Reprint no. 207

THE ROLE OF MICROMORPHOLOGY IN AGRICULTURAL RESEARCH

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STICHTING VOOR BODEMKARTERING / NETHERLANDS SOIL SURVEY INSTITUTE

REPRINT FROM: P. BULLOCK AND C.P. MURPHY (EDS.): SOIL MICROMORPHOLOGY. VOL. 1: TECHNIQUES AND APPLICATIONS. AB ACADEMIC PUBLISHERS, BERKHAMSTED, 1983: 111-138

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THE ROLE OF MICROMORPHOLOGY IN AGRICULTURAL RESEARCH

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ABSTRACT

Soil micromorphology is applied increasingly to several aspects of agricultural research, of which the most important are: (1) the influence of a change of land use on soil structure and humus forms; (2) the influence of moving implements and machines on the structure of the tilled layer; (3) the effects of zero-tillage; (4) the effects of crop rotations on the soil fabric; (5) the mechanisms of slaking; (6) the effects of fertilizers and straw mulch on microfabrics; (7) causes and effects of compactions occurring directly beneath the Ap horizon; (8) the effects of drainage, soil loosening and deep ploughing; (9) the micromorphometric analysis of patterns of water flow, in particular in heavy clay soils; (10) the effects of irrigation on the soil fabric; (11) the relationship between microstructure and root development; (12) effects of soil amelioration and (13) the influence of soil erosion on soil structure. The paper concludes with some comments on guidelines for micromorphological research in agriculture and on future developments.

INTRODUCTION

The application of soil micromorphology in research into soil-related agricultural problems has been considerable for many years. This paper looks at some thirteen different applications and considers possibilities for the future.

THE INFLUENCE OF A CHANGE OF LAND USE

Forest versus Arable

Altemüller (1957), comparing an Alfisol developed in loess under forest with one cultivated for at least 100 years, concluded that the original spongy structure formed under forest, changes completely to a structure consisting of compact aggregates under arable cultivation. Crust formation (see 'Surface slaking') is also a common feature on arable soils. Kowalinski (1960) noted a decrease in grade of development of soil structure in the cultivated layer of Polish black earths compared with the top layer of the same soils under forest. In sandy podzolic soils of the Netherlands the originally crumb or pellety moder fabrics occurring under forest often degrade on arable land to a 'debris' fabric, i.e. a fabric of skeleton grains covered by coatings of disintegrated pellety material (Jongerius and Schelling, 1960; Jongerius, 1961). Canadian Grey Luvisols under forest are characterised in their surface layers by moder fabrics which,under arable conditions,are transformed into complex fabrics of discrete and coalesced matric micro-aggregates and vughy porphyric material (Pawluk, 1980).

Heath versus Arable

Frercks and Puffe (1964) found that the surface layer of an uncultivated heath-covered ombrogenous bog raw humus, when drained, limed and put down to grass for many years, is transformed by the activity of small soil animals and micro-organisms into a kind of moder (bog moder). These results agree with those of Jongerius and Pons (1962 a and b) for Dutch peat soils. In the north-western part of the Netherlands large swamp areas occurred up to the Middle Ages. Gradually, drainage was improved and, as a result, the area became used as grassland. Jongerius and Jager (1964) found that the original anmoor associated with the swamp changed into an intergrade to mull, characterised by a crumb structure in the top layer. After World War II much land was ploughed up for tulip cultivation, a measure that initiated rapid slaking and compaction in the cultivated material notwithstanding an organic matter content of 15% or more and a clay content of at least 25%. This behaviour is characteristic of anmoor soils (e.g. Van Heuveln et al., 1960; Jongerius and Pons, 1962 a and b).

Grassland versus Arable

Differences between the structure of surface layers of soils under old grassland,or many years of ley,and under arable land respectively,have also been studied micromorphologically. Silt loam soils that have been under grassland for over 100 years in the south-western part of the Netherlands are characterised in their surface layers by very dark, stable, crumb or granular aggregates and a very high interpedal porosity. When ploughed, the structure gradually degrades due to decreasing faunal activity and organic matter content, effects of pressure and shear forces by machinery, and slaking. In the course of time the structure of the Ap of such a soil can deteriorate to compact apedal or weak angular blocky. Medvedev (1979), comparing chernozems under ley for more than 25 years with those under cultivation, reported a considerable deleterious change in size, shape and internal fabric of aggregates under the influence of cultivation.

THE INFLUENCE OF MOVING IMPLEMENTS AND MACHINES

The influence of machinery on the ploughed layer of some sandy loam soils was studied by Bouma (1969) using, among other methods, micromorphology. These soils can have a microstructure characterised by agglomeroplasmic to intertextic related distributions, but, if the moisture content of the soil material is sufficiently high, application of pressure and shear forces by machinery may result in puddling. This is a process whereby clay domains slip over each other, forces causing an internal load and limit to swelling are inactivated and more water will be taken up. Thin sections of soil material puddled at different moisture contents showed that in the wet puddled soil intergranular spaces are totally filled with swollen plasma, and that, on drying, the plasma becomes concentrated around skeleton grains, leaving fine intergranular voids. In an air dry state the consistency of such a structure is hard. When remoistened, the plasma does not swell to its original volume, intergranular voids remain, and the consistency remains slightly hard. If the wet puddled soil is only slightly dried, its consistency is friable, and remoistening then forms a weak, plastic soil material. Compression experiments on aggregates of natural and artificially puddled materials respectively showed that compression increases with moisture content and that puddled material has a higher compressibility at a certain suction than non-puddled material. This is due to the fact that at a certain suction the puddled material has a higher moisture content than the non-puddled material.

It follows from the above that machines and implements used on wet soil may cause rapid strong compaction of the surface layer. Murphy et al. (1977) described micromorphologically and micromorphometrically the effect of compaction by tractor wheels in a field experiment (Cavenham Compaction Experiment). The microstructure of the uncompacted top soil was vughy, and that of the compacted one consisted of large plates, in which more or less rounded voids occurred. The latter were much smaller than the vughs occurring in the uncompacted soil. Jongerius (1973) reported an immediate formation of a thin (usually just a few mm) strongly compacted zone at some depth in the Ap horizons of Dutch sandy loam soils due to harrowing at relatively high moisture content (Fig. 1.). In soils of loamy sand texture ploughing under very wet conditions may lead to a total loss of the binding between soil particles (complete puddling) and subsequent formation of a banded fabric (Van der Meer and Willet, 1964; Jongerius, 1970: lamiconcentration).

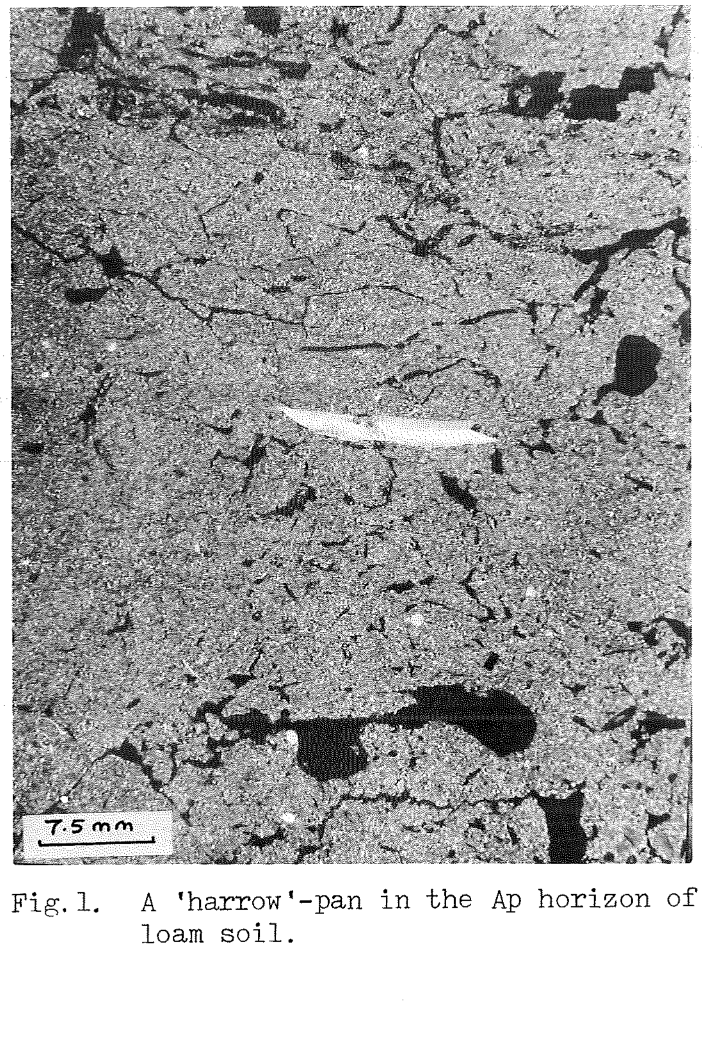

Fig. 1. A 'harrow'-pan in the Ap horizon of a sandy loam soil.

Pawluk (1980), studying the effects of tillage on Canadian Grey Luvisols micromorphologically, concluded that tillage operations in these soils were more significant for fabric than fertilizer treatments and differences in crop rotation.

Finally, it should be stressed that compaction of the surface layer due to puddling can also be caused on pasture by trampling of cattle. This phenomenon was investigated micromorphologically by Reijmerink (1967), Beckmann and Smith (1974) and Von Buch (1978).

THE EFFECTS OF ZERO-TILLAGE

Boone et al. (1976) compared the differences in soil structure between ploughing and 5 years zero-tillage on a fine-textured Dutch river levee soil. In the spring the ploughed soil contained many vughs and relatively few channels and craze planes, whereas by the autumn, vughs in particular, disappeared to a large extent. Zero-tillage produces a denser soil in which, in spring and autumn, only few vughs and channels are found whereas craze planes are common. Yet, the zero-tillage soil contained more voids < 100 μm than the ploughed soil, but void continuity was not much improved.

THE INFLUENCE OF CROP ROTATIONS

Internal slaking in Dutch sandy loam soils is suppressed to a large extent by the insertion of some years of ley, lucerne or green-manuring in the crop rotation. This was shown by a field experiment in which four different crop rotations were compared: (1)the traditional rotation for the area; vetch-potatoes followed by endive-lettuce followed by endive-cauliflower followed by tulips; (2) vetch-potatoes followed by phacelia-lettuce followed by phacelia-lettuce followed by phacelia-vetch followed by tulips; (3) vetch-lucerne-lucerne-lucerne followed by tulips; (4) vetch-grass-grass-grass followed by tulips. Qualitative and quantitative analyses of thin sections of samples of the Ap horizons taken one year after conclusion of the experiment showed considerable differences in soil structure (Jongerius, 1972; Reijmerink, in preparation). Rotation 1 showed strong internal slaking and, as a consequence, only a few isolated, mainly very small voids. Rotation 2 was somewhat more porous, but the soil material was still predominantly apedal. In rotation 3, however, a rather weak but evident development of a subangular blocky structure was

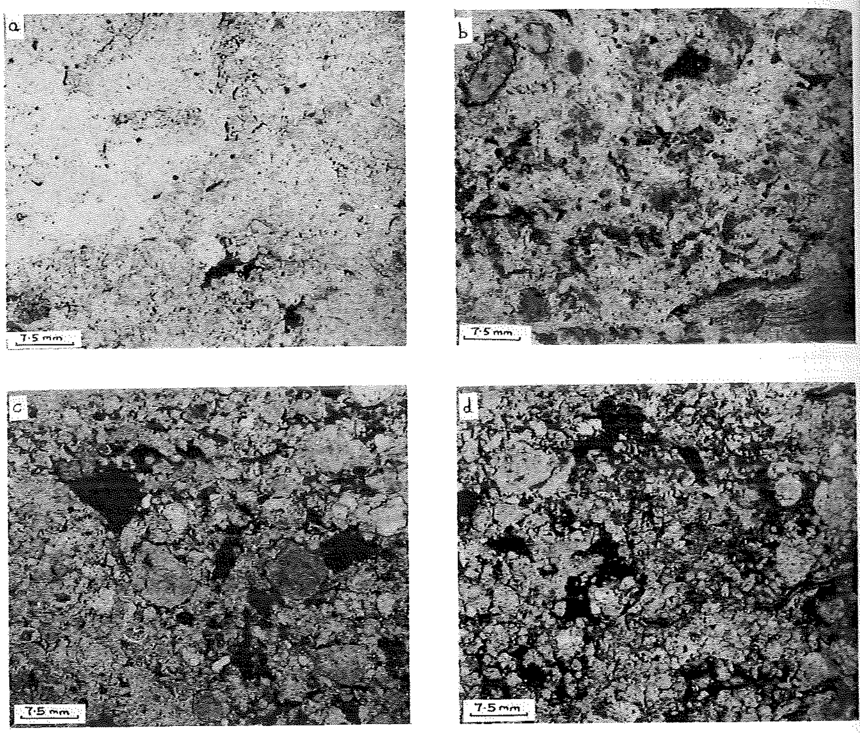

Fig. 2. The influence of different crop rotations on the microstructure of a sandy loam soil: (a) Object 1: very compacted soil material due to internal slaking; (b) Object 2: predominantly apedal soil material, but nests of voids; (c) Object 3: a developing subangular blocky structure, a continuous pattern of voids of different shapes and sizes; (d) Object 4: a highly porous crumbly structure.

observed together with a continuous pattern of voids of varying shapes and sizes. Rotation 4 showed a highly porous crumb structure (Figs. 2 and 3).

Jongerius and Jager (1964), investigating Dutch humic gley soils macro- and micromorphologically, found that cultivation of potatoes could have a favourable influence on the structure of the Ap horizon, whereas beet cultivation was very dangerous for structure. These differences were mainly due to harvesting procedure.

Pawluk (1980) noted that the formation of granules (micro-aggregates of 150-200µm) in Grey Luvisols was more pronounced if grasses and cereals were grown in rotation than if a wheat-fallow rotation was applied.

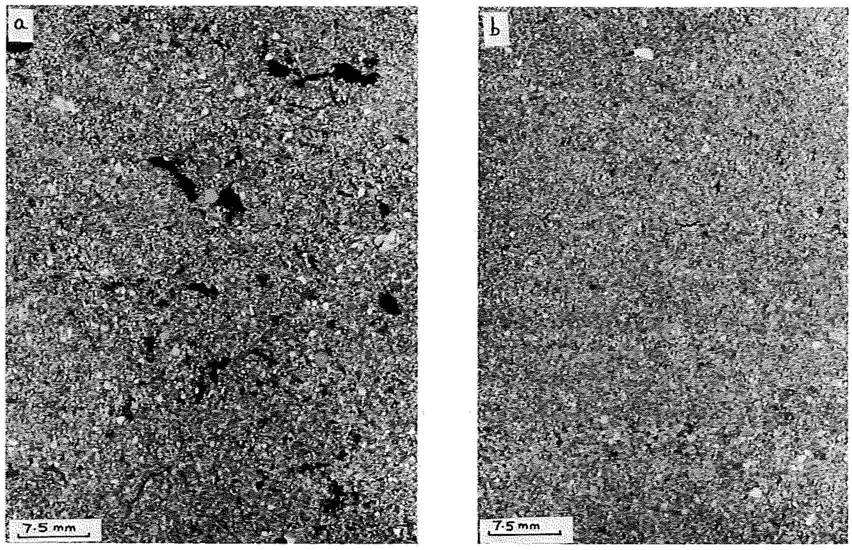

Fig. 3. A loamy coarse sand before (a) and after (b) vibration.

Swietochowski and Jablonski (1964) investigated micromorphometrically the effect of two types of crop rotation on Polish sandy loam soils: (1) potatoes-oats-lupin-rye and (2) potatoes-oats-rye-rye, and compared these with black fallow and fallow under natural vegetation. Samples were taken three times during the growing season in the crop rotations, and in the fallow fields. The average content of voids > 80µm was lowest in rotation 1 (20.4%), followed by the black fallow (20.8%), rotation 2 (21.7%) and the fallow under natural vegetation (24.8%). The order with respect to the average content of humic aggregates > 80µm was: rotation 1 (14.7%), rotation 2 (16.9%), fallow under natural vegetation (18.3%) and black fallow (19.6%). However, within the different fields strong variation occurred in the values during the growing season.

SLAKING

This phenomenon has been strongly emphasised in micromorphological research. Slaking can occur easily on arable and horticultural land that has a weak or moderate water-stability in the cultivated layers. Jongerius (1970, 1972, 1973) observed three types, namely surface slaking (or diruconcentration), internal slaking (or satuconcentration) and internal slaking following micro-erosion (abruconcentration). The first two types in particular occur frequently.

Surface Slaking

Surface slaking is a crust formation due to the impact of rain drops and subsequent or partial destruction of aggregates at the surface, followed by washing and sedimentation of separated particles and/or aggregate fragments into holes between clods. In serious cases a field can become entirely flattened and sealed by a fine laminated crust that is very compact and hard when dry. However, some crusts may also be rather porous and contain many micro-aggregates (Falayi and Bouma, 1975). In laminated crusts the soil particles, particularly the fine ones, usually exhibit a clear orientation parallel to the surface (e.g. Pagliai and La Marca, 1979), but this phenomenon may also be only weakly developed (Evans and Buol, 1968). Dense crusts can have deleterious effects upon seedling germination, water permeability and run-off. In the Netherlands (Jongerius, 1970), surface slaking occurs mainly on soils with a low content of clay and/or organic matter, and small amounts of iron compounds or Ca ions. However, as already stated, slaking can also occur on soils with a high content of anmoor humus. It was found that the time (autumn or spring), and the kind of tillage (degree of grading of the aggregates before a rainy period), duration of the soil cover, undersowing of grass crop rotations with green manuring, lucerne or ley farming, and manuring with earth-foam can all strongly influence the extent to which crust formation occurs. Falayi and Bouma (1975), studying crusts of Typic Hapludalfs on Miami silt loam with 26% clay in the tilled layer, found that a high surface roughness due to ploughing resulted in higher infiltration, and a later start to run-off, than a small surface roughness due to plough-disk-harrow treatment. They also found that on ploughed land, hydraulic conductivities of crusts formed on tops of clods were significantly higher than those of crusts formed in holes between clods. Pagliai and La Marca

(1979) reported that very compact crusts can occur on Italian Fluvisols and Ferralsols with clay contents of 27.8 and 38.6% respectively. Laboratory experiments proved that sodium increases the formation of a dense crust, whereas calcium and iron prevent crust formation to a large extent. Similar conclusions were drawn by Ferry and Olsen (1975). Evans and Buol (1968), studying the effect of cropping sequences on crust formation, found, on the same kind of soil, a very dense crust on a permanent cotton field, a rather porous crust on a field of cotton after alfalfa in the three preceding years, and a very porous crust on a barley plot in a cotton-barley rotation. Finally, Pagliai and La Marca (1979) and Pagliai et al. (1980) noted that application of dextrans to Fluvisols had a favourable effect by reducing crust formation (and on the material underneath), because such compounds increase the porosity of the soil material. SEM studies of crust formation have been made by Chen et al. (1980).

Internal Slaking

Internal slaking is the collapse of the structure of a cultivated layer or the lower part of it due to saturation with water, i.e. a moisture content of the soil material that exceeds the upper plastic limit. Bouma (1969) investigating laboratory experiments micromorphologically, attributed such a collapse to plastic deformation of aggregates. However, Jongerius (1970, 1972, 1973) found that under these hydrological conditions the soil material separates and freed soil particles move downwards and become sorted. During drying the material sets into a speckled compact layer (whitish spots of silt and fine sand). Internal slaking is usually coupled with a low water-stability, but it can also occur in rather water-stable materials provided that the moisture content for a certain period clearly exceeds the upper plastic limit. Such a situation can occur if the groundwater rises up to or just beneath the Ap horizon and/or if a compact layer (a plough pan or an abandoned furrow) occurs just beneath the cultivated layer. A remedy against this very severe form of structure deterioration is thus a more intensive and/or deeper drainage and grubbing, together with changes in the crop rotation for soils with a low water-stability.

EFFECTS OF FERTILIZERS AND STRAW MULCH ON MICROFABRICS

Kubiena (in: Ronde, 1958) investigated micromorphologically the influence of inorganic fertilizers on humus forms in two manuring experiments in Bavarian forests. The first experiment concerned a 52 years old pure stand of Scots pine characterised by peaty raw humus on dystrophic anmoor. The A_0 horizon consisted mainly of larger, only little altered, plant remnants, whereas the A_1 horizon (the dystrophic anmoor) consisted largely of intact plant remnants, some weakly humified brown fine organic substances and bare quartz grains. About 1½ years after manuring with 200 kg N/ha as gaseous NH_3, the humus form changed considerably, the amount of plant fragments strongly decreased, many dark-brown fungal hyphae occurred, and in the packing voids between the quartz grains large quantities of microaggregates consisting of strongly humified and coalesced arthropod excrements were found. Also 3000 kg $CaCO_3$/ha + 174 kg P_2O_5/ha given as superphosphate + 200kg N/ha in the form of gaseous NH_3 caused a distinct increase in the humification of the raw humus, worm excrements, and illuviation of humic substances in the mineral soil. In a weakly developed podzol with raw humus over weakly developed coarse moder on an A_2 horizon under a 72 year old pure stand of Scots pine, 2000 kg $CaCO_3$/ha + 5000 kg superphosphate/ha and 2000 kg sulphate of potash-magnesia + 2000 kg N/ha as gaseous NH_3 brought about an increase in humification of the raw humus, formation of dark brown arthropod excrements, and illuviation of humic substances in the A_2 horizon.

The effects of long-term topdressings on the microfabrics of two permanent hayfields laid out in 1856 and 1897 respectively, in Great Britain were investigated by Barratt (1967). Plots without top dressing were characterised by mullicol-argillicol intergrade microfabrics and a somewhat matted top-layer. Potassium fertilizers had little influence on the microfabrics. Ammonium sulphate promoted the formation of mor humus forms (microfabrics in the L and F horizons: humiskel; in the H horizons: pelleted humicol; and in the Ah_1 horizons: pelleted mullicol), on mullicol-argillicol intergrades. Superphosphate led to formation of mull-like mor humus forms. Organic fertilizers and liming to pH around neutrality promoted the formation of pelleted mullicol over vesicular mullicol microfabrics, and sodium nitrate or an increase of the pH with lime or basic slag to about 6.1 gave rise to vesicular mullicols

Humification of straw left on the surface of soils was investigated micromorphologically by Sauerlandt and Graff (1959) and Altemüller and Banse (1964). They found that it was transformed to a large extent by soil animals that breakdown and mix the straw with mineral soil material, producing excrements varying from purely organic to nearly purely mineral in composition. Dressing with acid chemical fertilizers (e.g. superphosphate) causes proliferation of fungal mycelium in the straw debris, a development not characteristic of alkaline chemical fertilizers such as calcium cyanamide and calcium carbonate. Turelle and McCalla (1961), investigating the differences in structure between corn plots on silty clay loam soils, ploughed and stubble-mulched respectively for a 20-year period, noted that the aggregates following the latter treatment were more porous. Sauerlandt (1960) reported on the favourable effect of a compost of straw, garden refuse, pig manure, blood meal and some nitrogen on crumb formation. Altemüller and Banse (1964) emphasised the importance of soil micromorphology for the investigation of humification occurring in different kinds of compost. A striking example given was the strong difference between a stable manure mixed with soil, and 5 and 1% superphosphate respectively. In the first case, after 4 years the straw fragments were still clearly visible and intact, whereas in the second case the material was totally transformed into faecal pellets. Pawluk (1980) observed, in cultivated Canadian Gray Luvisols, the formation of a weak mull plasma component and a higher organic matter content in plots that had received chemical or organic fertilizers. A considerable improvement of soil structure of a Dutch sandy loam arable soil originally in a poor physical state was reported by Bouma (1969) after 25 years of liming, dunging and green-manuring. Tang (1978) proved micromorphologically that 20 years of fertilizing (and intensive cultivation) on loessial deposits in Shansi (China) caused the formation of organo-mineral complexes and compound aggregates and a high, very heterogeneous porosity. These changes resulted in an excellent permeability and drought resistance. Application of organic and chemical fertilizers (Jongerius and Pons, 1962 a and b) or liming (Frercks and Puffe, 1964) also causes a considerable moulding of peats if combined with good drainage.

COMPACTION DIRECTLY BENEATH Ap HORIZONS

Compaction can arise in various ways.

1. The most common type of compaction is the traffic sole or plough-pan. Such a layer is usually formed by pressure and shear forces applied to the bottom of the plough layer at moisture contents at which puddling may occur (mecapedocompaction: Jongerius, 1970). Such a layer may considerably reduce the downward flow of water which in turn promotes internal slaking. It may also hamper root development. In Dutch marine soils, most pronounced compaction of this kind is found in silt loams containing <11.5% clay (Jongerius, 1970, 1972). The traffic sole may reach a thickness of 10cm or more, but micromorphometric analysis showed that it is usually the upper 1cm zone that is most strongly compacted (Jongerius, 1972; Anon., 1973).

2. A decrease in depth of tillage can lead to strong compaction of the abandoned furrow. This phenomenon has been studied micromorphologically by, among others, Altemüller (1957, 1959: "verlassene Krume") and Jongerius (1970, 1972: desti-pedocompaction). Such layers may be apedal and nearly without microscopically visible voids, with the exception of a few straight planar voids. They occur particularly in unstable materials (loess, marine silt loams) and are due to a marked decrease in animal activity and reduction of organic matter by micro-organisms. Their formation is accelerated by the development of a plough-pan that causes a contact break with the recent Ap, and/or by a periodical rise of groundwater into the zone of the abandoned furrow (Jongerius 1972). Initiation of an abandoned furrow in cultivated Gray Luvisols was described by Pawluk (1980): already two years after a decrease in depth of tillage from 18 to 10cm, the lower section of the Ap (10-18cm) had lost its pedal structure and was reorganised to vughy porphyric. However, provided that a soil is well drained and reasonably stable, abandoned furrows can maintain a good structure (e.g. Bouma , 1969).

3. Vibration due to heavy machinery (vibropedocompaction: Jongerius, 1970 , 1972) may cause considerable compaction down to 80-100cm below the surface even if the soil is only exposed to it for a short time. Large voids in particular are lost. Micromorphometric analyses show, for instance, that in a loamy coarse sand at about 30cm depth, 70% of the voids >300µm were lost after a heavy tractor with its engine running had stayed for a short period on a

particular spot (Fig. 3).

THE EFFECTS OF MOLE DRAINAGE, TILE DRAINAGE, DEEP SOIL LOOSENING AND DEEP PLOUGHING

Mole Drainage

Already in the 1950's the effect of mole drainage at 50 to 60cm depth on Austrian loamy stagnogley soils was studied micromorphologically by Blümel (1956). Mole drainage appeared to strongly loosen these soils. The direct mechanical effect was the formation of the drains and 2 to 5cm slits extending from the surface to the drains and a crack formation due to the lifting action of the plough. The slits, in which loosely-packed soil aggregates occurred, partly closed in wet periods, but re-opened when the soil dried. After some months the drains were partly filled with very porous soil material and, in and along the slits, a loosening of the soil started due to the activity of soil animals and roots. After about 4 years this loosening extended over a zone of 40cm to 1 m from the slits, whereas in another case after 6 years the loosening extended over the entire distance (5 m maximum) between the slits. The newly-formed aggregate structure was stabilised by ferruginous gels and newly-formed ferric nodules. In a fine sandy soil with low water stability the results of mole drainage were less favourable. After nearly 4 years many drains had disappeared, and the remaining ones were nearly closed. Loosening was also very weak. These observations suggested the need in the latter case to repeat mole drainage every 3 years.

The effects of mole drainage were also investigated micromorphologically by Borchert (1964, 1967, 1972). In a wet loess, with banded fabric, the drains were filled only one year after mole drainage due to illuviation of silty and fine sandy material, but in the slits a spongy fabric had developed. Samples taken 50cm from the slits showed no change after one year. In a soil with a very high silt content (63-73%) the drains were filled with angular fragments after only 6 months and some were totally blocked by an accumulation of illuviated clay and silt. Despite the drains being filled, the slits were very porous. The structure in and near the slits is stabilised by soil animals and roots, and a porous subangular blocky structure is evident four years after the mole drains were established.

Tile Drainage

Kowald (1968), studying the changes in backfill above drains in German alluvial gley soils, concluded that a deterioration in the structure took place in the backfill very soon after drain laying. This is due to the fact that the subsoils are often composed of alternating thin layers of clayey, silty and sandy materials. If such a structure is disturbed, the sandy and silty materials begin to move, causing filling of voids. This process can be counteracted by animal activity and an improvement to root distribution.

Sole-Benet (1979) investigated micromorphologically the causes and effects of translocation and accumulation of soil components in the drain backfill and within the drains in several French soils.

Deep Soil Loosening

Borchert (1967, 1972) investigated the effect of deep soil loosening on several soils. The results were variable. In heavy clay soil (a stagnogley soil in Rhine alluvium) the loosened zones appeared to be very narrow and after five years no improvements to the surrounding soil material were visible. The edges of the loosened zones were still strongly compacted and were red coloured due to accumulation of iron compounds. Animal activity was nearly absent. In a very wet soil consisting of re-sedimented loess and some weathered basalt, no differences between the upper part of the loosened area and the surrounding material were observable one year after loosening. The deeper part of the loosened zones, however, was still very porous and rich in earthworm excrements three years after loosening, but even here flow structures indicated a gradual deterioration of the porous structure, in spite of the fact that lime had been added during loosening.

Deep Ploughing

Borchert (1967) investigated the effects of deep ploughing on a moderately podzolised stagnogley soil developed in a mixture of loess and basalt. The surface horizon of this soil, under grassland, contained numerous iron nodules, and quasiferrans around root channels associated with a perched water-table together with micro-aggregates of mite excrements and/or comminuted plant fragments The horizon that caused the perching began at 55cm depth.

Deep ploughing to 75cm, combined with manuring with 3500 kg lime/ha, followed by a top-dressing of the same quantity of lime, improved the soil considerably after three years. The impermeable subsoil material brought to the surface was strongly loosened, though iron stains and rings could still be observed. Though pronounced clay accumulations occurred on the deep-plough sole, further improvement of the structure was expected.

FLOW PATTERNS

Saturated hydraulic conductivity is an essential factor in order to predict parameters like spring earliness, workability and trafficability in swelling clay soils. Because the physical measurement of K_{sat} is often rather costly and time-consuming, it is preferable to estimate this value in the field. As it is known from field observations and deductions from physical studies that water flows preferentially through relatively large voids, macrostructure should allow such an estimation, but experience has shown that in several cases no correlation can be found between K_{sat} and macrostructure in swelling clay soils. To obtain a better insight into this correlation, undisturbed columns 8 x 12 x 15 cm from saturated Dutch fluviatile clay soils representing a range of characteristic pedal structures in fine and very fine clayey horizons, were percolated with a solution of methylene blue in water until the effluent had the same colour intensity as the influent (Bouma et al., 1977, 1979; Bouma and Jongerius, 1979; Jongerius et al.,1979). The columns were cut into 2cm thick horizontal and vertical slices (Fig.4) which were then used to prepare thin sections following freeze-drying. Several conclusions could be drawn from the thin section examination: (1) no staining occurred in the matrix, and only a rather small part of the non-capillary voids had blue-stained walls, i.e. had conducted water; (2) in many cases the staining of the void walls showed an intermittent pattern, a phenomenon that demonstrates the occurrence of necks in the flow system; (3) in principle all types of voids can contribute to flow, but in some cases nearly all the water is conducted by planar voids, whereas in several other cases flow is preferentially via channels and/or interconnected vughs. This is due to the fact that in the investigated soils the planar void system and the system of channels and interconnected vughs are not functionally interconnected with respect to flow.

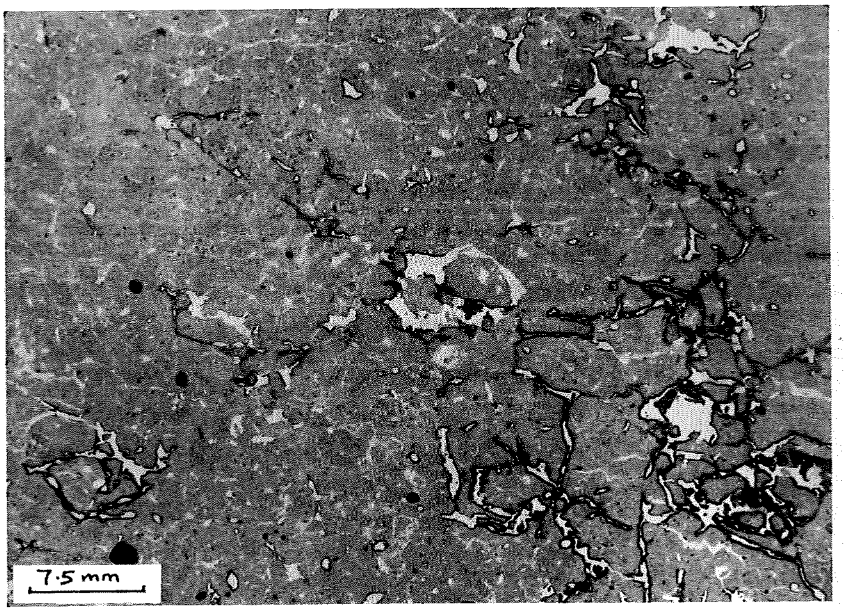

Fig. 4. Flow pattern of dye in a heavy clay soil. The blue-stained void walls are black.

Structure photograms of thin section images were quantified using a Quantimet 720. Voids were divided into three shape groups, i.e. channels, vughs and planar voids. The total number and area of all channels and vughs, and those of the blue-stained ones, were determined. Area distributions were also measured on the latter and these were converted into equivalent void diameter distributions (i.e. distributions of diameters of circles corresponding with the different area classes). For the planar voids the total area, the area of the blue-stained parts, their lengths, and spatial distribution of the widths and lengths of the voids with blue-stained walls were determined.

If the total volume of water that could have flowed at a gradient of 1 m/m through all blue-stained voids is calculated and divided by the total measured surface, a value of K_{sat} is obtained that is some thousand times higher than the physically determined K_{sat} value. This result suggests that during the saturated flow not all blue-stained voids are filled with water, rather only the smallest voids in the system, the necks, and that in the wider voids with blue-stained walls the water only flows along those walls. The overall hydraulic conductivity is thus determined by the necks in the flow system.

If the width of the necks of channels, interconnected vughs and planar voids is known, and it is assumed that all voids with blue-stained walls in a horizontal thin section have an effective size corresponding with that of the necks, K_{sat} ($m\ sec^{-1}$) can be estimated using the formula:

$$K_{sat} = \frac{\rho g}{\eta s}\left[\frac{d_n{}^3 I}{12} + \frac{r_n{}^4 n}{8}\right]$$

where ρ = liquid density ($g\ m^{-3}$); g = gravitational constant ($m\ sec^{-1}$); η = viscosity ($g\ m^{-1}\ sec^{-1}$); s = total measured area of the thin section (m^2); d_n = the largest width (m) of the water-filled necks in the planar void system; I = the total length (m) of planar voids with blue-stained walls; r_n = the radius (m) of the largest water-filled necks in the channel/interconnected vugh system; and n = the number of blue-stained channels and interconnected vughs.

To estimate d_n and r_n a statistical void interaction model has been used. The probability of a stained void of the smallest measured size class (d_i or r_i) to be vertically continuous into a same type of stained void of the same size or wider from one layer to the next is 100%, because there are no smaller stained voids, and stained voids of the same functional group (planar voids or channels and interconnected vughs) are assumed to be interconnected. However, for the next size class (d_{i+1} or r_{i+1}) the probability of vertical continuity into a stained void of the same size, or a wider one, is:

$$S_1 = \left[\frac{N_t - N_i}{N_t}\right] \times 100(\%)$$

where N_t = the total number of measured planar widths or channels and interconnected vughs, and N_i = the number of measured planar widths or channels and interconnected vughs with diameter d_i or r_i respectively, both in horizontal thin sections. The probability (S_2) that stained voids of the size class d_{i+1} or r_{i+1} are vertically continuous into stained voids of the same size or wider through a sample of L cm height is then:

$$S_2 = \left[\left[\frac{N_t - N_i}{N_t} \right]^{(L/h_v) - 1} \right] \times 100\ (\%)$$

where h_v is the average length of planar voids or channels and interconnected vughs, determined in vertical thin sections. If $S_2 < 5\%$, it is assumed that the diameter of the necks is i cm. If $S_s \geqslant 5\%$, S_2 is calculated for: $\left[\frac{N_t - N_{i+1}}{N_t} \right]$. When this S_2 is $< 5\%$, it follows that the necks are i+1 cm. However, if $S_2 \geqslant 5\%$ in this case, the necks are i+2 cm, but only if S_2 for this size is $< 5\%$, etc. If d_n and r_n are determined in this way, addition of the two calculated K_{sat} values gives the total calculated K_{sat} value These values appeared to be nearly the same as those measured in the field, which means that the calculated d_n and r_n are suitable for improving the correlation between field structure and K_{sat} values determined in the field. For details of the calculation procedure, see Bouma et al. (1979).

The staining method has also been used to analyse micromorphometrically the flow patterns occurring around tile drains in a heavy clay soil (Bouma et al., 1981 ; Bouma, 1980/81). Water flows into the drains via planar voids rather than through the channels and interconnected vughs. This observation implies that, because planar voids are formed by drying, lowering of the water-table by tile drainage in such soils results in more cracking and a higher K_{sat}.

In their investigation of flow patterns during saturated flow in swelling clay soils, Bouma and Wösten (1979) also used micromorphometric data obtained with the staining method.

Fahmy (1961) determined the distribution of void sizes in artificial mixtures of sand and very small illitic clay aggregates by point-counting. The hydraulic cross section

Od^2 was calculated from these data, where d is the diameter of a certain void size class and O is the surface per cm^2 thin section area of that void size class. There was a close relationship between the calculated hydraulic cross sections and the measured hydraulic conductivities in the mixtures.

IRRIGATION

Mathieu (1978) investigated the effect of 10 years irrigation on a soil in the Triffa plains (Western Morocco). The natural unirrigated soil has a spongy and crumbly structure with many interconnected irregular vughs and some channels in the A1 and B1 horizons (0-20cm), and planar voids, vughs and many channels in the B2 and Bxal horizon (20-75cm). The Ap1 horizon (0-10cm) of the irrigated soil consists of a mixture of spongy and compacted zones, the latter with joint planes, and small compact peds resembling Ap2 material. The Ap2 horizon (10-25cm) is compact with joint planes; embedded oval peds are oriented parallel to the surface and show joint plane formation near their upper side. In the B2 horizon (25-35cm) planar voids are dominant, whereas beneath, the structure resembles that of natural soil. Thus, in the irrigated soil, porosity is reduced and transformed due to compaction, and biological activity is also decreased. Furthermore, the soil material has undergone swelling and shrinkage that has led to the formation of pronounced plasmic fabrics. The author interprets these phenomena as a combination of the effects of irrigation and agricultural equipment.

The effects of irrigation on levelled meadow-steppe solonetz arable soils in the Pre-Caspian lowland were investigated by Tursina (1972). Removal of the A horizon followed by irrigation caused a considerable deterioration of the medium angular blocky structure of the solonetzic horizon now at the surface. The plasma completely peptizes and, as a consequence, aggregation disappears, porosity decreases from about 10% to less than 5, and surface crust formation occurs. If the solonetzic horizon is also removed, a saline, so-called pseudo-sand horizon, characterised by very loosely packed micro-aggregates of 100-300µm, forms the surface layer. Irrigation causes leaching of soluble salts and closer packing of the micro-aggregates which remain intact. An exposed solonetzic horizon of a steppe solonetz could be improved by the addition of

10-15 tons gypsum per hectare, and a meadow-steppe solonetz by mixing the material with the underlying solonchakous horizon; both measures lead to flocculation of the clay-sized mineral material.

Beckmann (1967) found that irrigation of meadow soils in the south of the Black Forest caused a more favourable soil structure. In particular, in the upper 20-30 cm, a very heterogeneous, highly branched void pattern developed, whereas in the non-irrigated soil the structure of the surface horizon was platy.

MICROSTRUCTURE AND ROOT DEVELOPMENT

The relationship between root development of asparagus and the microstructures of loamy sands (Aquods, Orthods, Psamments, Black Plaggepts and Brown Plaggepts) in Central Limburg (the Netherlands) was investigated by Reijmerink (1973). Rooting is only possible if sufficient voids $>200 \mu m$ are present, or if the roots are able to widen smaller voids. In microstructures with a total pore volume $<40\%$ these requirements are not fulfilled. At higher pore volumes rooting may also be impossible due to an unfavourable granular composition and packing of the sand grains, or by occurrence of cementing agents. In general, it appeared that (1) micro-aggregate structures are suited to root development, (2) matrix structures vary widely in rooting potential, but mainly only allow restricted rooting, (3) single-grain structures with open packing are moderately suited for root development, and (4) single-grain structures with dense packing voids inhibit rooting.

SOIL AMELIORATION

Collins and Coyle (1980) investigated the long-term changes in the macro- and micromorphology of a gray-brown podzolic soil covered artificially by peat layers ranging from 3 to more than 30 cm thick. Peat additions up to 3 cm improved the physical properties of the topsoil and increased faunal activity. Peat, 5-8cm thick, slightly worsened the soil structure, caused acidification and iron mobilisation. Thicker peat layers caused strong structure deterioration, the termination of animal activity and stronger acidification and reduction. In addition, there is increasing infiltration of humification products in the mineral soil and a change in the horizonation of the profiles.

Peeters and Stuurman (1980) studied the ripening of pump-sludged harbour mud under a newly planted forest. A micromorphological investigation was carried out seven years after planting. This showed no indication of illuviation of clay or sand. Above the reduced zone the material was very rich in deformed vesicles. Rota-tilling, following application of the mud, had caused a very fine crumb structure together with some rather big dense clods. It was concluded from these observations that the physical properties of the material are favourable for rooting of the vegetation.

THE EFFECT OF SOIL EROSION ON SOIL STRUCTURE

The influence of soil erosion on the structure of loam soils on basalt in various positions in the landscape was investigated micromorphologically by Borchert (1961). Soils on top of the slopes had lost their original A horizon, but the Ap horizon developed in the surface of the B horizon had a well aggregated and porous structure. On the slope, however, the Ap horizon is dense and nearly apedal due to a lack of organic matter and insufficient binding substances. The sedimentation of eroded material in the valleys caused a very dense laminated fabric.

In addition to this study many results of micromorphological investigations of soil erodability have been published by physical geographers.

SOME REMARKS ON GUIDELINES FOR MICROMORPHOLOGICAL RESEARCH IN AGRICULTURE

To investigate the micromorphological effects of agricultural measures on soil microstructure it is necessary to follow the execution of such measures from the very beginning. Good examples are soil ameliorations, e.g. deep-ploughing on certain fields and deep loosening on others. The investigator has to check in the field the kind of equipment used, the moisture conditions under which the work was done, whether the ploughing or loosening was executed homogeneously over the desired depth, etc. The investigator has also to check on the measures taken by the farmer afterwards. These observations give valuable and necessary information decisive for the right choice of sampling spots and selection of a reasonable number of samples. For the same reason it is advisable, if an Ap horizon is studied, to dig a shallow trench of some metres normal to the direction of cultivation so that the structure pattern can be analysed. Following this procedure, it is often possible to reduce the numbers of samples proposed by Murphy and Banfield (1978).

Another important question is the size and quality of the thin sections. If possible these should be mammoth-sized or even larger in some cases. Furthermore, the thin sections should exactly represent the structure as it is sampled in the field, which means that freeze-drying or acetone-drying should be applied.

THE FUTURE

There appears to be an increasing interest in the application of micromorphology in agriculture. It is very probable, therefore, that micromorphological investigations on the effects of deep loosening and several kinds of drainage will be considerably extended. This will be aided in particular by the very sophisticated equipment now available for image analysis which opens the way for direct links with soil physics.

Another important development is the application of submicroscopic techniques on thin sections. Nowadays, for instance, it is possible to take back-scattered electron scanning images of soils in thin section so that voids of 0.125 to 0.0075 µm minimum can be seen and measured with image analysis equipment (Jongerius and Bisdom, 1981). Submicroscopic techniques enable us also to detect chemical elements in thin sections of soils, an analysis that finds many applications in the study of, for instance, humification processes and soil pollution (Bisdom, 1981; Bisdom and Thiel, 1981).

Concluding, it can be said that soil micromorphology is developing into an important, independent branch of soil science that is well suited for studies of soil problems related to agriculture.

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