Advances in Soil Science

Structure and Organic Matter Storage in Agricultural Soils

Edited by

Martin R. Carter
Agriculture and Agri-Food Canada
Research Centre Charlottetown,
Prince Edward Island, Canada

B. A. Stewart
Dryland Agricultural Institute
West Texas A & M University
Canyon, Texas

CRC LEWIS PUBLISHERS
Boca Raton New York London Tokyo

Library of Congress Cataloging-in-Publication Data

Structure and organic matter storage in agricultural soils / edited by M. R. Carter, B. A. Stewart.
p. cm. — (Advances in soil science)
Includes bibliographical references and index.
ISBN 1-56670-033-7 (alk. paper)
1. Humus. 2. Soil structure. 3. Carbon sequestration.
I. Carter, Martin R. II. Stewart, B. A. (Bobby Alton), 1932– . III. Series: Advances in soil science (Boca Raton, Fla.).
S592.8.S78 1995
631.4'17—dc20 95-38348
CIP

This book contains information obtained from authentic and highly regarded sources. Reprinted material is quoted with permission, and sources are indicated. A wide variety of references are listed. Reasonable efforts have been made to publish reliable data and information, but the author and the publisher cannot assume responsibility for the validity of all materials or for the consequences of their use.

Neither this book nor any part may be reproduced or transmitted in any form or by any means, electronic or mechanical, including photocopying, microfilming, and recording, or by any information storage or retrieval system, without prior permission in writing from the publisher.

All rights reserved. Authorization to photocopy items for internal or personal use, or the personal or internal use of specific clients, may be granted by CRC Press, Inc., provided that $.50 per page photocopied is paid directly to Copyright Clearance Center, 27 Congress Street, Salem, MA 01970 USA. The fee code for users of the Transactional Reporting Service is ISBN 1-56670-033-7/96/ $0.00+$.50. The fee is subject to change without notice. For organizations that have been granted a photocopy license by the CCC, a separate system of payment has been arranged.

CRC Press, Inc.'s consent does not extend to copying for general distribution, for promotion, for creating new works, or for resale. Specific permission must be obtained in writing from CRC Press for such copying.

Direct all inquiries to CRC Press, Inc., 2000 Corporate Blvd., N.W., Boca Raton, Florida 33431.

© 1996 by CRC Press, Inc.
Lewis Publishers is an imprint of CRC Press

No claim to original U.S. Government works
International Standard Book Number 1-56670-033-7
Library of Congress Card Number 95-38348
Printed in the United States of America 1 2 3 4 5 6 7 8 9 0
Printed on acid-free paper

Soil Architecture and Distribution of Organic Matter

M.J. Kooistra and M. van Noordwijk

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

---

1-56670-033-7/96$0.00+$.50

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

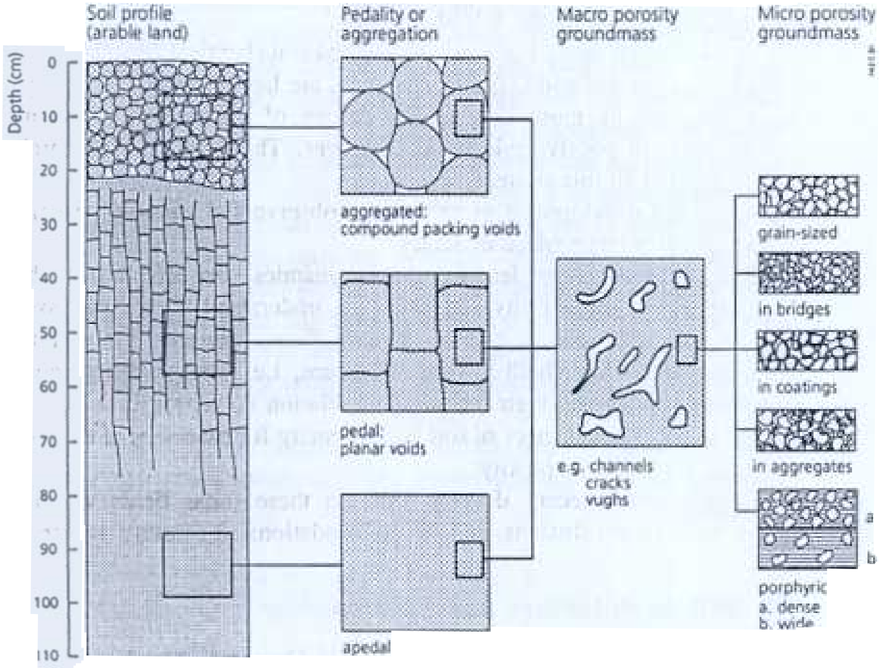

Figure 1. Overview of soil architecture scale range from field to microscopic level.

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

1. 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.

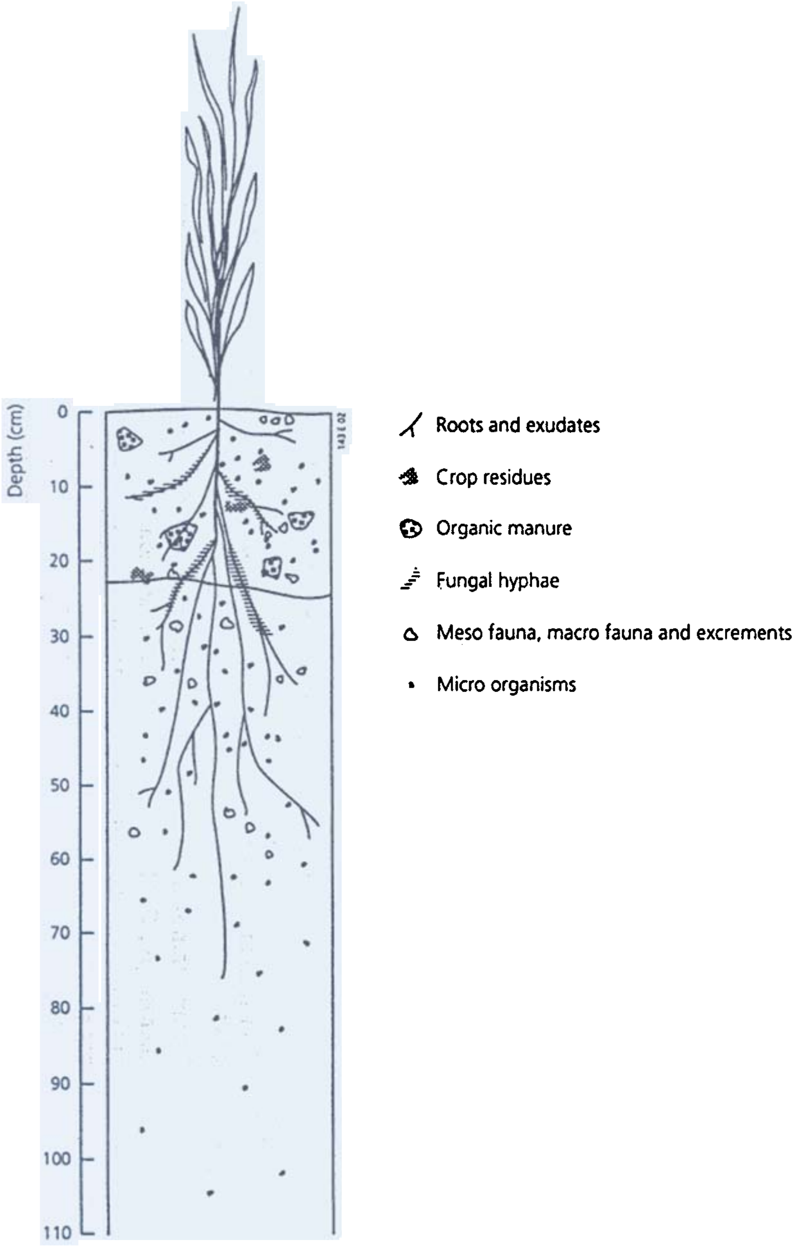

Figure 2. Overview of the occurrence of different sources of organic carbon in arable land.

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 residu, green and brown manures	m, dm	Profile wall observation, 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

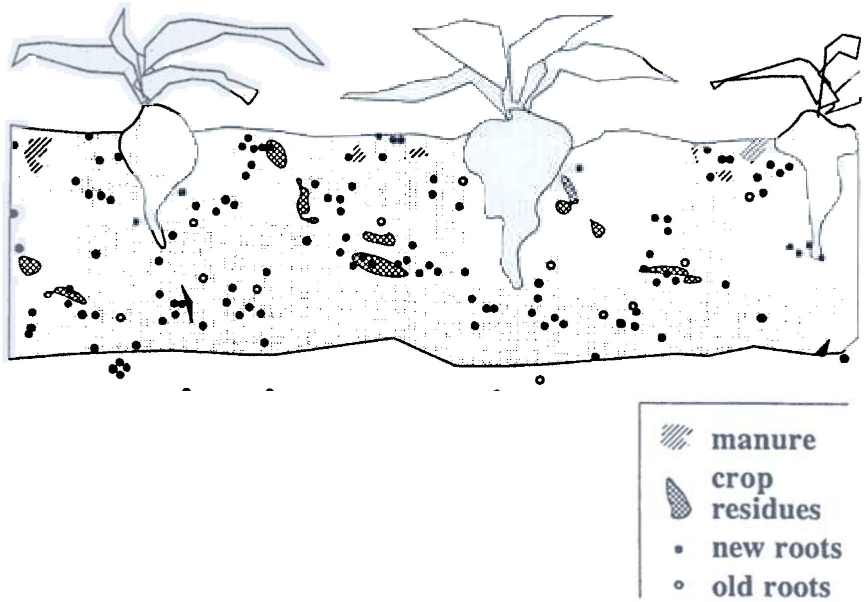

Figure 3. Schematic distribution of recent aboveground crop residues, recent organic manures, old and new roots in a sugar beet field in the plough layer.

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.

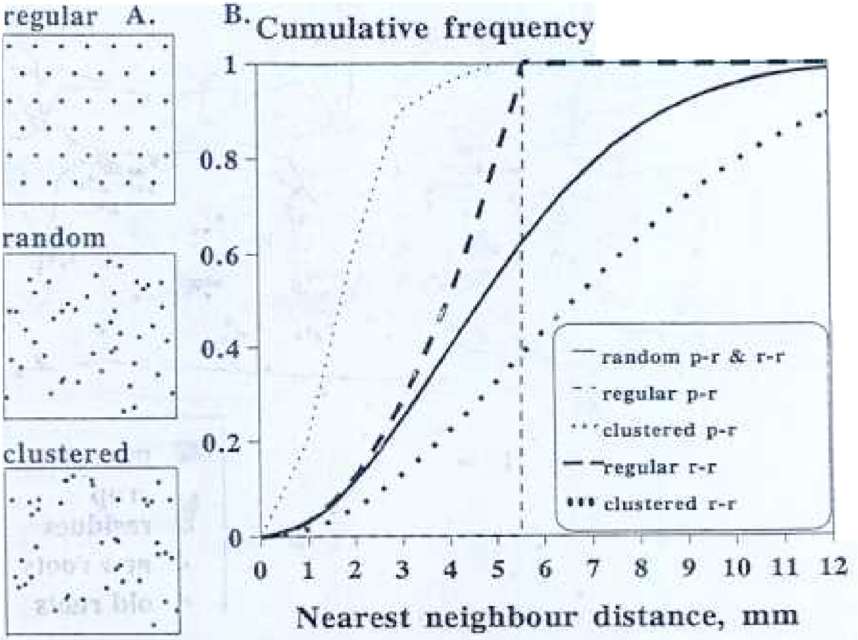

Figure 4. Basic types of point distributions - A: regular, random, and clustered, and B: cumulative frequency of nearest neighbour distances from root to root.

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

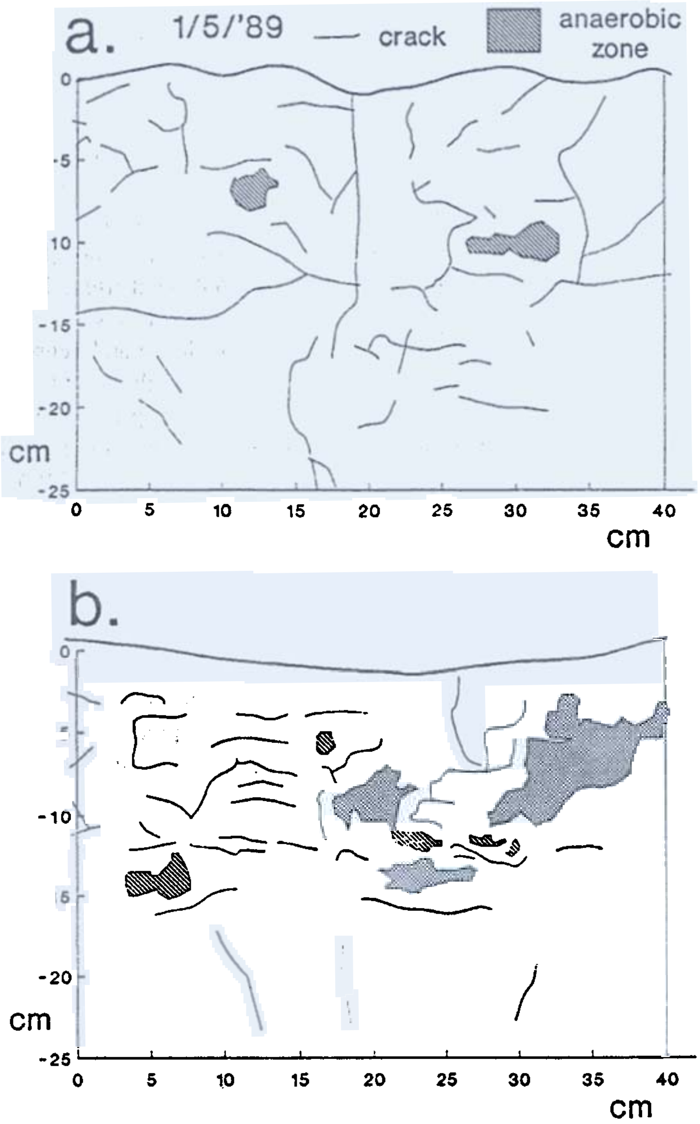

Figure 5. Maps of the plough layer in early spring of two plots (a. conventionally tilled, b. minimally tilled) of the Dutch programme on soil ecology of arable farming systems; hatched areas are anaerobic spots and lines the major cracks. Maps are made on polythene sheets.

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

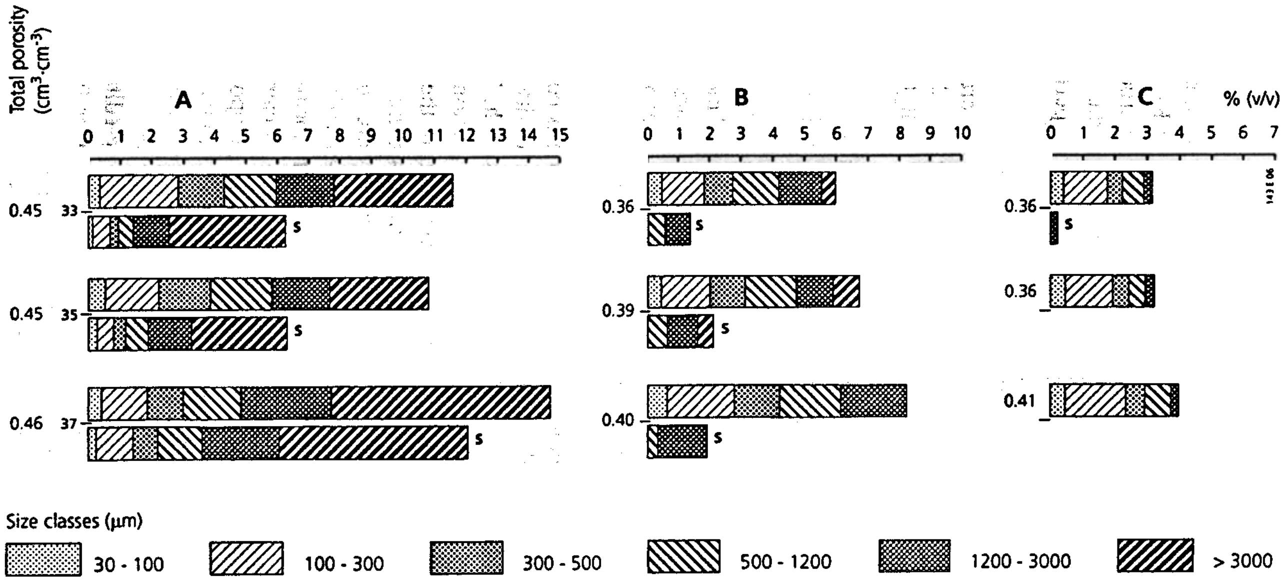

Figure 6. Total porosity and pore-size distribution by image analysis of horizontal thin sections of 33, 35 and 37 cm depth prepared from soil columns stained with methylene blue A. permanent pasture land; B. arable land with a primary ploughpan; C. arable land with a recompacted ploughpan, three years after deep tillage. s: proportion of voids with stained walls (adapted from Kooistra et al., 1985).

non-stained and stained voids explained the soil physical behavior of these layers and attributed to improved management of these soils (Kooistra et al., 1985).

During the last 10 years the staining of biological materials in soil thin sections has gained more attention to trace the presence of various groups of organisms. Non-fluorescent stains as well as fluorochromes are being developed (Altemüller and Haag, 1983; Tippkötter et al., 1986; Altemüller and Van Vliet-Lanoë, 1990; Postma and Altemüller, 1990). The latter aimed to examine the spatial distribution of certain bacteria strains and tested among other things the fluorescent brightener calcofluor white M2R. They developed a useful staining procedure, which is sufficiently documented for subsequent replication. The details are given in the referred publication. Bacterial cells, but also fungal hyphae and plant roots were clearly visible in relation to the groundmass. Most of the inoculated bacterial cells were detected, along surfaces of larger voids. Indigenous bacteria were less intensively stained and were found in smaller voids. The comparison to observations on stained soil smears suggested that some smaller cocoids, starving cells and bacterial spores remained unstained.

Single phenomena can also be studied when the soil material is disturbed. One of the most common phenomenon studied in disturbed soil material is the aggregate structure of soils. The size, quantity and stability of aggregates determined, reflect the local equilibrium of environmental forces which enhance aggregation or cause disruption. Kemper and Koch (1966) proposed a standard procedure for measuring aggregate stability, but modifications to the standard methodologies are increasingly being used. Nowadays the soil material can be disrupted with physical disruption as ultrasonic dispersion (North, 1976), with chemical dispersing agents (Tisdall and Oades, 1979), with gently misting and slaking (Elliott, 1986), dry-sieving (Gupta and Germida, 1988) and other methods. Beare and Bruce (1993) compared methods for measuring water stable aggregates and emphasized the value of comparing soil specific responses to different pretreatment procedures. They recommend that results of aggregate analyses be always accompanied by complete descriptions or references of the procedures applied, as these data can be critical to the interpretation of the data. Aggregate analyses are performed for different research questions varying from the structural stability in relation to faunal excrements to the physical separation of soil organic matter fractions.

A good example of the latter is the method for physical separation and characterization of soil organic matter fractions of different size classes developed by Cambardella and Elliott (1993). The method aimed to isolate and characterize soil organic matter fractions originally occluded within the aggregate structure to increase the current level of understanding about how the aggregate structure controls the turnover of soil organic matter. They improved the quantitative estimations of soil organic matter fractions in cultivated grassland systems. They concluded that adoption of reduced tillage management could be an important step towards the goal of sustainable production, which optimizes long-term profits to the farmer and minimizes damage to the environment.

Vittorello et al. (1989) combined a particle size fractionation (5 fractions sieved at different mesh sizes plus alkaline extractable C) with $^{12}C/^{13}C$ isotope ratios of the organic carbon for soil 12 and 50 years after conversion from forest to sugarcane. This isotope ratio allows distinction between organic material from plants with a C4 photosynthetic pathway (such as sugarcane) and material from plants with the more normal C3 photosynthesis. Their results show that 12 years after conversion, in the coarse sand fractions the majority of C was derived from sugar-cane and in the clay fractions 90% of the C still had a forest signature. Fifty years after conversion, about 70% of the clay fraction still had a forest signature. These data illustrate the importance of clay-organic matter linkages as C protection mechanism.

A recently developed method for fractionation of soil samples in suspended silica solutions of various physical densities, in combination with sieving (Meijboom et al., 1995; Hassink et al., 1993; Hassink, 1995) has a similar objective. Fresh plant material has a physical density of about 1 mg cm^{-3}; if organic material gets more and more associated with mineral soil particles (e.g. by faunal activity) it enters heavier fractions.

C. Spatial Correlation of Two or More Phenomena

All the methods dealt with in the previous section for describing the distribution of single phenomena *in situ* are also utilized to study the occurrence and spatial correlation of two or more phenomena. Depending on the research objectives more or less sophisticated qualitative methods are developed. The simplest way is a descriptive one for example noting that rare pollen grains as well as the few charcoal fragments, detected with microscopic analyses in thin sections of the subsoil, occurred in the partly infilled large root channels (Smeerdijk et al., 1994). A next step is the mapping of different phenomena on transparent sheets e.g. the occurrence of roots, cracks and crop residues in different soil horizons in a profile pit (see section B) or in thin sections. These results can be used for quantitative analyses, e.g. by means of an image analyzer.

Tests of spatial correlation can be based on the null-hypothesis of independent random distribution patterns. By quantifying the frequency of feature A in zones with increasing distance to feature B a simple test of synlocation is possible. Van Noordwijk et al. (1993c) gave examples of the distribution of roots and freshly introduced plant residues, quantified as a function of distance to the nearest macro voids in a soil profile. Two approaches are possible: enumerate all events x and determine their nearest neighbour of element y, or consider zones around all elements y with increasing distance and determine the density (number per unit area) of elements x. With image analysis computers the second approach is

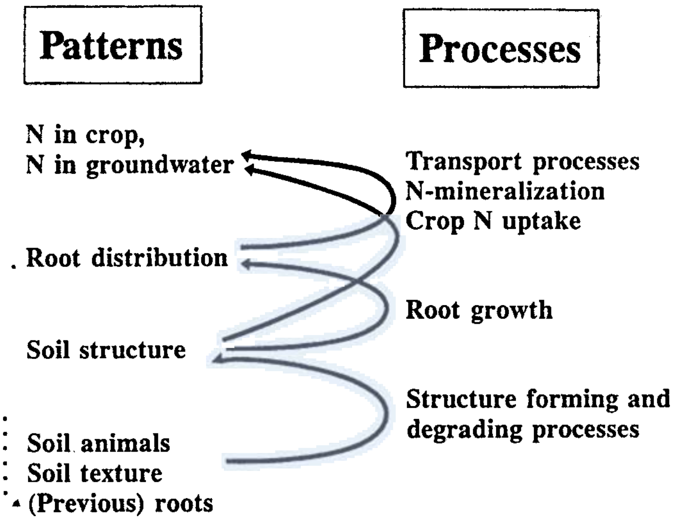

Figure 7. Chain linking patterns and processes from structure forming agents to N management.

preferrable and can run fully automatic, once elements x and y are properly identified and digitized.

III. Dynamics of Heterogeneity at a Range of Scales

A. General

The patterns of heterogeneity which can be observed with the methods of the previous section, are in a dynamic balance of rise and fall, due to counteracting processes. A causative chain of interrelations between "patterns" and "processes" can be developed (Van Noordwijk et al., 1993a), as patterns are derived from processes, but at the same time form the boundary conditions for such processes as well as those at a higher level of complexity. In general, patterns are more easily observed than processes, but processes can be better generalized and have a more universal value. In Figure 7 a possible chain linking the factors determining soil architecture with N management is summarized. This section is focused on the lower part of the chain, dealing with the processes (and underlying patterns) driving the dynamics of soil heterogeneity. These processes can lead to increasing or decreasing heterogeneity. The higher part of the chain is dealt with in the next section.

B. Processes Increasing Heterogeneity

Soil architecture is the dynamic result of many abiotic and biotic factors and processes. It may be difficult to imagine how heterogeneity, a non-uniform distribution, and patterns, a non-random distribution, can originate in a completely homogeneous environment. It is much easier to understand how existing heterogeneities are enlarged by processes taking place at different rates in the various micro-sites available. The basic, abiotic patterns with which biotic actors interact are: particle size distribution (texture) and gradients in soil water content, temperature and aeration between the soil surface and subsoil layers (with or without a water table). The latter group of patterns fluctuates in time with weather conditions. In non-cultivated land, the dynamics of heterogeneity in soil architecture are mainly governed by the weather regulating physical aggregate formation and biological processes. In cultivated land the human impact, viz. tillage, traffic and machinery, application of pesticides, fertilizers and manures, regulates the dynamics of heterogeneity in the topsoil throughout the year. The following subjects will be dealt with in more detail:

- physical aggregate formation,
- biological processes, especially plant roots and soil fauna,
- human impact (and related induced processes),
- preferential flow patterns.

1. Physical Aggregate Formation

The texture of the soil, especially the clay fraction ($\% < 2\ \mu m$), and the water content determine the basic physical soil structure. Depending on clay mineralogy and clay content, the soil material swells and shrinks upon wetting and drying. Due to desiccation shrinkage cracks are formed, which once formed reappear at the same place. These cracks may form specific patterns resulting in a pedal soil. Pedality is defined as the occurrence of individual, natural, soil aggregates or peds (Soil Survey Staff, 1975). The individual peds can be classified according to their shape and arrangement into prisms, columns, plates, blocky peds, granules and crumbs, delineated by planar voids. With increasing clay content of the soil the swell/shrink potentials increase and different kinds of pedality occur. Figure 8 gives an example of the different pedalities occurring in the subsoil of marine and riverine deposits in The Netherlands with increasing clay content. The figure shows that the various pedalities differ in range, but there are overlaps where more than one type occurs. Besides a stronger desiccation, the biological impact also plays a role in these overlaps. Between 8 to 30% clay the biological impact reaches a maximum, but the structure is still related to the physical swell/shrink potential of the soil. Desiccation is related

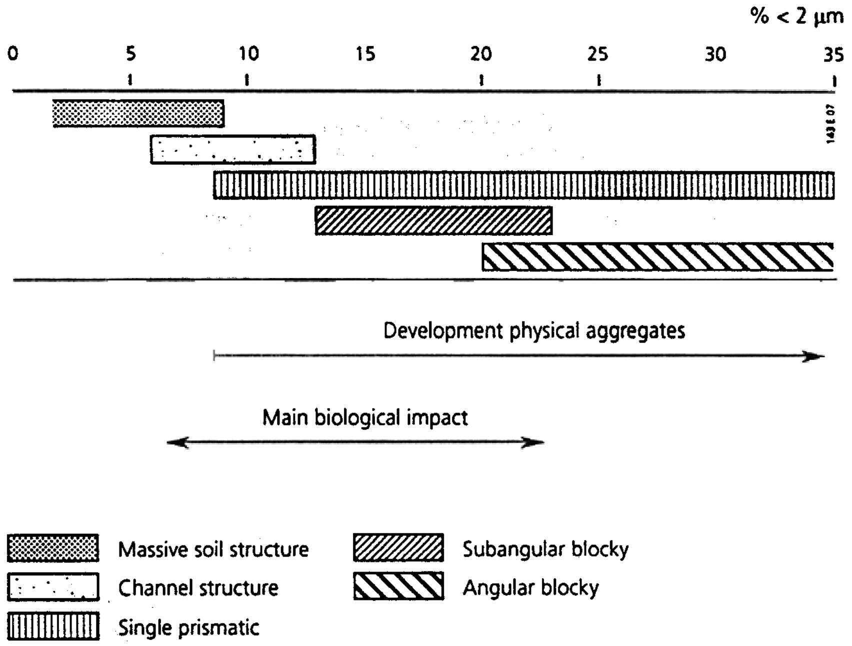

Figure 8. Pedalities occurring in the subsoil of marine and riverine deposits of The Netherlands with increasing clay content influenced by the physical aggregate formation and biological activity.

to the depth of water tables, the drainage and weather conditions. Soils with a high clay content, especially smectitic clays, strongly react on desiccation resulting in strong pedality. An example of this development, showing structure development on sedimentary deposits from sediment to vertisol is given by Blokhuis et al. (1990). The sequence in sedimentary deposits, subjected to a process of physical ripening (Pons and Zonneveld, 1965), starts with the development of widely spaced, wide and deep vertical desiccation cracks, followed by the formation of an angular blocky structure in the topsoil between the vertical cracks. Thereafter, large subhorizontal cracks develop in the ripening clays, which can be more horizontal, forming prisms that become subdivided into angular blocky structures (Inceptisols), or tend towards an oblique orientation, forming slickensides, that become subdivided into angular wedge-shaped structures (Vertisols).

2. Effects of Plant Roots

Roots not only give stability to the plant, they also regulate water, nutrient and oxygen uptake of the plant. Roots grow in such a way that they can fulfill these requirements. Roots, subsoil stem parts and filaments of algae produce channel systems by exertion of pressure on soil particles. Their diameter, more than their length, generally determines the effect on the soil. Roots and filamentous algae from about 40 μm in diameter can form lasting macropores.

They can produce systems of round channels which may be branched or not with different diameters. Roots often use available voids which they modify partly or completely by pressure during growth. In existing voids roots can adapt their own shape to a certain degree before modifying the void in which they grow (Figure 9a). Roots growing in larger voids can produce root hairs extending to the solid soil material to fulfill their nutrient requirements (Figure 9b). In the tilled zone of cultivated land, roots generally follow voids formed by tillage operations. Only a small percentage of the voids are primary root channels, which varies per crop and farm-management system. Sugar beet roots in a study of three cropping systems in The Netherlands in 1985 produced hardly any primary root channels in the tilled layer under conventional (i.e. moldboard ploughing, 20 to 25 cm) soil management, 0.4% in an integrated farming system (i.e. reduced N fertilization and pesticide use; and shallow tillage, 12 to 15 cm) and about 1% in a minimum tillage system. About 5% of the tillage voids in the conventional system were modified by the sugar beet roots and the percentage of modified voids in the integrated farming system and the minimum tillage system were not significantly higher (Kooistra et al., 1989). Below the tilled zone and in natural environments roots generally follow the cracks between the peds and faunal voids or former root channels which they all can modify to some extent.

If roots follow preexisting voids they will have no or only partial contact with the soil, except when they completely fill or expand a preexisting void. If, on the other hand, roots penetrate in the groundmass they will initially have a complete root-soil contact (100%). The degree of root-soil contact is an important parameter in studies on oxygen, water and nutrient uptake by plant roots (De Willigen and Van Noordwijk, 1987). Root-soil contact can be analyzed in thin sections which are freeze-dried before impregnation to avoid shrinkage of the roots. Analyses of maize (*Zea mays* L.) roots grown in pot experiments with soil material compacted to different bulk densities showed that roots do not shrink and that all root cross-sections are recognized (Van Noordwijk et al., 1992). In this pot experiment the degree of root-soil contact between the depths 9 to 14 cm was found to increase from 58 to 90% while soil porosity decreased from 60 to 44 % (Kooistra et al., 1992). The highest bulk density, corresponding with a total porosity of 44% reflect compacted layers in sandy loam soils. These soils are very susceptible to waterlogging after showers

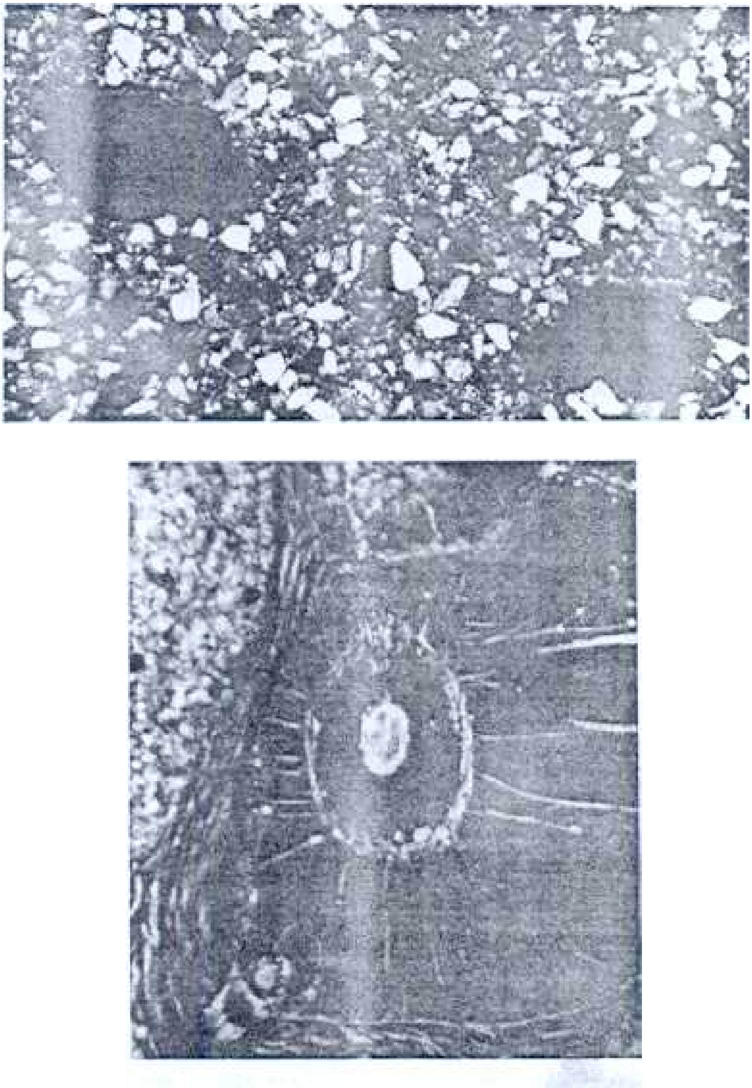

Figure 9. Roots in arable soils, a: modification of the root shape by growing into an existing void; b. production of roothairs when growing in large existing voids (magnification a: x 25; b: x 12).

and an average root-soil contact of 90% may be the limit for adequate oxygen supply. The lowest bulk density reflects a situation in which root growth is becoming limited in field situations. Here adequate nutrient supply seems to become the limiting factor, which is related to an average root-soil contact less than 58%. Root-soil contact of field grown winter wheat (*Triticum aestivum* L.) growing in 1990 in two of the above mentioned agroecosystems was quantified in horizontally oriented thin sections at 15, 25 and 45 cm depth (Van Noordwijk et al., 1993d). One day before sampling the soil surface was ponded with a methylene blue solution to stain surface-connected voids. The two fields, conventional and integrated farm management had different frequency distributions of root-soil contact in the plough layer. The percentage of roots with 100% root-soil contact was 65 and 37, and those with 0% root-soil contact 5 and 14, respectively. The average root-soil contact in the plough layer was 84% for the conventional and 66 % for the integrated system. The roots without direct contact with the soil were mainly growing in surface-connected, continuous voids, which rarely have aeration limitations. The roots with 50-100% root-soil contact were mainly the smaller roots occurring in non-stained voids. Below the plough layer, in the natural subsoil, the root-soil contact was less. In these two farm management systems, the soil structure in the plough layer was different. In the integrated system, the macroporosity of the soil was more than double (15% and 6%, respectively) than the conventional system and the biological impact by soil fauna was much larger resulting in a more open structure (Boersma and Kooistra, 1994). The existing porosity and its stability influences largely the root growth and root-soil contact of the crops in the plough layer. With increasing clay content, roots more and more follow existing pedal cracks, especially when 2:1 lattice clays are concerned.

Decaying root channels can be a major determinant in water infiltration patterns, e.g. where natural forest has been cut and the land is used for crop production in the humid tropics (Van Noordwijk et al., 1991).

3. Effects of Soil Fauna

The soil fauna is comprised of those animals which pass one or more active phases of their life cycle in the soil. They occur in the soil for several reasons e.g. protection, food and reproduction and their effects on the soil can be multifold. Their main impact on soil architecture is that they produce voids and excreta, whereby soil material, both organic and inorganic, can be dislocated, organic material fragmented, and mineral and organic material mixed. The basic products, voids and excreta, are considered in more detail below.

Many species produce voids, most of which are channels, but also other types of voids occur. Channels can be straight, curved or very convoluted, with or without branching or chambers. They can resemble root channels, but are rarely

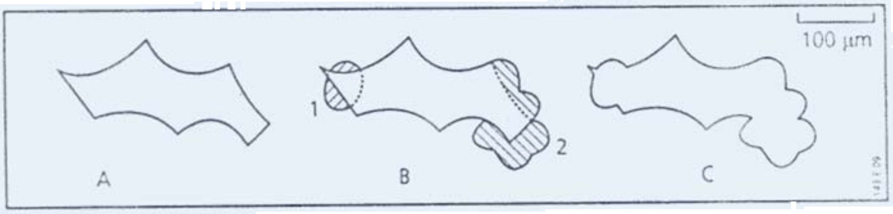

Figure 10. Modified void (c) developed from a void between earthworm excrements (a). In one end (b1) a root found its way; on the other end (b2) small mites modified the void.

as regular as these. The primary voids are formed in three ways: by pressure exerted on soil materials, by digging and removal of loose material and by soil consumption. Voids formed by pressure mainly occur in loosely packed, and in wet, plastic soil material and can be formed for example by worms and snails (Kooistra, 1978). Digging occurs in all kinds of soil materials. The result can be very regular channels as made by the dung beetle (Brussaard and Runia, 1984) or very irregular voids as made by termites. Also the digging purposes differ. Beetles dig to lay eggs at a specific depth and termites to collect fine-grained soil material for building and stabilization purposes. The same variety is found in voids due to soil consumption. Even within one group of soil organisms different void systems are produced. Earthworms, e.g. *Allolobophora longa*, can produce simple channel systems, while, e.g. *Hyperiodrilus* spp. and *Eudrilidae* can consume virtually all fine-grained soil material in specific zones in the soil in humid tropical forests (Kooistra et al., 1990). Soil animals also enlarge existing voids locally, which can be any type from cracks to root channels or other faunal voids. Necks in voids systems can be enlarged or cavities made in walls. Resulting voids can be very irregular (Figure 10). Many organisms can modify voids, especially mesofauna such as mites, collembola and enchytraeids. Void systems produced by soil fauna can start at the surface, but also deeper in the soil from existing voids. With increasing clay content, the effects of soil fauna become more restricted to modifications of existing cracks between the peds. Two features, produced by soil fauna, occur associated with faunal voids. These are wall plasters or coatings and cocoons. Plasters consist of fine-grained soil material or material from excrements. Termites generally use aggregates of fine-grained soil material, while earthworms use excreta, which are often darker coloured than the surrounding groundmass due to admixtures of organic material. The plasters occur in voids used for longer periods. Cocoons can locally be found in faunal void systems and consist of fine-grained soil material mainly derived from excrements. Earthworms can produce cocoons as retreat or hatching place for eggs (Figure 11a).

Recognizable excrements are only produced by soil fauna consuming solid materials, organic as well as inorganic. Excrements can be recognized by their shape, composition and/or organization. Many shapes can be distinguished, e.g. spheres, ellipsoids, cylinders, bacillocylinders, grooved plates, mammillated

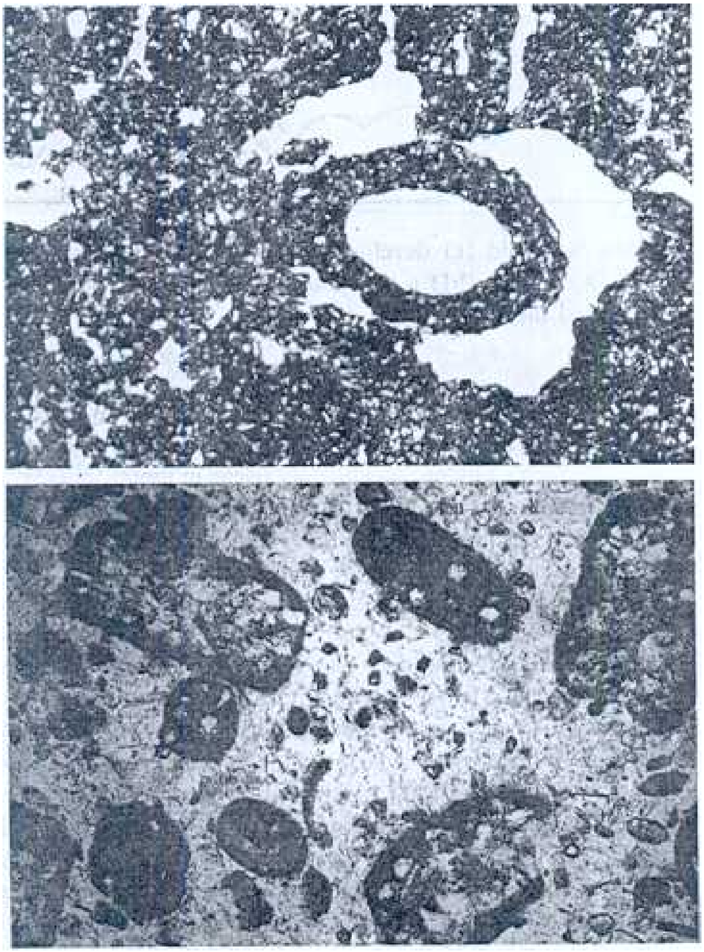

Figure 11. Faunal products, a. a cocoon produced by an earthworm; b. different shapes and composition of excrements in marine sediment, produced by pelecypods, worms and snails (magnification a: x 2.5; b: x 45).

excrements and threads (Bullock et al., 1985). Together with their size, some shapes can be ascribed to specific soil fauna. Excrements can be composed of only organic material or mixtures of organic and mineral material. The organic material is very varied and the mineral material is often fine-grained and has a distinct upper grain-size limit, which can be used for identification of the species (Figure 11b).

Shaped excrements can be organized as single units which either are loose or dense packed or form more or less coalescing units. Excrements of all shapes and organizations can partly or completely fill faunal voids. Mites, enchytraeids, diplopods and isopods generally produce accumulations of individual units, while earthworm excreta is more or less coalesced. Depending on the species, faunal voids can also be infilled with shapeless excreta (e.g. earthworm species), or be infilled with soil material by the soil fauna (e.g. dung beetle).

The impact of soil fauna is not only related to their population size but also to their mobility and activity. Sessile soil fauna, even if numerous, may have less impact on the soil architecture than mobile species, which always move around in search for food, protection or oviposition sites. On the other hand, a few distinct faunal channels produced by sessile soil fauna can have far more impact on soil physical parameters (Edwards et al., 1993) than the partly filled in tracks with soil material and/or excrements of the mobile soil fauna. In temperate climates and in forests the impact of the soil fauna is highest in the A horizon. In climates with extremes in temperature and dryness the highest impact is found in deeper horizons (Kooistra, 1982). Faunal voids often cross or follow for some distance cracks or root channels. In arable land soil fauna can produce more voids systems than plant roots, which mainly follow existing voids.

4. Human Impact

Human impact on soil architecture can be due to soil tillage, traffic (esp. at harvest time) and slaking. Soil tillage practices, especially the main or primary tillage, have the largest influence. During tillage the soil is loosened and partly pulverized as well as often mixed and inverted, whereby forming aggregates separated by rough-walled, irregular voids. Afterwards, by natural settlement, traffic and other cultivation activities, the aggregates merge. Thus, the continuity of the tillage-induced voids decrease, while isolated voids remain (see Figure 12). In the first month after ploughing and during the seedbed preparation most of the increased porosity disappears (by about 40% at both times) (Kuipers and Van Ouwerkerk, 1963). The soil is again loosened after the harvest. Tillage voids gradually become modified by soil organisms. Plant roots predominantly follow the irregular voids between the aggregates. With increasing bulk density and growth of crops their impact increases. Mesofauna enlarge necks between void systems or locally ingest fine-grained soil material. The macrofauna produce channel-like tracks on the surface of the aggregates and/or produce channel systems in aggregates, whether or not connected to the surface. The largest part of the voids occurring in arable topsoils are voids due to tillage (Figure 13). In topsoils of a conventional farming system in The Netherlands tillage voids during the years occupy about 90% of the total macroporosity

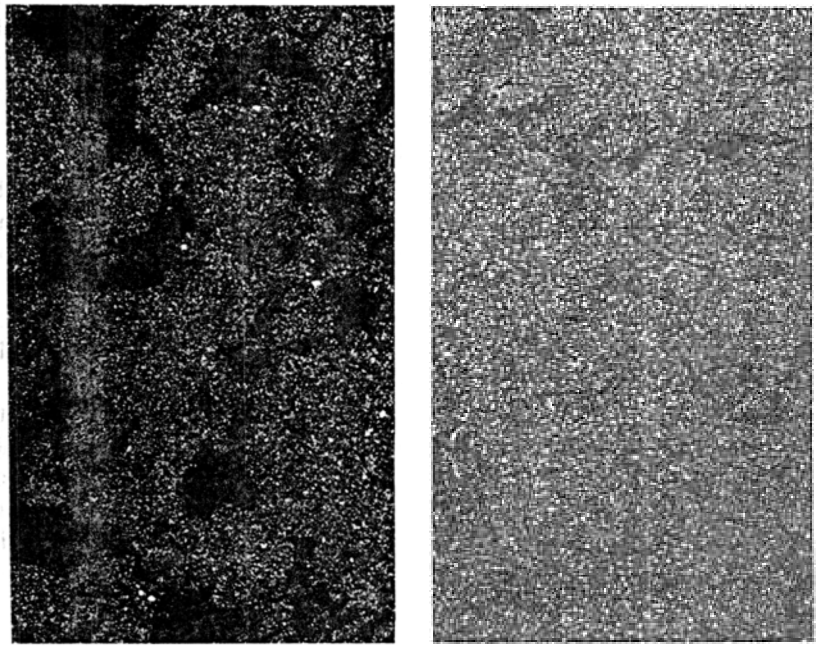

Figure 12. Settlement of soil aggregates after tillage. a: soil structure about a month after ploughing; b. soil structure after seedbed preparation (magnification a, b: x 2).

(> 30 μm diameter voids); in an integrated farming system they occupy 5-10% less as result of the increased impact of soil organisms (Boersma and Kooistra, 1994). Shrinkage cracks, starting from tillage voids, are included in this group, but they contribute only a minority of the volume occupied.

The equipment used in agricultural engineering has increased in size and weight over the last decades. This development has led to increased soil compaction and deformation of the groundmass and to rut formation. Existing voids are reduced in size and changed in shape during passage of wheels. They may become disrupted, closed or can disappear completely. A reduction of the volume occupied by voids with diameters > 100 μm by 3% (v/v) or more, and an increase on the volume of the voids < 100 μm is also common, resulting in an only slightly decreased total porosity (Kooistra, 1987). The stress exerted decreases with depth and continues below the tilled layer (Koolen et al., 1992). Maximum compaction, however, generally occurs between 4 to 8 cm depth

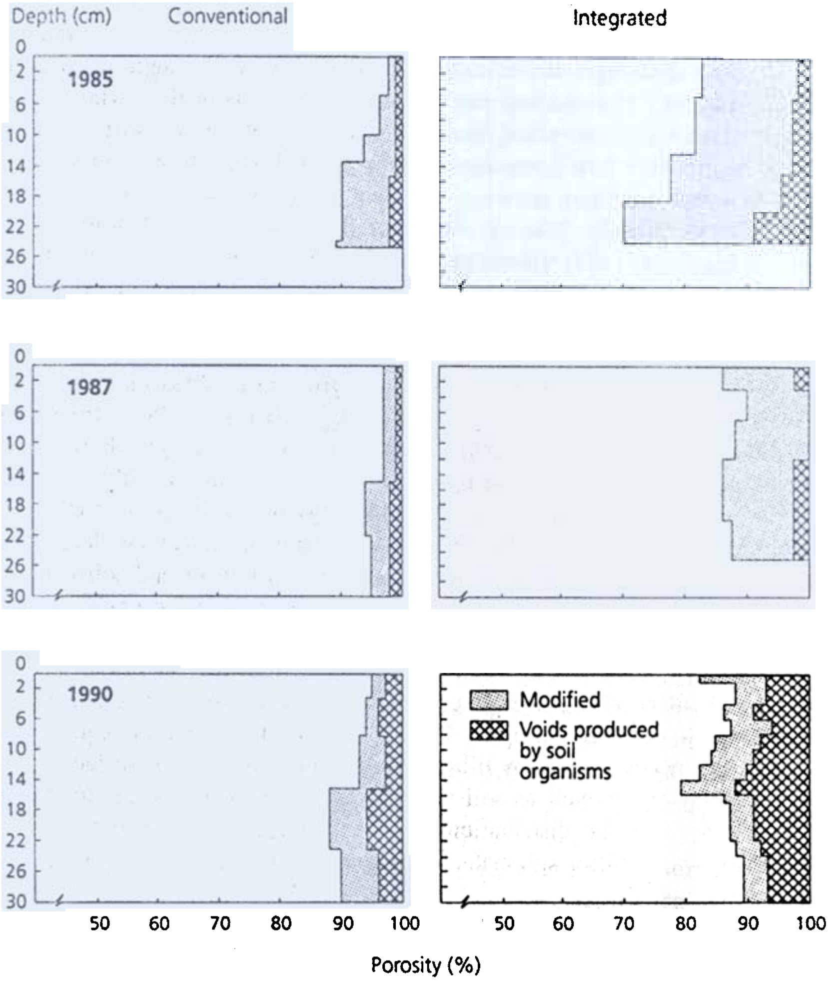

Figure 13. Proportion of biological induced voids as part of the total macroporosity (voids with diameters > 30 μm) in 1985, 1987 and 1990 in a conventional and integrated farming system.

(Tanaka et al., 1988), due to the deloading effect at the surface. This often results in the soil in the formation of sets of small horizontal cracks. These cracks can also be formed below the wheels driving over the furrow bottom during ploughing, which gives the platy appearance to ploughpans. Where these sets of cracks occur in the tilled zone most tillage voids have disappeared (Słowińska-Jurkiewicz and Domżał, 1991). When the soil is brought under cultivation, the surface soil is regularly tilled and the land is bare during several months of the year. When tilled and bare, the impact of wind and rain often lead to a disintegration of soil coherence. This starts with the aggregates at the surface. The disintegrated soil material can form crusts at the surface. When transport takes place, the soil material can move along the surface as soil erosion or flow downward into the soil as internal slaking. Microscopic studies reveal that there are many types of erosional and depositional crusts occurring in all climates (Courty, 1986; Kooistra and Siderius, 1986; Valentin and Ruiz Figueroa, 1987; Valentin and Bresson, 1992). Crusts cause restricted infiltration and limited plant germination due to their sorted, often laminated composition, lacking continuous voids. Transport of soil material along the surface due to wind and water erosion occurs on a large scale and is one of the main processes that takes place in areas with increased desertification. Also internal slaking occurs on a large scale. In the American soil classification "Soil Taxonomy" (Soil Survey Staff, 1975) a special diagnostic horizon, the agric horizon, has been defined to characterize the results of internal slaking. The illuviated soil material from the surface is deposited in voids where it forms coatings or complete infillings. The illuviated material can be deposited at any depth in the profile, depending on the present voids, quantities of water and soil material, and kind of soil material. Internal slaking results in a decrease of the total porosity and reduction of the continuous voids, which are essential for maintenance of water and air regimes and transport processes in the soil.

Repeated tillage also causes fragmentation, deformation and compaction of features due to the human impact. Although meant to loosen and equalize the soil, the aggregates formed by tillage can contain or consist of surface crusts, compacted layers, as well as soil material with infilled voids due to internal slaking. Moreover the distribution of crop residues etc. is also not evenly distributed. The resulting soil material is therefore often far more heterogeneous than natural soils.

5. Preferential Flow Patterns

In soils with large non-capillary sized voids, water and solutes flow via these voids. Large voids are cracks or planes formed by physical aggregate formation of soil tillage operations, or channels produced by roots or soil macrofauna. Coloured dyes and other traces are used by many investigators to determine and analyze large water-conducting voids (e.g. Ehlers, 1975; Bouma et al., 1977; Kooistra et al., 1985) The continuous water-conducting voids usually constitute only a few percent of the total void space and void necks have a substantial effect on the rate of flow. Dead-end voids and void necks are important locations where water with solutes can infiltrate into the soil matrix. Depending on the continuity of the macrovoids, water can bypass large volumes of soil (e.g. Bouma and Dekker, 1978; Bouma et al., 1982; Van Stiphout et al., 1987). Due to this bypass flow the effect of added fertilizers or pesticides can be restricted as their solutes can be leached deep into the soil (e.g. Dekker and Bouma, 1984; Steenhuis et al., 1990) and can cause contamination of groundwater.

Preferential flow of water in unsaturated soil need not to be restricted to large void systems. Also in zones without large void systems, the water and solutes often infiltrate in fingered patterns. Vegetation can cause uneven infiltration of rain water. Isolated trees with a 'funnel' shaped canopy, which have a high rate of stem flow, can cause deep water infiltration under their stem as found in African savanna vegetation (Knapp, 1973). These wetting patterns can, besides vegetation, also be caused by microtopography, soil layering and water repellency. When fingered flow occurs, the spatial variability in soil moisture content can be very high (e.g. Dekker and Ritsema, 1995). These patterns can be found in sandy soils as well as in clay and peat soils.

Also on a smaller scale preferential water flows have various consequences. Depending on the local soil architecture, increasingly smaller voids receive water that form films along walls or fill small voids. In these environments, microbial activities take place, depending on the presence of substrate, water tension and related diffusion of solutes and gasses, and the distribution of void diameters. McGill and Myers (1987) calculated that only about 40% of the volume of voids is small enough to retain water and is large enough to permit entry of microbes. Combined with the above mentioned decisive factors, microbial activity would take place in a smaller percentage of the occurring voids. Moreover, microorganisms are not equally sensitive to the water potential for their activities. Consequently, microenvironmental conditions are often so heterogeneous that in spots near to each other simultaneous apparently exclusive processes can take place, e.g. N mineralization or immobilization. In general, the presence and accessibility (which implies the distribution of continuous void-systems) of substrate, and the preferential wetting patterns are the main factors determining microbial processes.

C. Processes Decreasing Heterogeneity

Processes leading to heterogeneity can, when occurring at higher intensities and/or over a longer time-span, lead to homogeneity as well. This may be true, for example for the impact of soil fauna and for human impact by cultivation practices. A reduction of heterogeneity can be due to the fact that a process, such as channel formation, is gradually occurring in the whole soil matrix. A process which directly leads to a decrease of heterogeneity is diffusion of chemical compounds and organisms in the soil, which is driven by concentration gradients.