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Structure and Organic Matter Storage in Agricultural Soils

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Soil Architecture and Distribution of Organic Matter

M.J. Kooistra and M. van Noordwijk

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I. Introduction

Soil architecture deals with the spatial distribution and heterogeneity of the different components or properties of soils (Dexter, 1988). It determines and influences many soil processes: physical processes, such as water, air and temperature regimes, decomposition and transport processes, and the occurrence, survival and functioning of soil organisms and plant root systems. Soil architecture can be considered identical to soil structure. The term architecture, however, includes the aspect of a purposely made structure which fulfills special requirements. Several abiotic and biotic factors and processes can be distinguished to contribute to soil structure (Kooistra, 1991), but only the biotic ones are responsible for the architectural part of soil structure. The below-ground communities and plant roots are dependent and involved in the genesis and

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maintenance of soil structure for their functioning and growth. Yet, the various communities and plant roots have different requirements which can be mutually exclusive, mutually complementary or dependent, completely independent or mixtures of these. They also act at different hierarchical scales ranging from molecular level, via organisms level and pedon level to the fieldscale level (McGill and Myers, 1987). The impact of the biological component making up the soil architecture is therefore variable and depends on the land capability, i.e. the natural integration of soil properties with climate and plants, together with land use and management.

In cultivated land, human impact by soil tillage, traffic and machinery, application of pesticides, fertilizers and manures, regulates the overall soil structure throughout the year. In intensive agricultural systems, the natural physical aggregate formation and biological soil-structure formation processes generally play a secondary role. Farm management systems may try to increase the role of the natural processes, however, in as far as they contribute to the farmers purpose of growing and harvesting crops. In large parts of the tropics less intensive land use systems still predominate and the role of biologically mediated processes is larger. One of the major factors determining the abundance and the related impact of soil organisms is the presence of organic substrates as food, and thus the cropping pattern or agroforestry system used.

Organic carbon in soils normally originates from plants growing on site or in the direct neighbourhood, but considerable transport of organic material occurs as part of farming activities, by faunal action (e.g. termites) and in erosion/deposition cycles. Transformations and redistribution of organic carbon in soils from fresh organic inputs to release as CO_2 or incorporation in stable humus fractions can follow a number of pathways. A first distinction is between organic inputs which arrive via the soil surface, such as aboveground crop residues, tree litter or prunings, pollen and organic manures, and the below ground organic inputs to the soil from primary producers, such as exudates, root structural material and mycorrhizal hyphae. Structure-forming soil organisms normally play a role in physically fragmenting and redistributing organic inputs as well as modifying its chemical form and physical link with mineral particles in their excrements. Organisms which mainly follow existing soil structural voids or channels, such as mesofauna and microbes, modify the organic carbon pools, depending on the physical accessibility of the latter. Excrements of soil fauna are partly or completely composed of organic matter. Where mull, mull-like moder or moder humus forms occur in agricultural land, recognizable faunal excrements may contribute the bulk part of the organic carbon pools present in the soil.

The occurrence and distribution of organic matter in relation to the soil architecture thus depends on a number of processes. Generally, soil can be conceptualized in two ways:

a. As a perfectly mixed homogeneous medium responding uniformly to outside influences, and

b. As a highly structured, heterogeneous environment with large zones of little activity and scattered 'hot spots' full of activity.
The majority of existing models of soil physical and soil chemical processes and even of soil food webs and soil C transformations, are largely based on concept a, while reality may be more like b. The degree of heterogeneity and its consequences are still poorly understood, however. Three fields of research should be considered in this context:
1. The selection and development of methods to observe and quantify patterns of heterogeneity at a large range of scales.
2. Knowledge of the processes leading to the dynamics (rise and fall) of the pattern of 'hot spots' of activity. In order to understand these processes knowledge is also required on whether heterogeneous patterns for various phenomena coincide or not, both in time and space, i.e. what is their spatial correlation (synlocation) and their temporal correlation (synchrony).
3. Knowledge of the consequences of soil heterogeneity for processes at a larger scale, or higher level of complexity.

In this chapter some recent developments in these three fields will be reviewed as well as conclusions and recommendations for future research presented.

II. Soil Architecture and Distribution of Organic Carbon on a Range of Scales

A. General

Soil architecture can be studied on a range of scales. On a dm scale, pedality (presence of peds) or aggregation (Figure 1) can be observed in profile pits with the naked eye and can be characterized with a hand lens (Soil Survey Staff, 1975). Details on surface or interior of the aggregates and peds are beyond the resolution of the naked eye and hand lens, however. Most of the voids and other features occurring in the groundmass can only be analyzed and interpreted with the use of optical microscopy. The groundmass itself consists of primary particles which also can be arranged in different ways (packing). Separate 'grains' may occur and often finer material is present. To study the arrangement and organization of coarse and fine material other techniques such as electron microscopy and X-ray diffraction are often required (Kooistra and Tovey, 1994).

An overview of the occurrence of different kinds of organic carbon in an agricultural soil profile is given in Figure 2. Although the bulk part of the roots generally occur in the ploughed layer, roots are commonly found deeper in the soil. Crop residues and organic manure are normally restricted to the plough layer. After ploughing, the residues and manures which were present at the surface occur in inclined zones, due to the inversion and lateral transport of the soil material by the plough share. The occurrence of fungal hyphae is often

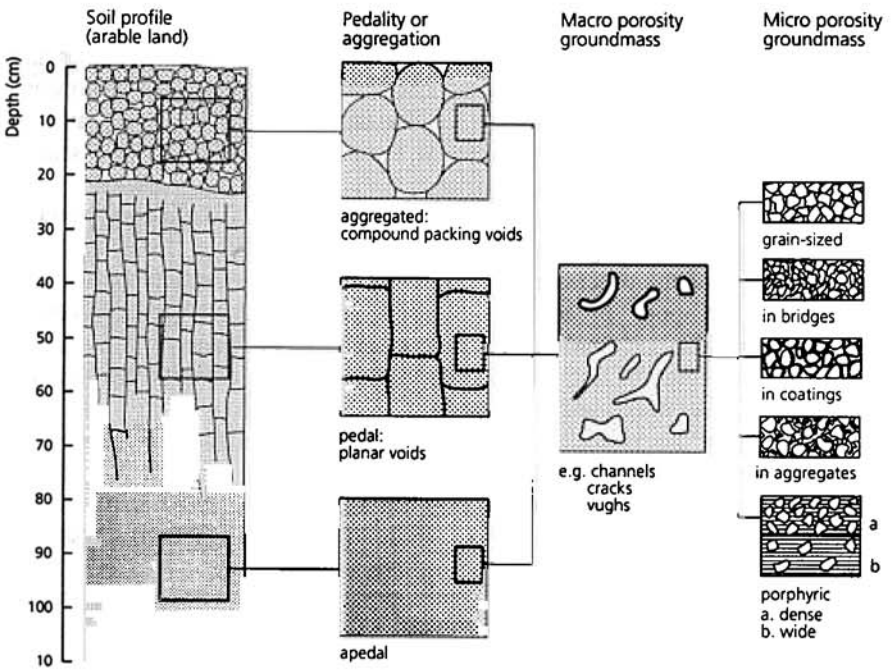


Figure 1. Overview of soil architecture scale range from field to microscopic level.

related to the locations of roots, but they may also be related to excrements, crop residues and organic manures, or be present in or adjoining voids. The bulk part of the meso- and macrofauna in agricultural land is present in the topsoil, but certain groups can also be found in the subsoil. Microorganisms can be found in the whole soil profile. Their greatest abundance is in the topsoil in and near accumulations of organic matter. The different kinds of organic carbon need to be observed and studied at different scales. An overview is given in the first columns of Table 1.

B. Methods to Observe Distribution Patterns of Single Phenomena

Profile Wall Observations

At a profile scale single phenomena can be marked with waterproof felt-pens on transparent sheets covering one of the cleaned and smoothened profile walls.

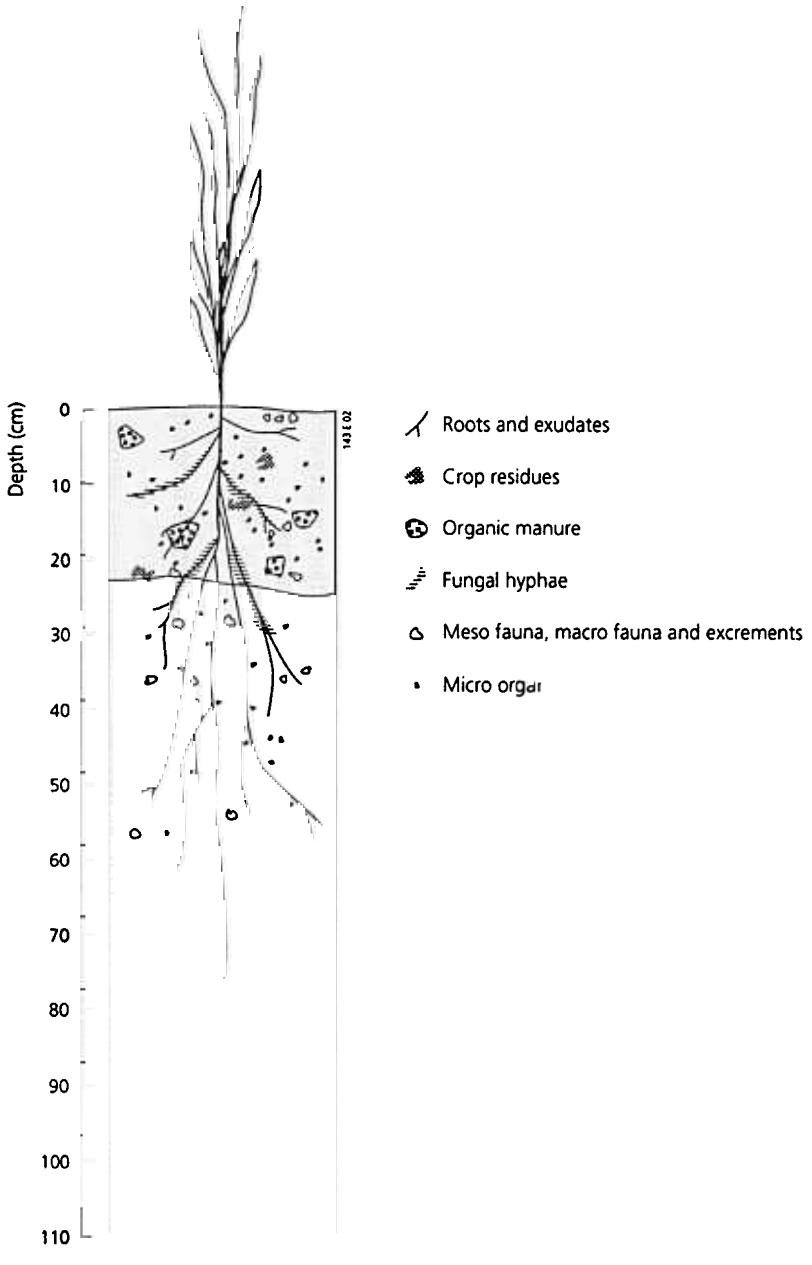


Figure 2. Overview of the occurrence of different sources of organic carbon in arable land.

Table 1. Patterns and processes influencing heterogeneity of soil organic matter sources at different scales

Organic matter source	Scale	Method to observe pattern	Process increasing heterogeneity	Process decreasing heterogeneity
Crop residues, green and brown manures		Profile wall observations, stratified soil sampling, thin sections	Soil tillage and residue incorporation, (Previous) crop heterogeneity, traffic, slaking	Soil tillage, selective feeding, meso- and macrofauna
(Dead) roots and exudates	dm, cm, mm	Profile wall observations, stratified soil sampling, thin sections: light microscopy	Patchy root growth, due to heterogeneous soil structure, soil fertility, or inherent branching pattern	Decomposition by soil microflora and fauna
(Dead) fungal hyphae	cm, mm	Stratified soil sampling, thin sections: light and fluorescence microscopy, SEM	Heterogeneous organic matter sources, heterogeneous macrovoid spaces	Decomposition by soil flora and fauna
(Dead) meso- and macrofauna	mm, μm	Stratified soil sampling, thin sections: light microscopy	Heterogeneous food supply, temperature, aeration, etc., movements and distribution (aggregated or dispersed) of organisms	Decomposition by soil flora and fauna
Excrements	mm, μm	Thin sections: light microscopy, SEM	Behavior of soil biota	Deaggregation
Microorganisms	μm	Smears, thin sections: fluor. microscopy, SEM	Heterogeneous food supply, temperature, aeration, etc.	Preferential grazing by soil fauna, diffusion
Humified organic matter from above sources	μm	Thin sections: light microscopy, SEM	Heterogeneous sources, physical aggregate formation	Soil consumption by soil fauna

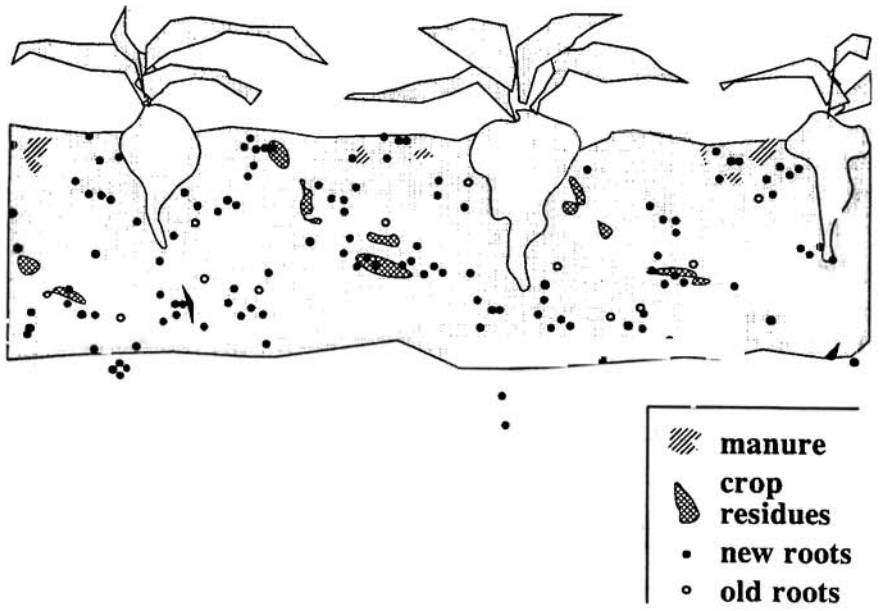


Figure 3. Schematic distribution of recent aboveground crop residues, recent organic manures, old and new roots in a sugar beet field in the plough layer.

The relevant organic features at this scale are roots, crop residues and organic manures. Figure 3 indicates schematically where aboveground crop residues, recent organic manures, old and new roots might be located in a sugar beet (*Beta vulgaris* L.) field under a certain tillage practice. Maps (1:1) of the real distribution of these features can be made in the field. The location of crop residues in the profile, as influenced by soil tillage operations, can be studied on profile walls made perpendicular to the direction of the main tillage operations. A length of several m may be needed, depending on the farm implements used, to cope with the spatial variability in depth and amounts of residues in the field.

Roots can be exposed by removing a few mm of soil from a fresh profile wall, by spraying with water, by blowing air over the surface or by carefully removing soil with a pin. The majority of roots will remain in place by such actions (Böhm, 1979). A considerable variation between laboratories exists in the way profile walls are prepared for this purpose and the absolute point density of observed roots should be calibrated with washed volumes of soil (Anderson and Ingram, 1993) to make quantitatively reliable conclusions.

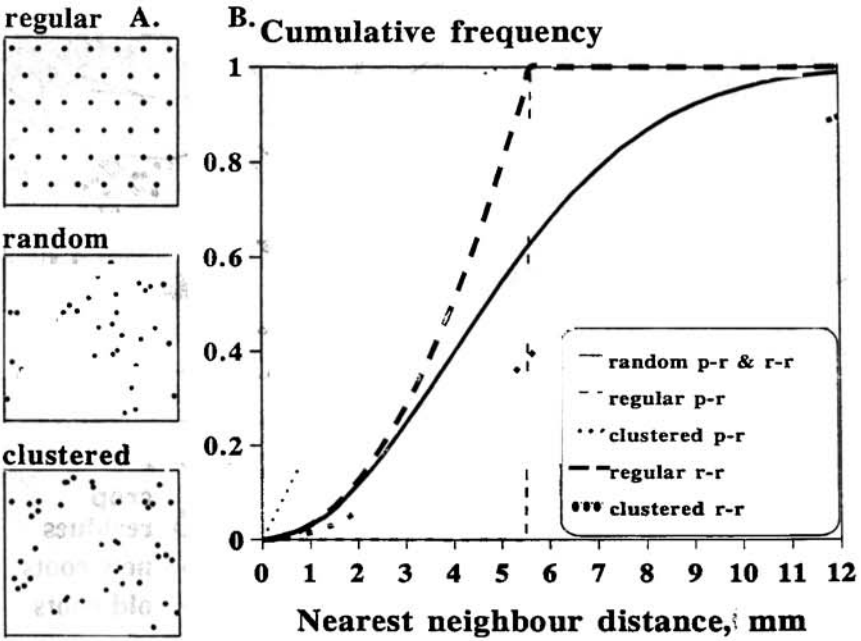


Figure 4. Basic types of point distributions - A: regular, random, and clustered, and B: cumulative frequency of nearest neighbour distances from root to root.

Figure 4 shows three basic types of point distribution patterns: regular, random, and clustered. Statistical tests of distribution patterns (Pielou, 1969) can conveniently be based on a comparison of the frequency distribution of nearest neighbour distances from roots to roots and from randomly chosen points to the nearest root. If roots are randomly distributed, the two frequency distributions are essentially the same (apart from sampling errors). In a regular pattern the root-root distances are larger, and the point-root distances on average smaller than in the random pattern. In a clustered pattern the root-root distances are smaller and the point-root distances larger. A simple test of the distribution pattern can be thus be based on the difference between the mean of the two types of nearest neighbour distances (Hopkins and Skellam test, quoted in Pielou, 1969). Analysis of root maps (or maps of any other point phenomenon) is normally based on digitization of the map, deriving the x,y coordinates of the points and a routine for selecting nearest neighbour distances (Diggle, 1983). In computerized image analysis, distance classifications of the whole map can routinely be based on a circular expansion around identified objects, as a circle of radius r contains all points within a distance r to the centre (Van Noordwijk et al., 1993a, b). Actual root distribution patterns may be random in local areas,

while being clustered when larger areas are considered. The root distribution is on one hand determined by the branching pattern, with branch roots originating from main axes and thus clustered to some extent, and on the other hand modified by soil structure and heterogeneity of soil conditions, which restrict or stimulate local root development. A study of the pattern as such does not allow distinction between these two pattern forming processes, however (Diggle, 1983). A two-parameter description of a large range of theoretical distribution patterns can be based on a layered Poisson process, where a variable number of offspring (intensity) of the pattern is randomly located within a certain distance (grain size) of parent points (Diggle, 1983; Van Noordwijk et al., 1993a,b).

The spatial distribution of recognizable plant residues on the profile in arable soils can often be understood from the soil tillage implement used. The pattern can be mapped, or quantified by grid based soil sieving (Staricka et al., 1991). The presence of cracks and (tillage-induced) zones of loose and dense soil can be similarly mapped. Figure 5 gives an example of the distribution of anaerobic, blue zones in the plough layer of a clay loam soil in early spring, in relation to tillage cracks. Statistical tests of uniformity (or randomness) of the distribution first require identification of a sampling unit, which is not as straightforward as for the point patterns.

Using a hand lens or a simple field microscope soil material from selected depths can be studied either *in situ* in small boxes or disturbed on a hard surface. The material studied can be obtained from a profile wall or from augering. The organic features studied vary from humus forms, faunal channel systems to fungal hyphae and generally concern occurrence, type and quantity in relation with depth. This method is used in the Pleistocene sandy areas of The Netherlands to map the occurrence of moder humus and plaggen soils as part of the mapping procedure of the soil map scale 1:50 000, viz. sheet 34 W/O and explanation (Bodemkaart, 1979).

2. Microscopic Observations

Microscopic analyses are required when smaller scale features need to be studied *in situ* or more detailed information is to be obtained. Microscopic analyses are performed by means of visible light microscopy using polarized light, and by submicroscopic techniques.

Submicroscopy is used when morphological or chemical information is required that cannot be obtained using light microscopy. Submicroscopy involves the use of instruments that analyze emitted radiation of wavelengths shorter than that of visible light. The most common techniques are scanning electron microscopy (SEM), transmission electron microscopy (TEM) and energy dispersive X-ray analysis (EDXRA) (Kooistra and Tovey, 1994). The methods available for preparing samples for microscopic studies, including the commonly

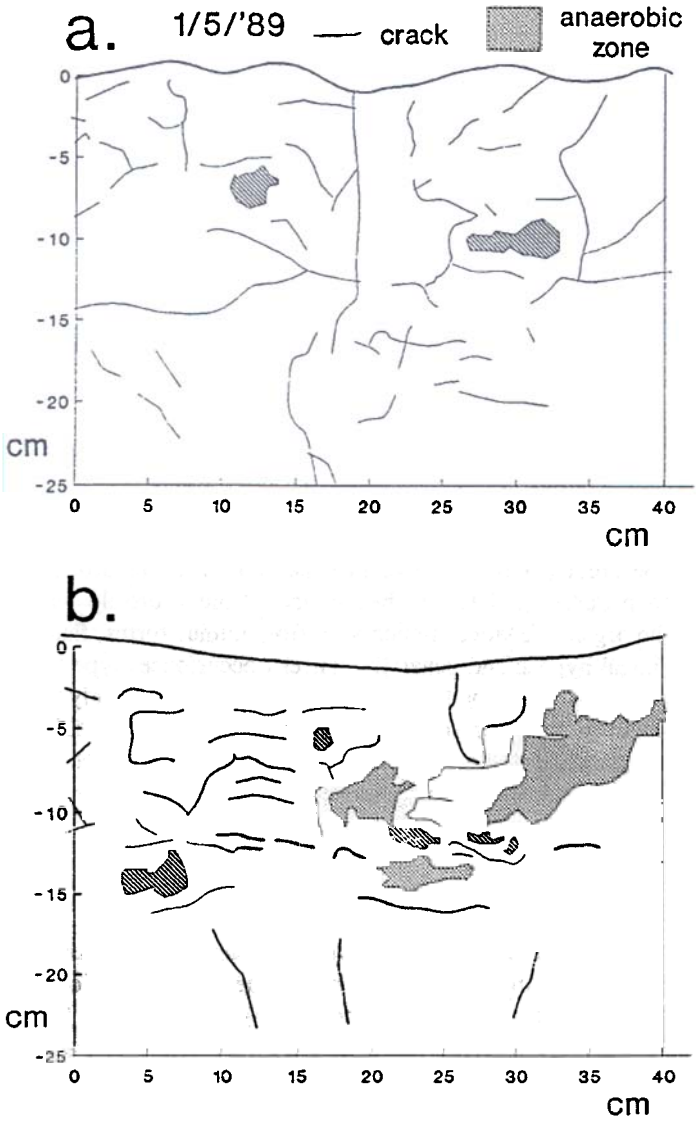


Figure 5. Maps of the plough layer in early spring of two plots (a. conventionally tilled, b. minimally tilled) of the Dutch programme on soil ecology of arable farming systems; hatched areas are anaerobic spots and lines the major cracks. Maps are made on polythene sheets.

used thin sections are summarized by Kooistra and Tovey (1994). The basic techniques for sample preparation in soil micromorphology are well documented in the literature (e.g., Jongerius and Heintzberger, 1975; Murphy, 1986; Whalley, 1979; Bennett et al. 1990). Specific sample preparations are required for research on organic materials and microstructure as they are very susceptible to shrinkage. Overviews of other techniques are given in Kooistra (1991) and Kooistra and Tovey (1994). The occurrence of organic materials can be studied qualitatively as well as quantitatively. Depending on the possibilities and research requirements, quantitative analyses can be performed using a microscope with a calibrated eye piece graticule or other types of grids, or digitized images can be analyzed using image analyzers. This permits the establishment of a number of characteristics, such as area/volume ratio, perimeter, number, length, width, orientation, position, shape factors and neighbour distances. An overview of the procedure used in light and submicroscopy is given in Kooistra (1991).

Two examples of the application of microscopic analyses are given here viz. the determination of water-conducting macrovoids and the study of the occurrence of bacteria in soil material.

A protocol was developed for studying the surface connectivity of macrovoids (Bouma et al., 1977, 1979). Large undisturbed columns of moist soil (16 cm x 15 cm x 8 cm) are carefully carved out in the field. They are slowly saturated with water in the laboratory from the bottom upwards to avoid entrapment of air. When the saturated water conductivity, K_{sat}, of these columns agrees well with the measurements of a larger group of columns, a solution of 0.5% methylene blue is ponded on top of the sample. Ponding is continued until the colour of the influent and the effluent has the same intensity. Afterwards the columns are cut into horizontal slices of 2 cm thickness each. Thin sections are prepared using the freeze-drying method to avoid contamination with methylene-blue stain on the walls of voids conducting water during the drying process. Quantitative analyses of the pore-size distributions are made on these thin sections using an image analyzer. Measurements were made on special photographs of the thin sections, obtained with crossed polarizing filters, causing voids to be black (Kooistra, 1991). Recently, however, measurements can be performed using a special CCD (Charge Coupled Device) camera whereby the thin section is placed between polarizing filters. A composite image of 5 separate images taken while crossing the polarizers from plane polarized light to crossed polarized light is computed on which all voids have the same gray level and are separated as such (pers. comm. D. Schoonderbeek). Voids with blue-stained walls are selected individually using an image-editing device or are computed from the previous images. The results for a layer from 35 to 45 cm depth in pasture land, arable land with a primary ploughpan and one with a recompacted ploughpan are given in Figure 6. Microscopic analyses of the