak (22–35 cm): dark grayish brown (10YR/4/2), sandy loam, humic, weak angular blocky structure, compacted, individual concretions of secondary carbonate, diffuse boundary.

C (35–100 cm): very dark grayish brown (10YR/3/2), sandy loam, coarse granular structure.

Arenic Chernozem (experimental plot, pit No. 3):

Apk (0–25 cm): dark grayish brown (10YR/4/2), sandy loam, humic, weak angular blocky structure, moderately compacted, individual concretions of secondary carbonate, diffuse boundary.

A/Ck (25–55 cm): grayish brown to pale brown (10YR/6/3), sandy loam, weak granular structure, compacted, moist, small concretions of secondary carbonate.

Arenic Chernozem (experimental plot, pit No. 4):

Apk (0–20 cm): dark grayish brown (10YR/4/2), sandy loam, humic, weak angular blocky structure, individual concretions of secondary carbonate, diffuse boundary.

Ak (20–45 cm): dark grayish brown (10YR/4/2), sandy loam, humic, weak angular blocky structure, compacted, small patches of secondary carbonate, diffuse boundary.

A/Ck (45–65 cm): transition of colour up to pale brown (10YR/6/3), increasing content of sand, frequent carbonate concretions, gradual boundary.

Ck (65–100 cm): pale brown to brownish yellow (10YR/6/3 to 10YR/6/6), sand without compaction, small concretions of carbonate.

Arenic Chernozem (experimental plot, pit No. 5):

Apk (0–25 cm): very dark grayish brown (10YR/3/2), sandy loam, humic, weak angular blocky structure, individual concretions of secondary carbonate, diffuse boundary.

Ak (25–45 cm): dark grayish brown (10YR/4/2), sandy loam, humic, weak angular blocky structure, individual concretions of secondary carbonate, diffuse boundary.

A/Ck (45–70 cm): gradual change of colour from grayish brown to pale brown (10YR/5/2 to 10YR/6/3), slight increase of sand with depth but still sandy loam, weak granular structure, with depth less distinguished, moderate content of small carbonate concretions, gradual boundary.

Ck (70–100 cm): light brownish yellow (10YR/6/4), loamy sand with thin sublayers of light reddish brown sand, moderate content of small carbonate concretions.

Hungary

Fluvic Gleysol (cultivated alluvial meadow soil):

A (0–30 cm): yellowish brown (10/YR/4/4), moist, loamy clay, compacted, strong crumby and subangular blocky structure, many small roots, clear smooth boundary.

B (30–70 cm): black (10/YR/2/1), moist, very strongly compacted, weak coarse subangular blocky structure, few iron and manganese mottling, many pressure faces, gradual boundary.

BC (70–90 cm): yellowish gray (10YR/4/4), dry, compacted, subangular blocky structure, clay, few roots, many Fe- and Mn-mottles, clear smooth boundary.

C (90–120 cm): yellowish gray (10YR/4/4), moist, slightly compacted, coherent structure, silty loam, few roots, many blue Fe- and Mn-mottles.

Fluvic Gleysol (uncultivated alluvial meadow soil):

A (0–40 cm): dark grayish brown (2,5Y/3/2), moist, strongly compacted, crumby structure, heavy clay loam, many roots, clear smooth boundary.

B (40–70 cm): dark grayish brown (2,5Y/3/1) but darker when compared to upper horizon, compacted, strong polyhedrical structure, heavy clay, slickensides, clear smooth boundary.

BC (70–110 cm): dark gray (2,5Y/3/2), moist, less compacted than B, clay loam, breaking into subangular blocky structure, few iron mottles, no roots, gradual boundary.

C (110–140 cm): dark gray (2,5Y/4/1), wet, strongly compacted silt loam, coherent structure, reddish mottling and bluish spots or mottles.

Vertic Gleysol (deep loosened meadow soil):

A (0–45 cm): very dark grayish brown (10YR/3/2), moist, fine subangular blocky structure, loam, many roots, clear smooth boundary.

B (45–75 cm): black (10YR/2/1), moist, compacted, fine subangular blocky to mediocre prismatic structure, clay loam, few roots, few slickensides, gradual boundary.

BC (75–100 cm): very dark grayish brown (10YR/3/2), few yellowish red mottled spots, slightly moist, compacted, coarse prismatic structure, clay loam, gradual boundary.

C (100+ cm): dark gray (10YR/4/1), moist, slightly compacted, coherent structure, clay loam, mottles of dark brown colours (10YR/3/3).

Vertic Gleysol (unloosened meadow soil):

Ap (0–30 cm): black (10YR/2/1), compacted, crumby to subangular blocky structure, clay loam, many roots, gradual boundary.

B (30–60 cm): black (10YR/2/1), moist, compacted, moderate fine subangular blocky structure, clay, few roots, smooth boundary.

BC (60–90 cm): dark grayish brown (10YR/4/2), few very dark mottles, moist, compacted clay loam, coherent structure, clear smooth boundary.

C (90 + cm): dark gray (5Y/4/1), many dark mottled spots, moist, coherent structure, silty loam.

Orthic Solonetz (ameliorated and cultivated salt affected meadow soil):

A (0–3 cm): pale gray (10YR/6/1), moist, weak crumby structure, many fine roots, solodized loam, abrupt boundary.

B1 (3–20 cm): gray (10YR/5/1), dry, extremely hard, distinctly columnar structure, clay loam, many fine roots, abrupt boundary.

B2 (20–60 cm): gray (10YR/5/1), somewhere darker than B1, dry, hard, prismatic structure, gradual boundary.

BC (60–78 cm): brownish gray (10YR/5/2), dry, fine prismatic structure, clay loam, few roots, Fe-mottles and Fe-concretions increasing with depth, white carbonate spots and concretions, abrupt boundary.

C (70+ cm): pale brown (10YR/6/3), moist, moderate hard, loess-like clay loam, carbonate mottles and concretions.

Orthic Solonetz (uncultivated salt affected crusty meadow soil):

AB1 (0–20 cm): the original A and B1 horizons are mixed by previous tillage operations. Gray (10YR/5/1), dry, hard, coarse subangular blocky structure, abrupt boundary.

B2 (20–60 cm): gray (10YR/5/1), darker, hard, prismatic structure, gradual boundary.

BC (60–70 cm): light brownish gray (10YR/6/2), medium subangular blocky, Fe-mottles and Fe-concretions, white carbonate spots and concretions, abrupt boundary.

C (78 + cm): pale brown (10YR/6/3), moist, moderate hard, loess-like clay loam, white carbonate spots and concretions.

Poland

Orthic Luvisol (forest soil):

O (3–0 cm): leaves and twigs, partly decomposed.

Ah (0–6 cm): grayish yellow brown (10YR/6/2), dry, silt, angular blocky/coherent structure, many roots, clear boundary.

E (6–27 cm): dull yellow orange (10YR/7/3), dry, silt, coherent structure, clear boundary.

Bt1 (27–57 cm): bright yellowish brown (10YR/6/6), dry, silty loam, coherent structure, gradual boundary.

Bt2 (57–103 cm): bright yellowish brown (10YR/6/6), dry, with lighter horizontal streaks (10YR/7/4), silty loam, coherent structure, gradual boundary.

Ck (103 + cm): dull yellow orange (10YR/7/3), calcareous loess, silt, coherent structure.

Orthic Luvisol (cultivated soil under private farm):

Ap (0–24 cm): dull yellow orange (10YR/6/3), dry, silt, angular blocky/coherent structure, clear boundary.

E (24–35 cm): dull yellow orange (10YR/7/4), dry, silty loam, coherent structure, gradual boundary.

Bt1 (35–75 cm): bright yellowish brown (10YR/7/6), dry, silty loam, coherent structure, gradual boundary.

Bt2 (75–127 cm): dull yellow orange (10YR/6/4), dry, with lighter horizontal streaks (10YR/7/4), silty loam, coherent structure, gradual boundary to BC.

Orthic Luvisol (cultivated soil under state farm):

Ap (0–28 cm): dull yellow orange (10YR/6/3), dry, silt, coherent structure, clear boundary.

E (28–37 cm): dull yellow orange (10YR/7/4), dry, silt, coherent structure, clear boundary.

Bt1 (37–76 cm): dull yellow orange (10YR/6/4), dry, silty loam, coherent structure, gradual boundary.

Bt2 (76–126 cm): dull yellow orange (10YR/6/4), dry, with lighter horizontal streaks (10YR/7/4), silty loam, coherent structure, gradual boundary.

BC (126–142 cm): dull yellow orange (10YR/7/4), dry, silt, coherent structure, gradual boundary to Ck.

Slovak Republic

Calcaro-haplic Phaeozem:

Akp (0–38 cm): dark brown (10YR/3/3) moist matrix colour, coarse angular to subangular blocky structure, loam, calcareous, common very fine to fine roots, some gravels, clear smooth boundary.

Ak (38–48 cm): dark brown (10YR/3/3) moist matrix colour, friable, fine angular to subangular blocky structure, loam, calcareous, common very fine to fine roots, gradual boundary.

A/Ck (48–65 cm): yellowish brown (10YR/5/4) moist matrix colour, friable, fine angular to subangular blocky structure, loam, calcareous, few very fine to fine roots, clear smooth boundary.

Ck (65–85 cm): very pale brown (10YR/7/4) moist matrix colour, very fine coherent structure, loam, no roots, gradual boundary.

Cgk (85+ cm): very pale brown (10YR/7/4) moist matrix colour with 10 % Fe^{3+} mottling, firm coherent structure, loamy sand, calcareous, without roots.

Calcaro-gleyic Phaeozem:

Agkp (0–33 cm): black to very dark brown (10YR/2/1,5) moist matrix colour with Fe^{3+} mottling, very firm consistence, moderately developed coarse angular to subangular blocky structure, silty clay loam, calcareous, few fine roots, abrupt boundary.

A/Cgk (33–47 cm): grayish brown (10YR/5/2) moist matrix colour with Fe^{3+} mottling, firm consistence, moderately developed medium angular to subangular blocky structure, silty loam, calcareous, few fine roots, gradual boundary.

Cgc (47–100 cm): very pale brown (10YR/7/4) moist matrix colour with rusty and gray mottling (10YR/6/2), firm consistence, weak developed blocky structure, silty loam, calcareous, with accumulation of hard nodules of lime in 50 to 60 cm and 85 to 100 cm, no roots, abrupt boundary.

Abgrk (100–117 cm): black to very dark brown (10YR/2/1,5) moist matrix colour with rusty and dark gray mottling, very firm consistence, medium to coarse prismatic structure, silty loam, calcareous, no roots, gradual boundary.

A/Crgk (117+ cm): gray (10YR/5/1) moist matrix colour with Fe^{3+} mottling, very firm weak prismatic structure, silty loam, calcareous.

Fluvic-calcaric-Phaeozem:

Akp (0–32 cm): very dark grayish brown (2,5Y/3/2) moist matrix colour, very friable, moderate crumby structure, loam, calcareous, common fine to medium roots, clear boundary.

Ak (32–68 cm): very dark grayish brown (2,5Y/3/2) moist matrix colour, friable, subangular blocky to prismatic very weak grade structure, loam, calcareous, common very fine roots, gradual boundary.

A/Cgk (68–88 cm): light olive brown (2,5Y/5/3) moist matrix colour with Fe^{3+} mottling, very firm, subangular blocky to prismatic very weak grade structure, loam, calcareous, common very fine roots, gradual boundary.

Cgk (88 + cm): light yellowish (2,5Y/6/4) moist matrix colour with Fe^{3+} mottling, firm, coherent structure, loam, no roots.

2.2 Methods

Since the uniformity and standardization of methods is the main basis for any comparison of results, especially at international level, the methodology to be used within this project was discussed and designed in detail during the first workshop.

The parameters to be measured were subdivided into *"general" parameters*, which were standardized according to BLUM et al. (1989) and carried out by all cooperating partners, and *"specific" parameters*, which were investigated only by those institutions which disposed of the relevant technical facilities and according to the national procedures respectively.

2.2.1 "General" parameters

Physical parameters:
- Particle size distribution
- Bulk density
- Particle density
- Total porosity
- pF-curve and differential porosity

Chemical parameters:
- pH-value
- Organic matter
- Electric conductivity
- $CaCO_3$-content
- Cation Exchange Capacity (CEC) and exchangeable cations

2.2.2 "Specific" parameters

Austria:
- Mineral composition of the fine earth using x-ray diffraction (Cukα-radiation, Ni-filter), see SCHULTZ, 1964.
- Semi-quantitative clay mineral distribution in the fine earth using x-ray diffraction (Cukα-radiation, Ni-filter), according to GARCIA and CAMAZANO (1968), BRINDLEY and BROWN (1980).
- Determination of "free" Fe-, Al- and Mn-oxides using extractions with Na-dithionite-citrate-bicarbonate (DCB), NH_4-oxalate and Na-pyrophosphate, according to SCHWERTMANN (1959 and 1964).
- Saturated hydraulic conductivity using a steady state procedure, according to HARTGE and HORN (1989).
- Soil aggregate stability, according to MURER et al. (1993).

Czech Republic:
- Measurement, modeling and spacial variability of water infiltration.

Hungary:
- Water retention characteristic using tension infiltrometry
- Swelling and shrinking behaviour
- Microaggregate analysis
- Mathematical description of pF-curves

Poland:
- Relative Oxigen Diffusion Coefficient (D/Do)
- Oxigen Diffusion Rate (ODR)
- Redox potential (Eh)
- Air permeability
- Enzyme activities
- Microbial counts
- Respiration rate
- Specific surface area
- Micromorphometrical analysis
- Calculation of thermal properties
- Pore size distribution by Hg-porosimetry
- Compaction test
- Water retention and K_{unsat} by TDR

Slovak Republik:
- Micromorphological analysis of soil thin sections

3. Results and discussion

3.1 Classification of soil structure parameters based on 4 soil functions

Soils as part of ecosystems are inhomogeneous porous substrates with different functions. A possible way to assess the structural status of a soil is to investigate its functionality considering specific soils functions as follows:

1. Soil as porous medium (*physico-chemical reaction function*)
2. Soil as transport medium (*transport function*)
3. Soil as transformation medium (*transformation function*)
4. Soil as biological habitat (*bio/ecological function*)

In each of those functions soil structure, as the architectural distribution of solids, voids, liquids and gases plays a central role. But, since soil structure is the result of interrelations between many parameters, see Figure 1, the question arises, how many and which parameters are at least necessary to be investigated in order to get a clear information about the soil structural status. It seems clear that the methodological approaches used for soil structure assessment depend mainly on the specific target, e.g. soil functions, chosen.

Therefore, the diagnostic value of each single soil structure parameter varies in relation to the soil function which has to be evaluated. The "general" and "specific" parameters used in the cooperation project were classified as shown in Table 1.

Table 1 shows that for the description of specific soil functions only a certain number of parameters is at least necessary, whereas other parameters have low or only complementary diagnostic value.

3.2 Applicability of methods in relation to specific soil characteristics

The determination of parameters on a very wide spectrum of different soils allowed to give a differentiation of the applicability of single methods with respect to specific soil characteristics.

Methods with unlimited applicability:

- Particle size distribution;
- Particle density;
- pH;
- Organic matter;
- Electrical conductivity;
- CEC and exchangeable cations;
- Total and clay mineral composition;
- "Free" Fe-, Al-, Mn-oxides;
- Redox-potential;
- Specific surface area.

Methods with limited applicability, which can still be improved:

- Thin and thick sections for heavy textured soils because of impregnation problems;
- Infiltration rate, saturated and unsaturated hydraulic conductivity, bulk density, water retention, pore size distribution and porosity for strong swelling and cracking soils;
- Air permeability and gas diffusion coefficient for loose sands and for shrinking soils.

Methods with limited applicability, which cannot be improved:

- Aggregate stability for heavy textured soils and for salt affected soils;
- Air permeability and gas diffusion coefficient for light textured and heavy textured soils;
- $CaCO_3$-content in dolomitic soils.

Biological and biochemical methods which need a standardization of soil physical conditions before application:

- Enzyme activities;
- Respiration rates;
- Microbial counts.

3.3 Interactions between soil mineralogical, -micromorphological parameters and soil structure

The coarse "primary" soil minerals accumulate mostly in the sand and silt fraction. Besides their influence on chemical soil parameters (pH, cation release, CEC, etc.), their size, shape and arrangement seem to characterize particular types of soil macrostructures. As an example, soil horizons with massive, coherent structure are mostly sandy/silty loessial horizons, with few non-swelling clay minerals. These horizons possess few voids, if any, and become very compact and dense when moistened, see Figure 2.

On the contrary, soils with abundant amounts of clay minerals, especially of the swelling type (smectite, randomly interstratified illite), have a very pronounced swelling/shrinking behaviour. This leads mostly to a typical cracky, prismatic macrostructure, as shown for example in the heavy-textured Solonetz of Hungary (RAMPAZZO et al., 1993), see Figure 3.

Considering the effect of Fe-oxides on aggregation, this is probably less due to crystall growth but more to the attraction between positively charged Fe-oxide particles and negatively charged matrix particles, particularly clay silicates.

Table 1: Classification of the diagnostic value of soil structure parameters with respect to specific soil functions (+) = high value, (–) = low value
Tabelle 1: Aussagekraft (Indikatorwert) einzelner Bodenstrukturparameter für spezifische Bodenfunktionen (+) = hohe, (–) = niedrige Aussagekraft

Parameters	Specific soil functions			
	porous medium	transport medium	transformation medium	biological habitat
Inherent soil parameters				
Particle density	+	-	-	-
Particle size distribution	+	+	+	-
Specific surface area	+	+	+	+
Electric conductivity	+	+	+	+
$CaCO_3$	+	+	+	+
pH (H_2O, KCl, $CaCl_2$)	-	+	+	+
Organic matter	-	+	+	+
CEC	-	+	+	+
Exchangeable cations	-	+	+	+
Clay mineralogy	+	+	+	+
„Free" Fe-, Al-, Mn-oxides	+	+	+	+
Total mineralogy	-	-	+	+
Structural state parameters				
Bulk density and total porosity	+	+	+	+
Standard bulk density	+	+	+	+
Bulk density of aggregates	+	+	+	+
Soil water retention (pF)	+	+	+	+
Swelling and shrinking	+	+	-	+
Water, air and energy flow parameters				
Solute, air and energy transport	+	+	+	+
Saturated hydraulic conductivity	+	+	-	-
Unsaturated hydraulic conductivity	+	+	-	-
Bypass flow	+	+	-	+
Air diffusion	+	+	+	+
Air permeability	+	+	+	+
Oxigen diffusion rate	-	-	+	+
Eh – Redox-potential	-	-	+	+
Soil strength and stability parameters				
Compaction test	+	-	-	+
Penetration resistance	+	-	-	+
Soil morphological parameters				
Macropore continuity	+	+	-	-
Soil thin sections	+	+	+	+
Morphometry of thin sections	+	+	+	+
Submicroscopy	+	+	+	+
Soil biological parameters				
Meso- and macrofauna	+	+	+	+
Rooting system	+	+	+	+
Enzymatic activity	-	+	+	+
Respiration rate	-	-	+	+

Because the charge of Fe-oxide particles is pH-dependent, their aggregation effect is also pH-dependent.

The aggregation effect of Fe-oxides has been demonstrated in various ways:

a) by a significant correlation between the percentage of water-stable aggregates or related structural properties and the content of Fe-oxides (McIntyre, 1956; Kemper, 1966; Arca and Weed, 1966).
b) by the dispersion of aggregated soils after removal of Fe-oxides with a reducing agent (McNeal et al., 1968).
c) by the aggregating effect of added synthetic Fe-oxides (Kuron and Walter, 1964; Schahabi and Schwertmann, 1970; Blackmore, 1973).

These data indicate that Fe-oxides are the more effective in aggregating silty, e.g. loessial soils, the lower their crys-

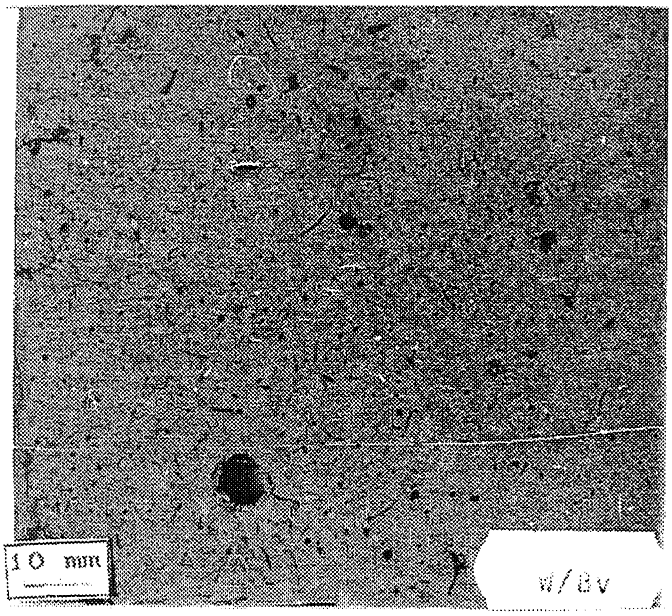

Figure 2: Soil thin section of the Bv-horizon (40–80 cm) of a Cambisol (Austria). Coherent microstructure with few macropores (no enlargement)

Abbildung 2: Bodendünnschliff des Bv-Horizontes (40–80 cm) einer Braunerde (Wieselburg, Österreich). Kohärentstruktur mit wenigen Makroporen (keine Vergrößerung)

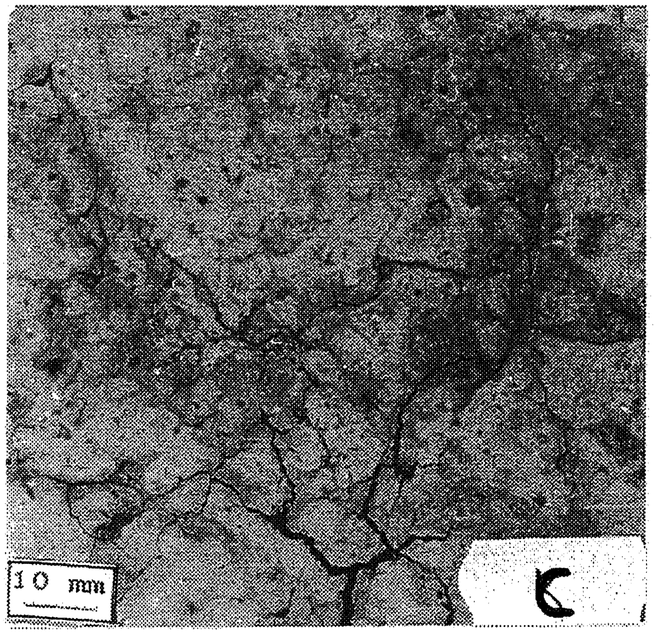

Figure 3: Soil thin section of the BC-horizon (60–70 cm) of a Orthic Solonetz (Hungary).Subangular blocky microstructure, with many cracks where the aggregate faces largely accomodate each other (no enlargement)

Abbildung 3: Bodendünnschliff des BC-Horizontes (60–70 cm) eines Solonetzes (Ungarn). Blockig-kantige Struktur, mit vielen Rissen und geschlossener Lagerung der Aggregatoberflächen (keine Vergrößerung)

tallinity and the higher their oxalate solubility (i.e the higher their Fe_o/Fe_d ratio). Therefore, very small, highly charged Fe-oxide-Polymers were found to be particularly effective in binding soil particles together (RENGESAMY and OADES, 1977). Microscopical soil investigations (using light microscope and submicroscopic techniques) are very useful in studying natural peds, crumbs, aggregates and associated voids. With these procedures voids and aggregates produced by soil fauna and due to tillage, root and faunal channels, can be distinguished. Soil micromorphology gives the possibility to identify the coagulating and cementing effect of components, the properties and occurance of peds. Some of these components can be quantified in a global (porosity, volume fraction of homogeneous zones) as well as in the feature-specific sense (informations about individual objects). All observed facts can be presented and documented as graphs, pictures and descriptions, see RAMPAZZO et al. (1993).

3.4 Interactions between soil hydraulic parameters and soil structure

The comparative study on the applicability of infiltration carried out by KUTILEK et al. (1993) could show that the 3-parameters equation of PHILIP (1957), SWARTZENDRUBER (1987) and BRUTSAERT (1977) were best applicable for infiltration tests. Among the Probability Density Function (PDF) for fitting hydraulic characteristics, the log-normal distribution is a well acceptable approximation for sorptivity S, saturated hydraulic conductivity K_{sat} and rate of infiltration. A close correlation of soil structure stability and spacial and time variability of infiltration could be detected.

This study presented two new techniques for studying the functional consequence of the structural status of soil on hydraulic conductivity (RAJKAI et al., 1993). The tension infiltrometer allows to measure the unconfined infiltration rate of the soil *in situ*. This technique makes it possible to gather infiltration data both in space and time for studying the consequence of the cultivation practice and changes in the structural status under soil conditions close to saturated water conductivity. The parametrization and fitting of measured pF-curve aimed to express the consequence of soil aggregation on the water retention characteristic (WRC) of the soil.

WALKZAC et al. (1993) showed how the TDR (Time Domain Reflectometry) technique, together with the

"Instantaneous Profile Method" (MALICKI et al., 1992; SOBCZUK et al., 1992) permits the determination of the effect of changes in the soil structure, for instance through agricultural practices, on the hydrophysical properties of soils.

3.5 Interactions between soil strength parameters and soil structure stability

Investigations carried out in 3 polish soils from the same parent material (deep loess deposits) revealed a significant differentiation in the soil structural status as a result of different landuse practices (DEBICKI et al., 1993). Although most of the tested methods are believed to be sensitive enough to recognize the changes in the structural states of silty soils under different landuse, as for example pore size distribution, total porosity and infiltration rate, there are sometimes contradictorial interpretations which may lead to a misunderstanding of the measured data and to wrong conclusions. Therefore, it could be shown that the assessment of the structural state of agricultural soils should focus on clearly defined targets, either the classical approaches (soil morphology, soil classification) or in the view of the role that soil structure plays in various soil functions, see BLUM and RAMPAZZO (1993).

3.6 Interactions between aeration parameters and soil biological parameters

Aeration parameters as relative oxygen diffusion coefficient (D/Do), oxygen diffusion rate (ODR), and air permeability (*k*) are strongly influenced by the structural status of soils. STEPNIEWSKI et al. (1993) showed during this project how such parameters vary between different soils and with soil depth. Moreover, he showed a close relation between aeration parameters and biological parameters as dehydrogenase and catalase activities, respiration rate and microbial counts.

The highest D/Do, ODR and *k* values were measured in the Slovakian Phaeozem and the Austrian Chernozem, the lowest in the Hungarian Gleysol. In general the aeration parameters increased with soil moisture tension and decreased with soil depth. The dehydrogenase activity was linearly and positively correlated with all areation parameters, the catalase activity only with D/Do and *k*. Consequently, the enzymatic activities were higher in the well aerated soils and significantly lower in the heavy textured Gleysols in Hungary.

3.7 Interactions between thermal properties and soil structure parameters

The most basic thermal parameters of soils besides temperature T, are the *Heat Capacity per soil unit* (Cv) [J/m^{3}K°], as the amount of heat which has to be supplied to/or removed from a soil unit to increase/or decrease its temperature by K° and the *Thermal Conductivity* (λ) [W/mK°], which is defined as the amount of energy passing during a unit of time through a unit of surface area at a temperature gradient equal to one. Both parameters are known to be dependent on the composition of the bulk soil (minerals, organic matter, liquids, gases) and their spacial distribution.

USOWICZ (1993) analyzed the whole spectrum of selected soils in this project and could show that the termal conductivity of soils (λ) increased with increasing soil moisture and bulk density, as the two main structural parameters, and that the increase was more intensive in soils with higher quartz content. The other components of the solid phase showed a weaker effect on the thermal conductivity of soils. Organic matter contents <10 % in a mineral soil does not contribute much towards the total thermal conductivity. The relation of (λ) to the moisture content of the soil was non-linear, the form of the non-linearity was affected by the bulk density and the slope of the curve was considerably affected by the quartz content.

The characteristics of the heat capacity (Cv) of soils as a function of the moisture content were linear and slightly affected by the bulk density and organic matter content. Under condition of water saturation, Cv decreases with decreasing total porosity.

3.8 Results of the second part of the project

Basing on the results and considerations of the first cooperation period, a second project started (1994–1995) aiming at a qualitative and quantitative assessment of soil structure functions for the sustainable agricultural plant production. Because of limited time and fonds it was agreed to concentrate the investigations to one special soil function. Thus, the aim of the second project was to evaluate and to test suitable crop-, soil moisture- and groundwater-models, based on agricultural, meteorological, hydrological and soil parameters to describe and quantify the *transport function* of soils in relation to their structural status. For this purpose, data from the first project and new investigations were performed on the same soils.

From the analysis of 75 models considering soil structure, within the mentioned models it resulted that the most relevant soil structure parameters appearing in them are (see WALCZAK et al., 1997):

- soil water retention characteristic (pF)
- rooting intensity
- bulk density and porosity
- unsaturated and saturated water conductivity

In particular 4 deterministic models were selected and discussed as appropriate to predict plant groth and yield production, as shown on Table 2.

The common feature of the chosen models is that they assume the possibility of limiting the availability of soil water for plants and that they quantitatively analyse the yield loss as a result of water shortage.

The CTSPAC-model is a theoretical model where the theory of water, solutes and heat transport in the soil-plant-atmosphere continuum and the biomass growth are based on constitutional physical equations.

The WOFOST-model is a versatile model, where a simultaneous analysis of development, growth and yielding of different plant species in diversified climatic and soil conditions basing on easily measurable physico-chemical quantities is possible.

The EPIC-model allows for the analysis of the relation between soil erosion and plant productivity.

The CERES-model allows for the simulation and forecasting of growth and yield of a given crop (maize). KURAZ and DOLEZAL (1997) demonstrated the use of CERES for investigating the interactions between soil structure and plant growth.

Generally, models of plant production include two groups of parameters: soil parameters and plant parameters. At least measurements of the time and the depth of the crop root development are necessary plant parameters if crop growth should be coupled with soil structure effects. RAJKAI et al. (1997) and WIMMER et al. (1997) demonstrated the use of the SOIL- and SOILN simulation models for studying different effects of the soil structural status for winter

Table 2: Selected models of plant growth and yield prediction indicating the soil input parameters (WALCZAK et al., 1997)

Tabelle 2: Ausgewählte Pflanzenwachstums- und Pflanzenertragsmodelle mit den entsprechenden bodenkundlichen Eingangsparametern (WALCZAK et al., 1997)

Models and their origin	Soil input parameters	Description of soil profile in soil submodels
CTSPAC (Coupled transport of water, solutes and heat) in the Soil-Plant-Atmosphere Continuum) (Oregon State University, USA)	- soil water characteristics - soil thermal characteristics - characteristics of soil solid phase - soil and water chemical characteristics	Soil submodel is constructed for vadose zone. Soil profile is divided into 5 or more thin horizontal layers. The depth of water table is assumed constant.
WOFOST (World Food Studies) incorporated in the CGSM (Crop Growth Monitoring System) for regions of the European Union (Holland)	- moisture content of root zone - depth of ground water table - percolation rate - rate of capillary rise - runoff - surface storage - soil evaporation rate - rooting depth - rate of net influx through the lower and upper root zone boundaries	The textural profile of the soil is homogeneous. Initially the soil profile consists of three layers: - rooting zone between soil surface and actual rootin depth - lower zone between actual and maximum rooting depth - subsoil below maximum rooting depth
EPIC (Erosion-Productivity Impact Calculator) (USDA-ARS, USA)	- soil water retention (pF) - bulk density and porosity - particle size distribution - pH (H_2O, KCL, $CaCl_2$) - solute, air and energy transport - depth of soil profile - albedo	Soil and management are treated spatially homogeneous. Soil profile is divided into a maximum of 10 layers.
CERES - maize (Crope - Environment Resource Synthesis) (USDA-ARS, USA)	- soil water retention (pF) - bulk density and porosity - particle size distribution - solute, air and energy transport	Up to 10 soil layers may be identified. Layers can be the horizons described in soil characterization data (with 3 constraints).

wheat and maize crop's development and yield. It could be shown that the effect of the saturated water conductivity and bulk density on the crop yield alone was not always significant. But, as soon as root distribution was introduced as a plant parameter, a strong effect on the plant growth was detected as an overall consequence of the soil structural status.

HARTGE (1997) pointed out once more that physical soil parameters provide the same kind of methodological troubles as all other scientific measurements. But compared with chemical soil parameters there is an additional difficulty. This is based on the fact that structure-dependent parameters cannot be determined from composite, disturbed samples. Each core sample or each *in situ* measurement has to be treated separately. This creates very specific problems of sampling in terms of replications, time and costs.

In order to get a complete overview on the water transport phenomena, a combination of different field and laboratory methods should be used, especially considering the wide soil moisture range from saturation to dry conditions. An important task of this cooperation was to test different kinds of new and innovative field and laboratory equipments on different soils for the assessment of soil hydraulic parameters, in particular the tension infiltrometer (RAJKAI et al.,1997; WIMMER et al., 1997), the disc infiltrometer and the Guelph-permeameter (KURAZ and DOLEZAL, 1997; WIMMER et al., 1997), the Laboratory Evaporation Controlled Instantaneous Profile Method (WIMMER et al., 1997) and the Laboratory Multistep Outflow Method (WIMMER et al., 1997; VAN DAM et al., 1994).

Moreover, CURLIK and HOUSKOVA (1997) showed how micromorphologic studies contribute to understand the organization of soil constituents, their distribution, forms and shapes in the matrix. Interpreting soil features as a reflection of processes within the pedon and in the landscape, allows to understand the stability of soil structure and its functionality.

4. Conclusions

Through this international cooperation in the field of soil structure analysis and interpretation for agricultural plant production, it became clear that the diagnostic value of single soil structure parameters for agricultural landuse practices strongly depends on specific soil functions. Therefore, an accurate selection of parameters is needed in order to choose appropriate methods. Moreover, it became clear that in most of the cases it is impossible to compare results from field experiments directly with those of laboratory investigations. A combination of both approaches is needed as well as a careful standardization of methods for a safe evaluation of results.

Many problems resulting from the validation and application of crop models derive from the fact that modellers consider soils as a structurally homogeneous substrate. This is in most cases not true, and especially not under field conditions. Therefore it is very important to develop future models which consider in more detail the variability in time and space of soil physical parameters.

In this sense, the cooperation was a considerable step forward in the field of soil structure analysis and interpretation for agricultural plant production in Central and Eastern Europe.

References

ARCA, M. N. and S. B. WEED (1966): Soil aggregation and porosity in relation to contents of free iron oxide and clay. Soil Sci., 101, 164–170.

BLACKMORE, A. V. (1973): Aggregation of clay by the products of iron (III) hydrolysis. Aust. J. Soil Res., 11, 75–82.

BLUM, W.E.H. and N. RAMPAZZO (1993): Assessment of structure in agricultural soils. Results of a multilateral cooperation project between Austria, Czech Republic, Hungary, Poland, and Slovak Republic. Intern. Agrophysics, Vol. 7, Special Issue, Nrs. 2–3, 93–97.

BLUM, W.E.H., H. SPIEGEL und W. W. WENZEL (1989): Bodenzustandsinventur. Konzeption, Durchführung und Bewertung. Arbeitsgruppe der ÖBG, im Auftrag des BMLF.

BREWER, R. (1976): Fabric and mineral analysis of soils. Robert E. Kreiger, New York.

BRINDLEY, G. W. and G. BROWN (1980): Crystal structures of clay minerals and their X-ray identification. Min.Soc. London.

BRUTSAERT, W. (1977): Vertical infiltration in dry soils. Water Res., 13, 363–368.

BURKE, W., D. GABRIEL and J. BOUMA (1986): Soil Structure Assessment. A.A. Balkema, Rotterdam, Boston.

CURLIK, J. and B. HOUSKOVA (1997): Physical parameters and micromorphological description of sandy Slovak soils. Intern. Agrophysics, Vol. 11, Special Issue, Nrs. 1–2, 129.

Debicki, R., J. Glinski, J. Lipiec, A. Pukos and R. Turski (1993): Soil strenght, stability and structural state of Orthic Luvisols under different land use. Intern. Agrophysics, Vol. 7, Special Issue, Nrs. 2–3, 155–161.

Garcia, S. G. and M. S. Camazano (1968): Differentiation of kaolinite from chlorite by treatment with Dimethyl-Sulphoxide. Clay Min., 7, 447–450.

Glinski, J. (1993): General characteristics of soils included to the multilateral programme. Intern. Agrophysics, Vol. 7, Special Issue, Nrs. 2–3, 99–116.

Hartge, K. H. und R. Horn (1989): Die physikalische Untersuchung von Böden. Enke Verlag, Stuttgart.

Hartge, K. H. (1997): Accessibility of most frequently used physical parameters of soil structure, reliability of measured values, lack of replicates and ways out of this dilemma. Intern. Agrophysics, Vol. 11, Special Issue, Nrs. 1–2, 89–96.

Kemper, W. D. (1966): Aggregate stability of soils from western United States and Canada. SDA Tech. Bull. 1355, U.S. Gov. Print Office, Washington, D.C.

Kuraz, V. and F. Dolezal (1997): Evaluation of soil physical conditions with the use of CERES model, penetrometer and infiltrometer methods. Intern. Agrophysics, Vol. 11, Special Issue, Nrs. 1–2, 43–88.

Kuron, H. and B. Walter (1964): Über die Bildung und Bindung von Mikroaggregaten in Böden. Z. Pflanzenernähr. Bodenkd., 104, 12–24.

Kutilek, M., V. Kuraz and M. Krejca (1993): Measurement time and spatial variability of field infiltration. Intern. Agrophysics, Vol. 7, Special Issue, Nrs. 2–3, 133–140.

Malicki, M. A., R. Plagge, M. Renger and R. T. Walczak (1992): Application of time-domain-reflectometry (TDR) soil moisture miniprobe for the determination of unsaturated soil water characteristics from undisturbed soil cores. Irrigation Sci., 13, 65–72.

McIntyre, D. S. (1956): The effect of free ferric oxide on the structure of some Terra Rossa and Rendzina soils. J. Soil Sci., 7, 302–306.

McNeal, B. L., D. A. Layfield, W. A. Norwell and J. D. Rhoades (1968): Factors influencing hydraulic conductivity of soils in the presence of mixed salt solution. Soil Sci.Soc.Am.Proc., 32, 187–190.

Murer, E. J., A. Baumgarten, G. Eder, M. H. Gerzabeck, E. Kandeler and N. Rampazzo (1993): An improved sieving machine for estimation of soil aggregate stability (SAS). Geoderma, 56, 539–547.

Philip, J. R. (1957): The theory of infiltration: 1. The infiltration equation and its solution. Soil Sci., 83, 345–357.

Philip, J. R. (1957): The theory of infiltration: 4. Sorptivity and algebraic infiltration equations. Soil Sci., 84, 257–264.

Rajkai, K., J. Zsembeli, L. Blasko and G. Varallyay (1993): Use of tension infiltrometer and water retention characteristics in the assessment of soil structure. Intern. Agrophysics, Vol. 7, Special Issue, Nrs. 2–3, 141–154.

Rajkai, K., K. R. Vegh, G. Varallyay and C. S. Farcas (1997): Impacts of soil structure on crop growth. Intern. Agrophysics, Vol. 11, Special Issue, Nrs. 1–2, 97–110.

Rampazzo, N., W.E.H. Blum, P. Strauss, J. Curlik and A. Slowinska-Jurkiewicz (1993): The importance of mineralogical and micromorphological investigations for the assessment of soil structure. Intern. Agrophysics, Vol. 7, Special Issue, Nrs. 2–3, 117–132.

Rengesamy, P. and J. M. Oades (1977): Interaction of monomeric and polymeric species of metal ions with clay surfaces. II. Changes in surface properties of clays after addition of iron (III). Aust. J. Soil Res., 15, 235–242.

Schahabi, S. and U. Schwertmann (1970): Der Einfluß von synthetischen Eisenoxiden auf die Aggregation zweier Lößbodenhorizonte. Z. Pflanzenernähr. Bodenkd., 125, 193–204.

Schultz, L. G. (1964): Quantitative interpretation of mineralogical composition from x-ray and chemical data for the Pierre Shale. U.S.Geol.Surv.Prof.Pap., 3913.

Schwertmann, U. (1959): Die fraktionierte Extraktion der freien Eisenoxide in Böden, ihre mineralogischen Formen und ihre Entstehungsweisen. Z. Pflanzenernähr. Bodenk., 84, 194–204.

Schwertmann, U. (1964): Differenzierung der Eisenoxide des Bodens durch Extraktion mit Ammoniumoxalat-Lösung. Z. Pflanzenernähr. Bodenk., 105, 194–201.

Sobczuk, H. A., R. Plagge, R. T. Walczak and Ch. H. Roth (1992): Laboratory equipment and calculation procedure to rapidly determine hysteresis of some soil hydrophysical properties under nonstady flow conditions. Z. Pflanzenernähr. Bodenkd., 155, 157–163.

Stepniewski, W., Z. Stepniewska, T. Wlodarczyk, M. Dabek-Szreniawska, M. Brzezinska, A. Slowinska-Jurkiewicz and G. Przywara (1993): Aeration related properties and their influence on soil biological parameters. Intern. Agrophysics, Vol. 7, Special Issue, Nrs. 2–3, 163–173.

Swartzendruber, D. (1987): A quasi-solution of Richards' equation for downward infiltration of water into soil. Water Res., 23, 809–817.

USOWICZ, B. (1993): Thermal properties of some soils from Lower Austria, Central Bohemia and Lublin upland. Intern. Agrophysics, Vol. 7, Special Issue, Nrs. 2–3, 183–191.

VAN DAM, J. C., J.N.M. STRICKER and P. DROOGERS (1994): Inverse method to determine soil hydraulic functions from multistep outflow experiments. Soil Sci. Soc. Am. J., 58, 647–652.

WALCZAK, R. T., C. SLAWINSKI, M. MALICKI and H. SOBCZUK (1993): Measurement of water characteristics in soils using TDR technique: water characteristics of Loess soil under different treatment. Intern. Agrophysics, Vol. 7, Special Issue, Nrs. 2–3, 175–182.

WALCZAK, R. T., B. WITKOWSKA-WALCZAK and P. BARANOWSKI (1997): Soil structure parameters in models of crop growth and yield prediction. Physical submodels. Intern. Agrophysics, Vol. 11, Special Issue, Nrs. 1–2, 111–128.

WIMMER, B., N. RAMPAZZO and W.E.H. BLUM (1997): Influence of soil structural parameters on hydraulic functions for soil-water balance modelling. Intern. Agrophysics, Vol. 11, Special Issue, Nrs. 1–2, 5–42.

Corresponding Authors

Dipl.-Ing. Dr. Nicola Rampazzo, o. Univ.-Prof. Dr. Winfried E. H. Blum, Dipl.-Ing. Bernhard Wimmer, Institut für Bodenforschung, Universität für Bodenkultur Wien, Gregor Mendelstraße 33, A-1180 Wien.

Eingelangt am 2. März 1998
Angenommen am 11. Mai 1998