Degradation of soil structure by welding — a micromorphological study

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Abstract

In 1985 a plot study was started on sloping cultivated loess soils in South-Limbourg (The Netherlands) to evaluate the effects of various cropping systems of fodder maize on runoff, soil loss and crop yield under natural rainfall. To monitor degradation of soil structure including crust formation, undisturbed vertical samples (15 × 7 cm) for soil micromorphological analysis were taken of the top 7 cm of soil at ten dates chosen in relation to times of tillage and sowing, crop stage, harvest and winter frost. Wheel marks, if present, were also sampled. Contrary to accepted views, no disintegration of structural elements by slaking or dispersion was observed. Freshly tilled soil exhibited a loss of its original granular structure by coalescence of the aggregates into larger units, eventually leading to a structureless state of part of the top soil. Processes held responsible for this are mainly welding of wet aggregates and seldom fusion by silt infillings in vertical inter-aggregate pores. The two layer model of soil crust formation of McIntyre could not be confirmed, as no important vertical translocation of fines or washed-in layers were observed. Horizontal cracks developed in the structureless soil, giving rise to a platy structure in part of the top soil. Transitional stages of loss of soil structure were observed, characterized by the progressive reduction of compound packing voids to vughs, which ultimately disappeared completely and sometimes were replaced by planar voids. Besides structural crusts, sedimentary crusts including splash deposits were observed.

1. Introduction

Soil crusting is generally seen as an important causal factor of soil erosion on agricultural land. In order to be able to prevent soil crusting we need to know the causes and processes of soil crusting. Our knowledge of soil crusting and sealing has increased steadily since the classic papers by McIntyre (1958a,b) on soil crust formation by raindrop impact (Tackett and Pearson, 1965; Evans and Buol, 1968; Farres, 1978; Callebaut et al., 1986; Norton, 1987; Mücher et al., 1988; Mualem et al., 1990; Gimenez et al., 1992; Slattery and Bryan, 1992; Sumner and Stewart, 1992). French

scientists studied the processes of soil crusting and the morphology of soil crusts on silty or loamy soils (Boiffin, 1984; Boiffin and Bresson, 1987; Le Bissonnais, 1988, 1989, 1990; Bresson and Boiffin, 1990; Bresson and Cadot, 1992; Le Bissonnais and Singer, 1992, 1993; Le Bissonnais et al., 1989; Valentin, 1981, 1991; Valentin and Bresson, 1992). Israeli scientists have devoted special attention to the role of dispersion in crust formation and the influence of soil sodicity and water salinity on surface sealing (Agassi et al., 1981, 1985; Ben-Hur et al., 1985; Levy et al., 1986). The majority of authors envisage a two stage process of surface sealing or soil crust formation. As the first stage, soil structural units or elements (aggregates, peds, clods) are assumed to disintegrate or break down into smaller fragments (micro-aggregates) and/or primary particles (clay particles, silt and sand sized skeleton grains). Secondly, the fine fragments or primary particles that are released by this breakdown should unite to form a crust. The breakdown of soil structure is ascribed to the explosion of entrapped air (dry aggregates) or to the impact of falling raindrops (wet aggregates), and is referred to as "slaking", micro-cracking or micro-fissuration. Soils with exchangeable sodium may suffer from aggregate breakdown due to dispersion of the clay particles. Only Bresson and Boiffin (1990) mention the possibility of crust formation by coalescence of aggregates without a preceding phase of aggregate breakdown. The often cited two layer model of McIntyre (1958a,b) on soil crust formation remains a keenly discussed issue, especially the so called "washed-in layer".

It seems that ideas on the mechanisms of soil crusting have been influenced by the behaviour of single aggregates during tests of aggregate stability in the laboratory, such as exposing single aggregates to falling water drops (Low, 1954) or immersion of single aggregates in water (Emerson, 1967; Loveday and Pyle, 1973). The overriding aspect of single aggregate behaviour is some form of breakdown or disintegration. In natural soils, however, aggregates form a mass of soil and it is the mass behaviour or mutual interaction of aggregates that must be understood with reference to surface sealing and crusting.

In 1985 a plot study was started on sloping cultivated loess soils in South-Limbourg, The Netherlands (Fig. 1), to evaluate the effects of some conservation cropping systems of fodder maize on runoff, erosion and crop yield. Cropping systems influence runoff and erosion through their effect on a number of intervening variables, related to soil structure, such as degree of slaking, surface roughness, infiltration capacity, hydraulic conductivity and soil shear strength. In 1988, therefore, in addition to runoff and soil loss measurements, a soil micromorphological investigation was undertaken of the soil layer at and immediately below the soil surface on the experimental plots. In this paper the results of the micromorphological analysis of the processes of soil structure degradation and crust formation are presented including the applicability of the McIntyre model of soil crust formation. No previous work of this kind has been carried out in the region.

2. Terminology and definitions

The term slaking is confusing and needs clarification. Originally it was used as a

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✻ Location of study

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Fig. 1. Location of the experimental plots in South-Limbourg, The Netherlands.

descriptive term for the loss or breakdown of soil structure that can be observed in the field with the naked eye. Baver (1956) writes that "Common experience has taught us that compact, tightly cemented clods slake down into smaller aggregates as a result of alternate wetting and drying." Baver et al. (1972) mention four possible causes of aggregate breakdown related to wetting and drying: (a) stresses and strains set up by unequal swelling of different parts of the clod, (b) compression of entrapped air, (c) reduction in cohesion with increasing moisture content, and (d) dispersion of cementing material. These processes cannot be recognized as such in the field and are not implied by the verb "to slake". However, it has become common usage to apply the term slaking to aggregate breakdown due to the "exploding" effect of entrapped air that is compressed by water uptake in the capillary pores of originally dry aggregates, when there are no escape pores present. This is termed "slaking s.s." in this paper. Slaking implies an increase in bulk density. Besides surface crust formation, a total collapse of the structure of the whole plough layer can be observed in some Dutch soils. The formation of surface crusts is termed "surface slaking" and the collapse of the whole plough layer is termed "internal slaking" in Dutch literature (Van der Sluis

and Locher, 1987). Surface slaking is ascribed to the mechanical force of rainfall or the explosion of enclosed air in aggregates. Internal slaking is a form of so-called regrouping phenomena in Dutch soils (Jongerius, 1970). It is caused by saturation of the plough layer due to a high groundwater table or slow drainage due to an impermeable layer below the plough layer. The term "structure" as used in the following sections implies the presence of aggregates. The material of which aggregates are composed is referred to as "pedal material" (Brewer, 1976). The term "aggregate" in this paper includes peds as well as clods. The term "structureless" refers to a soil without aggregates. Such a soil consists of "apedal" material. The term "massive" is used for a structureless soil without pores. The term granular is used for the macroscopic description of soil structure (F.A.O., 1977). It implies the presence of relatively non-porous peds occurring as spheroids or polyhedrons with plane or curved surfaces which have slight or no accomodation to the faces of the surrounding peds.

3. Materials and Methods

South-Limbourg has a hilly relief with land surface elevations ranging from 40 to 321 m a.s.l. Land use is mainly agricultural. A large part of the area is covered with a 2 to 20 m thick layer of loess, in which Luvisols (F.A.O., 1989) are developed (Mücher, 1986; Stiboka, 1970). These soils are highly erodible. Soils at the experimental site were imperfectly drained, truncated gleyic and/or stagnic Luvisols (F.A.O., 1989) with less than 0.80 m overlying loess derived colluvium. During part of the year a (perched) water table was present within 1.00 m of the soil surface. Average particle size distribution of the plough layer was 13% clay, 81% silt (2–50 μm) and 6% sand (50–2000 μm). Textural classes were silt and silt loam (F.A.O., 1977). Organic matter content of the plough layer was 1.8%.

South-Limbourg has a temperate oceanic climate with rainfall in all seasons. Average annual precipitation of the area is 750 mm. Monthly rainfall amounts during the period of study are given in Fig. 2.

Twelve plots with three replications of three cropping systems of maize and permanently bare soil were laid out in a randomized block design (Quenouille, 1953) on a 6% sloping field. Plot length was 25 m and plot width 10 m (cropped plots), or 5 m (fallow plots). Direction of tillage and sowing was up and down slope. Plots were laid out in October 1985. Maize was grown continuously on the plots from 1986 to 1989.

Fodder maize (Zea Mais L., cultivar Sonia) was grown as a continuous culture on the experimental plots. The characteristics of the maize cropping systems were as follows (Geelen, 1987):

(a) conservation cropping system A; ploughing and seedbed preparation by rotary harrowing after harvest of preceding maize crop in October, directly followed by drilling of winter rye; winter rye killed by spraying late April; maize sown by direct drilling in surface mulch of winter rye,

(b) conservation cropping system B; coarse loosening of the soil with point tine cultivator after harvest of preceding maize crop in October; ploughing and seedbed preparation late winter/early spring, followed by sowing of summer barley; direct
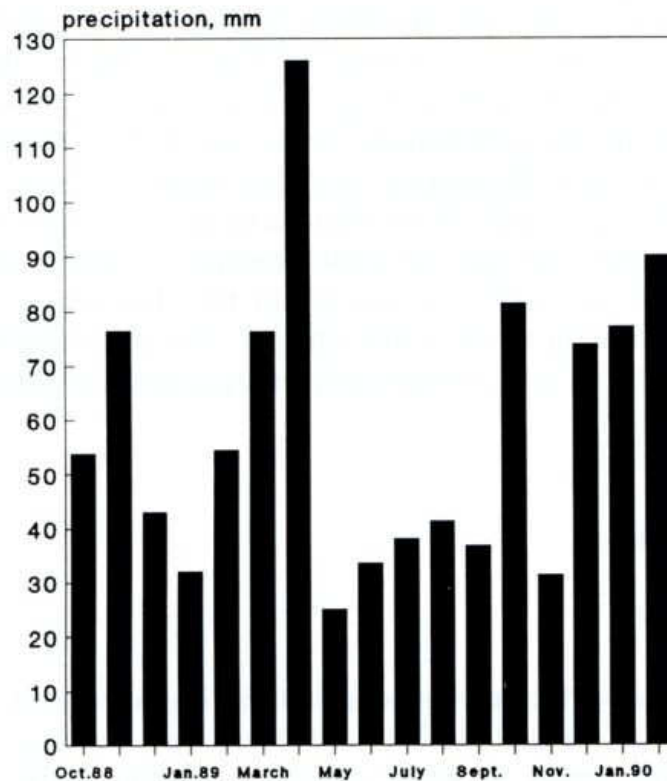
precipitation, mm

Fig. 2. Monthly rainfall amounts, Wijnandsrade, October 1988–February 1990.

drilling of maize in growing summer barley; summer barley killed by spraying before emergence of maize,

(c) conventional cropping system C; stubble field from time of harvest of preceding maize crop until next spring; ploughing and seedbed preparation late April/early May, immediately followed by maize drilling,

(d) permanently bare fallow (system C'); ploughing and seedbed preparation as on system C. The plots of C' were passed over with sowing and harvesting machinery at the time of sowing and harvesting of system C.

Plough depth was 30 cm. Seedbed preparation in autumn and spring on all systems included loosening of the top 5 cm of soil with duckfoot tines, rotary harrowing of the uplifted clods and light rolling of the broken up clods, all in one combined operation.

Naturally occurring runoff and soil loss was collected and measured with four weekly intervals (Kwaad, 1994). The structural state of the soil surface was assessed by visual comparison of the soil surface with a series of 10 reference photos of surfaces showing increasing stages of structure degradation; results are expressed on a scale of 1 to 10, with a freshly tilled soil rated as 10 and a fully degraded soil surface rated as 1 (Boekel, 1973).

To monitor changes in the structural state of the top soil, undisturbed vertical samples (15 × 7 cm) were taken of the top 7 cm of soil on all cropping systems on ten dates from November 1988 until March 1990. Sampling dates were chosen in relation to times of tillage and sowing, crop stage, and times of harvest and winter frost. Wheel marks, if present, were also sampled. Altogether 64 samples were taken. After air-drying, soil thin sections of 7 × 15 cm were prepared according to the

technique described by Jongerius and Heintzberger (1975). Thickness of the thin sections is 20 μm. A consequence of this is, that pores < 20 μm cannot be accurately observed and measured in the thin sections. The thin sections were analysed microscopically, mainly using the terminology of Brewer (1976). The term "infilling" is from Bullock et al. (1985). Microscope magnifications up to 125× were used. A quantitative analysis was made of 40 thin sections by means of point counting along a grid with regular grid spacings of 0.5 cm (ca. 370 points per thin section of 7 × 15 cm). A magnification of 7× was used for this. In the case of 370 points the reliability of point counting results ranges from ±3% at a volume percentage of a given feature of 10% to ±5% at a volume percentage of 60% (Van der Plas and Tobi, 1965).

4. Results and discussion

4.1. Field observations

After tillage the soil surface exhibited structural breakdown on all cropping systems. The evolution of the soil surface took place in a stepwise manner that was controlled by type and timing of tillage operations and the pattern of rainfall (Imeson and Kwaad, 1990). Visual evidence of soil structure degradation consisted of decreasing number of loose aggregates, decreasing number and size of large packing voids between clods, decreasing random surface roughness, increasing surface area consisting of non-aggregated soil, increasing degree of roundness of large clods, and occurrence of sedimentary crusts in depressions of the microrelief and in wheel tracks. Boekel class decreased from 10 directly after tillage to 2 or 1 on cropping systems A, C and C' that were tilled once a year (either in autumn or in spring), and to 3 on cropping system B that was tilled twice a year (in autumn and early spring). This means that the structure that was created by tillage was no longer visible at the soil surface under cropping systems A, C and C' after a year.

4.2. Microscopic analysis of soil thin sections

The solid part of the S-matrix of the soil on the experimental plots was mainly composed of silt-sized skeleton grains (dominantly quartz) with little argillaceous plasma, and showed intertextic and porphyroskelic related distribution patterns. In the case of a porphyroskelic arrangement the coarser grains have points of contact. Plasma was mainly silasepic and locally, in the porphyroskelic pattern, skelsepic. Very few plant remains and very few lithorelicts and biorelicts (charcoal) occurred on all cropping systems. Sesquioxidic cutans and sesquioxidic subcutanic features were not observed. Few infillings of clean washed silt particles occurred in compound packing voids between the aggregates. Few sharply bounded, inherited and/or transported, normal ferric nodules with an undifferentiated internal fabric were present. Pedotubules were not observed. Very few organic fecal pellets were observed, mainly from enchytreae and/or collembolae activity. Collembolae fecal pellets can be confused
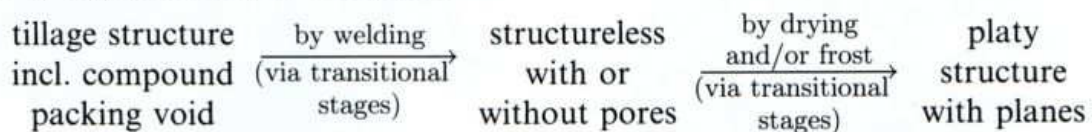
with those of enchytreae (Babel and Vogel, 1989; Dawod and Fitzpatrick, 1993). Matric fecal pellets from earthworms were only observed in one thin section. All cropping systems exhibited a very low level of biological activity at all sampling dates.

Directly after tillage, the top 7 cm of all cropping systems consisted of fully aggregated soil which exhibited a granular structure with many inter-aggregate compound packing voids of macro-pore size. Total volume of pores > 20 μm was estimated as 30 to 40%. The size of the individual aggregates ranged from < 2 mm to > 10 mm. Aggregates were mostly single i.e. not welded. They showed high sphericity and were mostly subrounded. The aggregates were mostly non-porous i.e. did not contain intra-aggregate pores > 20 μm. The smaller aggregates resembled matric fecal pellets. See Fig. 3a.

In the months following tillage, changes of soil structure took place, not only of the soil surface but also of the bulk of the tilled layer, referred to as "substrate" in this paper. The change of soil structure mainly affected the degree and type of aggregation of the soil in situ and the type, number and size of voids (see Figs. 3a–f).

Unexpectedly, no disintegration or breakdown of structural elements was observed, neither in the "substrate" nor in the structural crusts. Evidently, no slaking s.s. has occurred. In fact, the opposite has happened. The bulk of the freshly tilled Ap-horizon exhibited a loss of its original granular structure by coalescence of aggregates into larger units, ultimately leading to a structureless state of part of the topsoil. This was clear from the vanishing of the many very fine aggregates that were present in the soil immediately after tillage, and from the appearance of aggregates in various stages of "welding", ranging from single via partly and strongly welded aggregates to apedal material (see Figs. 3a–f). In some very wet months a complete collapse of soil structure of the tilled layer has occurred on cropping systems B, C and C′, as is apparent from a structureless state of the top 7 cm of soil. This is termed "internal slaking" in Dutch literature (Jongerius, 1970). The process held responsible for this is liquefaction of aggregates in a very wet state at soil moisture contents exceeding the liquid limit of the soil. This may have occurred under the influence of a temporary high (perched) water table, which was observed on the experimental plots in the winter half of the year (Kwaad, 1991). Evidently, the bulk of the tilled layer has lost its granular structure in one of two ways: (a) by a gradual welding of aggregates in a non-saturated state over a period of some months, or (b) by a collapse of aggregates and inter-aggregate pores when the soil was saturated. Very locally, "fusion" of aggregates by silt infillings in vertical inter-aggregate pores was observed. Transitional stages of loss of soil structure were characterized by the progressive development of compound packing voids into vughs, which ultimately disappeared completely and sometimes were replaced by planar voids.

Model of degradation of soil structure

tillage structure incl. compound packing void	by welding (via transitional stages) →	structureless with or without pores	by drying and/or frost (via transitional stages) →	platy structure with planes

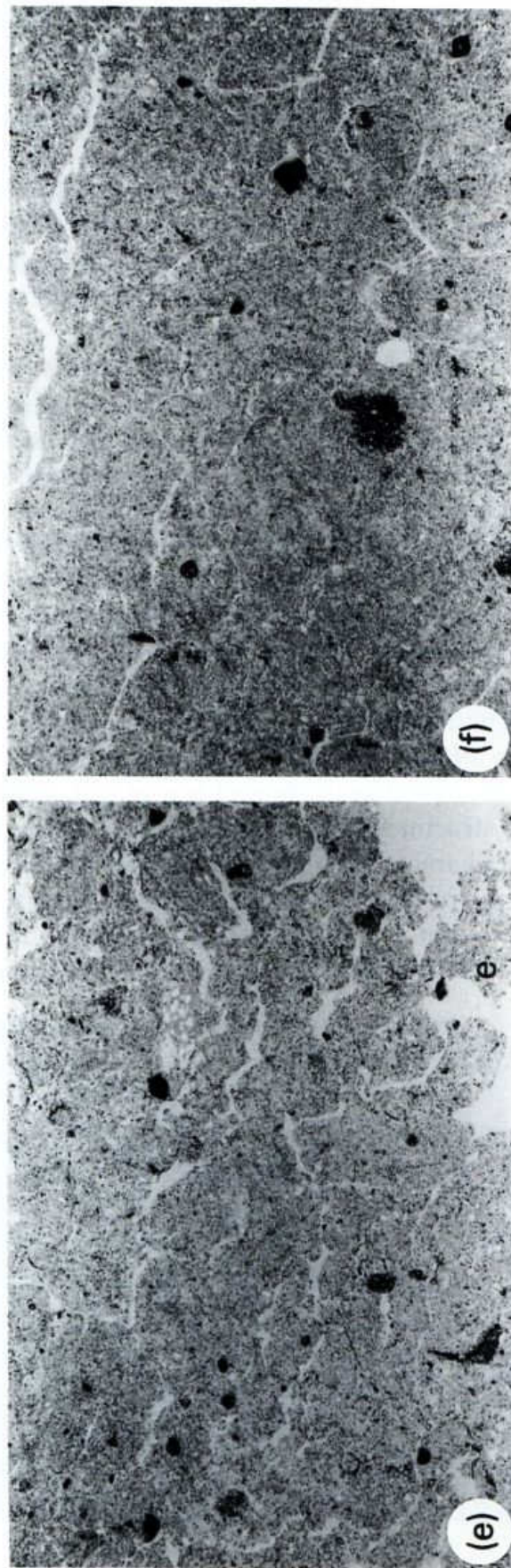The cropping systems under which total collapse of the tilled layer occurred, in later
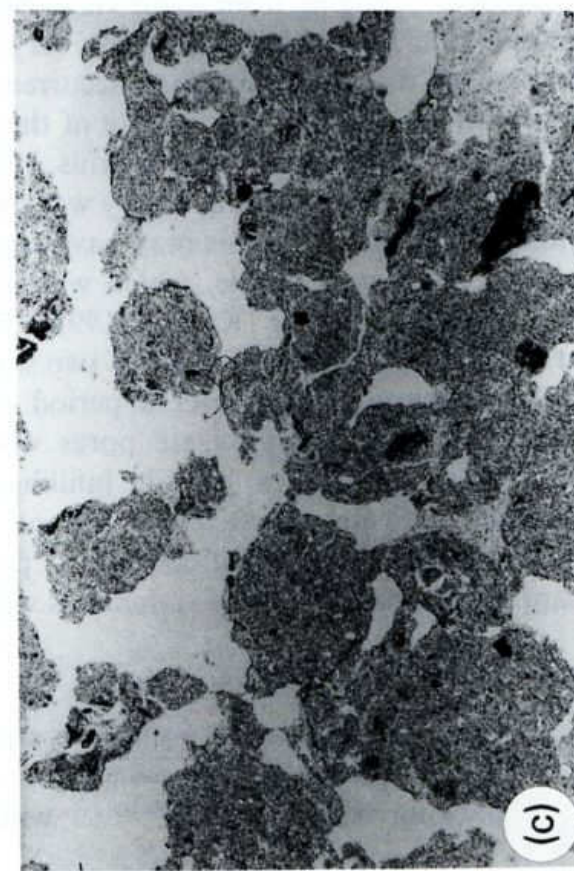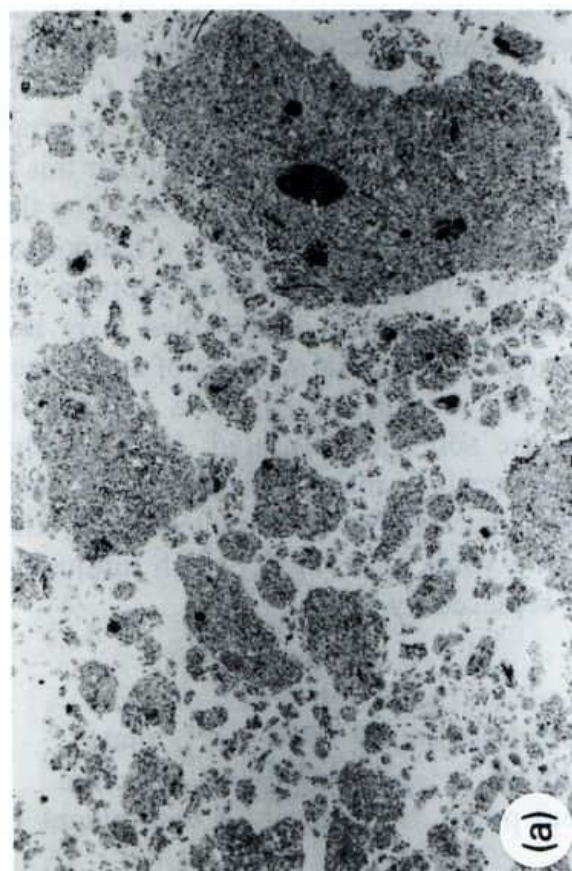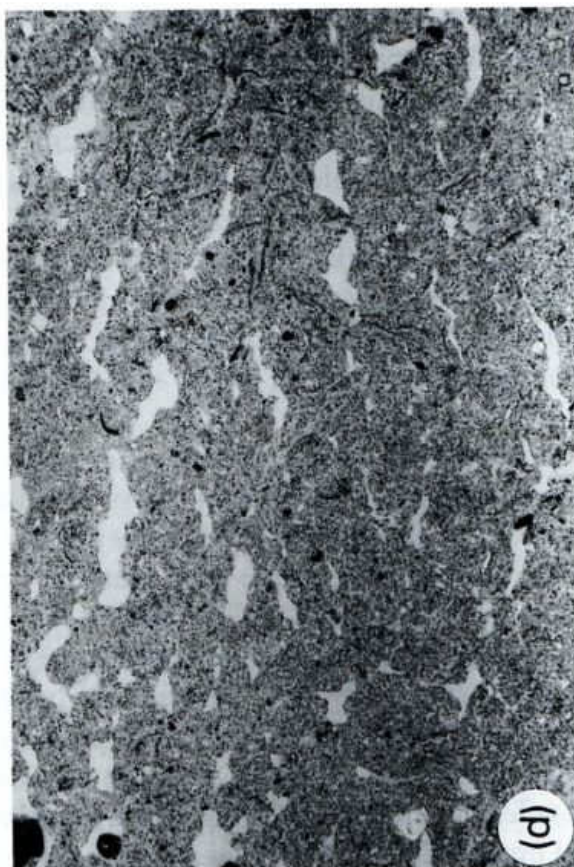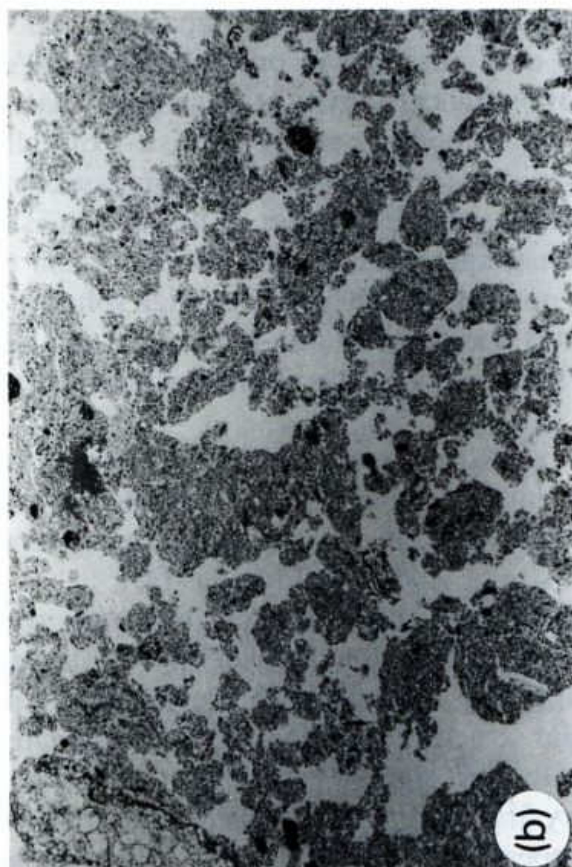
Fig. 3. Stages of welding of aggregates in substrate. Note disappearance of finest aggregates between (a) and (b), compound packing voids in (a) and (b), appearance of vughs in (c) and (d) and disappearance of voids in (e) and (f). Frame length 16.6 mm.

months exhibited some degree of soil structure again, without being tilled. Partly this was a subangular blocky structure, which may have been caused by the formation of shrinkage cracks through drying of the soil. Partly it was a granular structure. The granular structure can only be explained as remnant of the original tillage structure in parts of the soil that were not fully saturated and did not collapse. In some cases horizontal cracks (planes) developed in the structureless soil, giving rise to a platy structure of part of the topsoil. No restoration of soil structure was observed in wheel tracks, which had a structureless or platy topsoil from the beginning. Apparently, compaction by tractor wheels has a longer lasting effect on soil structure than lique-faction and compaction of the soil under its own weight.

In the uppermost 1 to 10 mm of soil a structural crust was formed. A structural crust is defined here as a dense, coherent and continuous layer of soil particles, formed by processes of structural degradation at the soil surface. The structural crust is less porous (apart from vesicles) than the immediately underlying soil. Protruding parts of clods larger than ca. 5 cm are not considered as part of a soil crust but represent erosion surfaces. They become slightly rounded by surface abrasion due to drop impact. The structural crusts were composed of aggregates showing various stages of welding, and apedal material (Fig. 4). Evidently, the structural crusts were formed by coalescence of aggregates, in some cases to the point of completely merging in each other. No aggregate breakdown was observed in the structural crusts. In some cases fusion of aggregates by infillings of silt in inter-aggregate pores has occurred. No washed-in layer (McIntyre, 1958a) was observed in any of the 64 thin sections.

The substrate and structural crust both showed loss of soil structure in the form of welding of aggregates. The structural crusts, however, were denser than the substrate. This was the main diagnostic characteristic of the structural crusts in the thin sections. The low porosity of the structural crusts is ascribed to compaction due to raindrop impact.

Also material was deposited on top of the in situ soil, mostly in depressions of the microrelief. This material formed sedimentary crusts. The maximum observed thick-
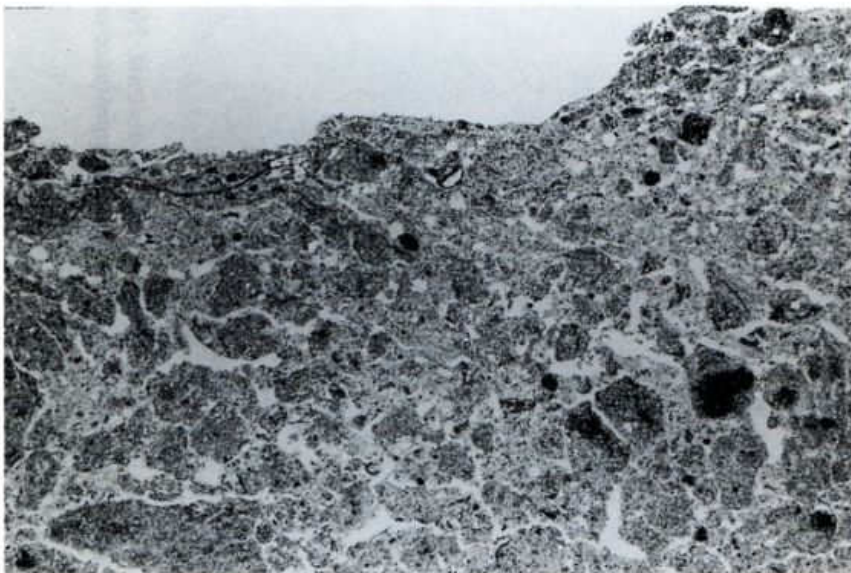

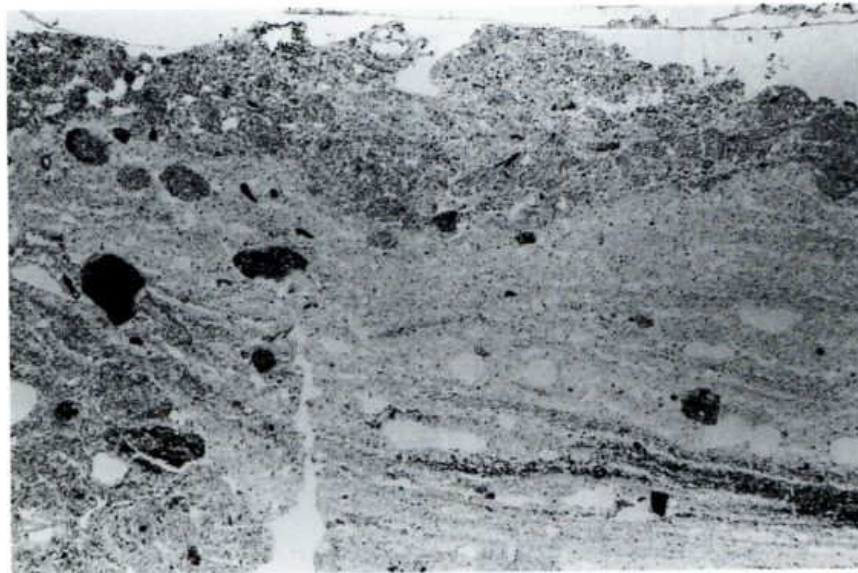Fig. 4. Welded aggregates in structural crust. Frame length 16.6 mm.

Fig. 5. Non-laminated splash deposit on top of laminated sedimentary crust. The laminated sedimentary crust shows vesicles in the right lower part. Frame length 16.6 mm.

ness of the sedimentary crusts was 33 mm. Vesicles were commonly observed in or immediately below the sedimentary crusts. The sedimentary crusts were either well laminated, poorly laminated or not laminated. Individual laminae consisted of clean washed silt particles with or without clay or almost pure clay. The different types of lamination are caused by overland flow without drop impact, overland flow with drop impact and only drop impact (splash deposit) (Mücher and De Ploey, 1977). Splash deposits, which are not laminated, could be recognized with certainty, if they occurred on top of a laminated (part of a) sedimentary crust (Fig. 5). The observed splash deposits consisted of rounded aggregates up to 1.2 mm. This agrees well with the maximum size of 1.1 mm of splashed aggregates observed by Mücher and De Ploey (1977) and Mücher et al. (1981) in laboratory experiments. Crusts, not overlying laminated deposits but consisting of well sorted, rounded aggregates < 1 mm, have been classified as splash deposits in this study. However, it was not always possible to distinguish strongly welded splash deposits from crusts formed in situ.

4.3. Quantitative analysis of thin sections

From the point countings of the thin sections (see Figs. 6–9) the following conclusions could be drawn.

(a) The degree of welding and the proportion of welded aggregates in the substrate and structural crust showed an increase with time.

(b) The proportion of apedal soil material as the end-product of welding showed an increase with time in the substrate and structural crusts.

(c) More apedal soil material and/or more (strongly) welded aggregates occurred in the structural crusts than in the underlying substrate.

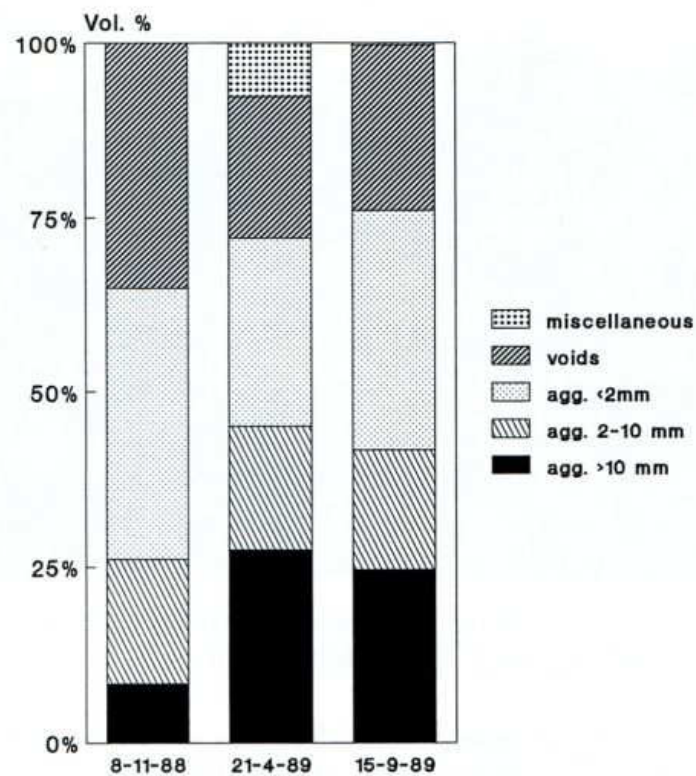(d) Average aggregate size did not decrease with time in the substrate or the structural crusts.

Fig. 6. Change of aggregate size in time. Cropping system A, substrate.
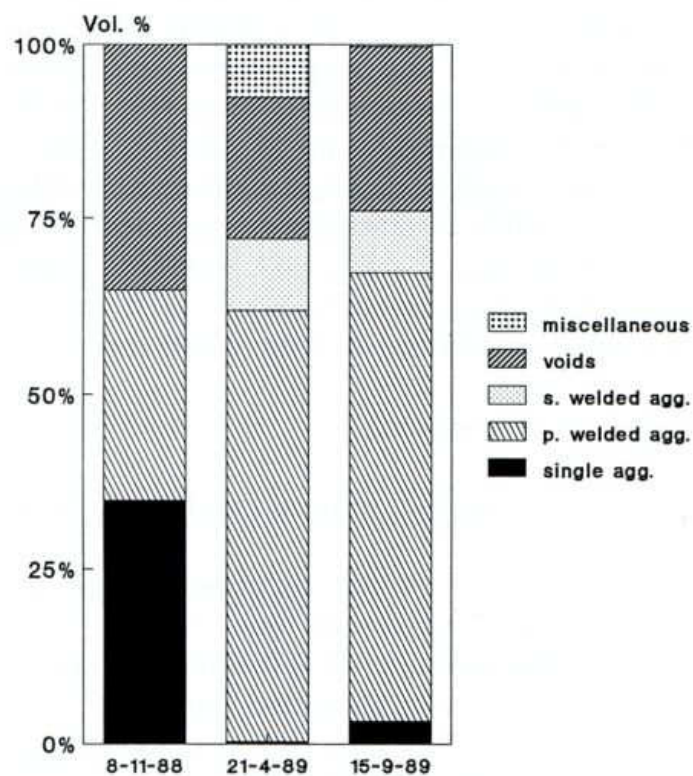

Fig. 7. Change of welding of aggregates in time. Cropping system A, substrate (p. welded = partly welded, s. welded = strongly welded).
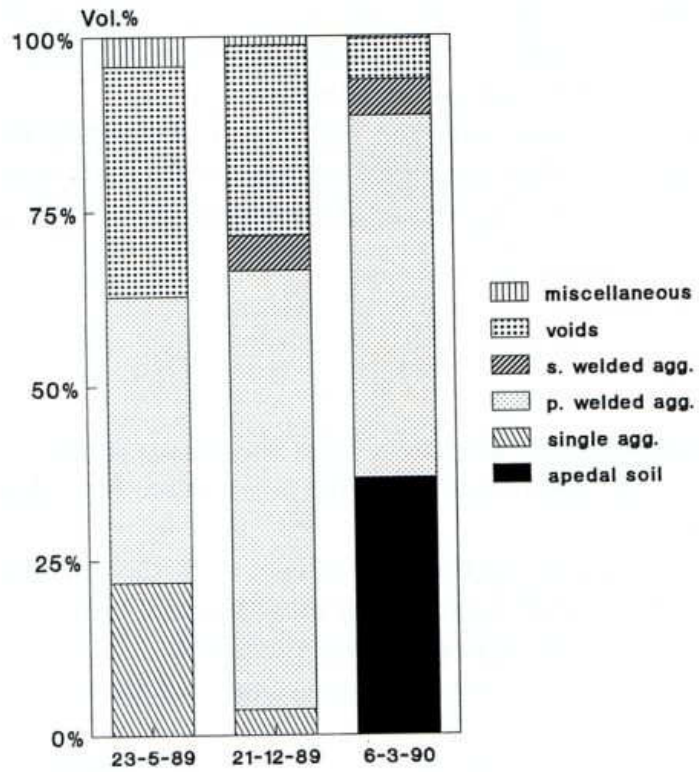
Fig. 8. Change of welding of aggregates in time. Cropping system C, substrate.
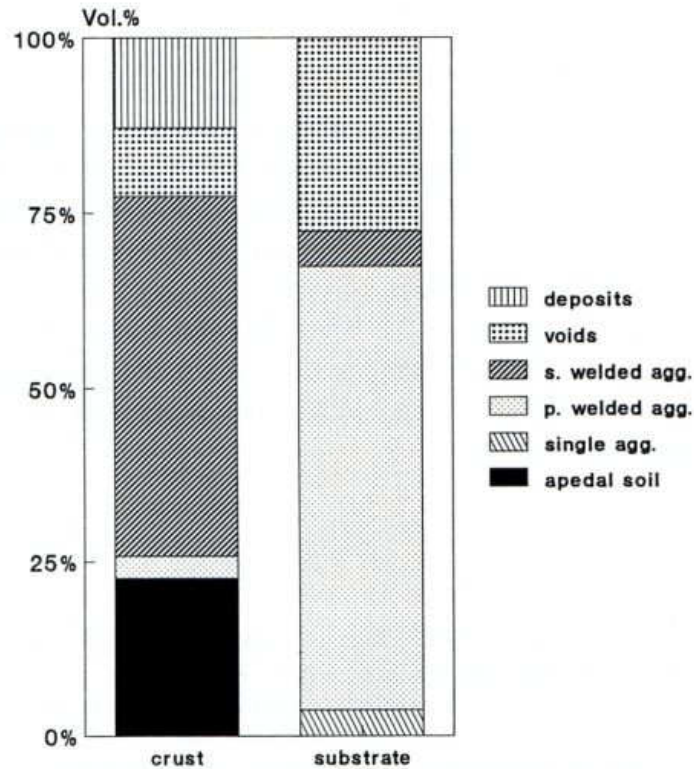

Fig. 9. Comparison of welding of aggregates in substrate and crust. Cropping system C; 21 December 1989.

(e) Average size of the aggregates in the structural crusts was not smaller than in the underlying substrate, taking into account that aggregates > 10 mm occurring at the soil surface were considered as part of the substrate.

These results are in agreement with the hypothesis, derived from the qualitative analysis of the thin sections, that structural change of the loess soils on the experimental plots was not caused by aggregate breakdown but by coalescence of aggregates.

5. Conclusions

The following conclusions can be drawn from the results of this study:

– Structural change was not restricted to the soil surface but affected also deeper parts of the tilled layer.

– Structural change took place in the form of coalescence or welding of aggregates, both in the substrate of the tilled layer and in the structural crust. No breakdown or disintegration by slaking s.s. of aggregates was observed.

– In some instances, a more or less sudden collapse of the structure of the tilled layer has occurred.

– Apart from a few localized infillings of silt, no vertical translocation of fines was observed. No washed-in layer was observed.

– Non-laminated sedimentary crusts consisting of splash deposits could be identified.

Acknowledgements

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