COMPARATIVE MICROMORPHOLOGICAL STUDY OF S IL CRUSTING IN TEMPERATE AND ARID ENVIRONMENTS

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INTRODUCTION

In temperate areas, surface crusts mainly develop on unstable loamy soils (Mücher and De Ploey, 1977), especially when cultivated (Boiffin, 1984; Norton and Schroeder, 1987). In arid areas, surface crusts occur on a wider range of soils, because aggressive rainstorms fall on dry soils, vegetation is scarce, and soil organic matter content is low (Chen et al., 1980; Valentin, 1981) ; therefore, soil crusting affects the most part of the landscape, i. e. both cultivated and pasture soils. Field studies (main references above), together with many laboratory experiments (McIntyre, 1958; Agassi et al., 1981; Mücher et al., 1981; Onofiok and Singer, 1984; Le Bissonnais, 1988), have shown that various mechanisms could be involved.

In this paper, we intend to describe more precisely these mechanisms and their respective role, according to soil and environment conditions. For this purpose, we studied soil crusting in both temperate and arid areas : (i) we described the macro- and micro-morphological characteristics of the various crust types which occur, (ii) we studied the crusting pattern (i. e. the space- and time-dependent sequence for each crust type) in each environment, and (iii) we compared both crust morphology and crusting pattern under temperate and arid conditions.

MATERIALS AND METHODS

The temperate soils studied were cultivated loamy Alfisols of the Paris basin, which showed some variations in clay, organic matter, calcium carbonate or exchangeable sodium contents (Boiffin, 1984; Bresson and Boiffin, 1990). The arid soils studied were Aridisols and Entisols from western Africa (Burkina Faso, Cameroon, Mali, Niger and Senegal) ; located on extensively grazed pasture lands with a low organic matter content, they showed a wide range of texture. This study was carried out in the field, because soil crusting processes greatly depend on specific conditions which are not easily reproduced in the laboratory, such as : (i) soil surface moisture and suction gradient in the first top centimeters, (ii) initial structural state and surface microrelief, (iii) free water flow and particle movement over several meters. Simulated rainfall was used on some specific sites in the arid areas (Valentin, 1981), whereas crusting was studied only under natural conditions in the temperate areas where height and intensity of rainfall events are generally very low (Boiffin, 1984). Moreover, soil crusts from both arid and temperate areas were studied at the development stages that can be determined from the macroscopic facies of the soil surface (Boiffin, 1984). Such an approach ensures a close monitoring of the crusting process, and allows valuable comparison between crusts developing on different soils and in different environments. 49 crust samples from 7 temperate soils and 396 crust samples from 67 arid soils were air-dried and impregnated with polyester resin ; thin sections were studied with optical microscope and S.E.M. (B.E.S.I. mode).

RESULTS AND DISCUSSION

Temperate soil crusts

Structural crusts mainly consisted of a thin, dense layer, the m2 microhorizon (Boiffin and Bresson, 1987). Typically, the m2 microhorizon was apedic, but remained rather porous with a weak void interconnection (Photo 1). Generally, no clear textural disjunction (i.e. separation between granomass - skeleton - and micromass - plasma -) could be observed in m2, even in sodic soils. In some cases, however, bare silts could clog the interaggregate interstices and form net-like infillings (Photo 2). The boundaries between m2 and the underlying undisturbed horizon could be diffuse, which led us to describe a transitional microhorizon, m1-2. Most macropores of the m1-2 were typical packing voids with a polyconcave shape. Such crusts (m2/m1-2) were generally thicker and the void convexity increased toward the surface (Fig. 1).

In temperate loamy cultivated soils, structural crusts mainly resulted from aggregate breakdown induced by entrapped air compression (Boiffin, 1984; Norton, 1987; Le Bissonnais, 1988) or microcracking from shrinking and swelling (Valentin, 1981; Le Bissonnais, 1988). This disaggregation process predominated when the soil was dry before rainfall. Nevertheless, dispersion due to drop erosion could occur when the soil was wet and the rainfall intensity low (Le Bissonnais, 1988; Bresson and Cadot, unpublished) : detached particles illuviated further between the undisturbed underlying aggregates (Photo 2). In the same way, gradual compaction due to aggregate coalescence by deformation under plastic conditions (m1-2 microhorizon development, Photo 1) took place in wet soils under rainfalls with rather high kinetic energy (Bresson and Boiffin, 1990). The top of the structural crust was generally compacted due to raindrop impact when the kinetic energy of rainfall was high enough (McIntyre,1958; Onofiok and Singer, 1984; Valentin and Ruiz-Figueroa, 1987).

Depositional crusts were always characterized by a sedimentary layer, the m3 microhorizon (Boiffin and Bresson,1987). Typically, the m3 microhorizon was apedic and very compact. Disjunction between micromass (plasma) and granomass (skeleton) induced alternate submillimetric microbeds more or less contrasted in texture and uncomformable with the underlying horizon (Photo 1). Generally, in the lower part of m3, the bedding was less distinct and the particle sorting was poorer in that some microaggregates were often mixed with poorly sorted basic particles. On the other hand, the clayey microbeds were usually thicker, better sorted and more birefringent when they were located in the middle of the microdepression where the depositional crust had formed. M3 microhorizons always overlaid the m2 microhorizons, with sharp boundaries (Photo 1 and Fig. 1).

The main micromorphological features of depositional crusts such as microbedding, sorting, packing and orientation of coarse and fine particles could be related to the hydrodynamic conditions of particle sedimentation (Mücher et al., 1981; Valentin, 1981; Bresson and Boiffin, 1990). Poorly sorted, dense microbeds deposited in turbulent flow, well-sorted microbeds deposited in laminar flow, and sedimentation in puddles induced gradual sorting and horizontal orientation of particles. The flow type depended on the runoff conditions (velocity, solid charge, surface roughness), as well as on splash which was an important source of turbulence. In this respect, abundance, size and duration of puddles played a major part in the characteristics of the sedimentary microhorizons, which therefore appeared to be partly controlled by the properties of the underlying structural crusts (Bresson and Boiffin, 1990). On the other hand, the beginning of runoff was characterized by a muddy flow which constituted a clear crusting stage in temperate areas (Bresson and Boiffin, 1990). This process would explain the frequent presence of microaggregates in the lower sedimentary microbeds.

Crusting pattern. Crusting always followed the same pattern : (i) sealing of the surface by a structural crust, and (ii) development of a depositional crust (Fig. 1). The change from the first to the second stage mainly depended on a decrease in infiltrability due to the structural crust properties that induced microrunoff under rainfall (Boiffin, 1984).

Arid crusts

In silty and clayey topsoils, arid surface crusts were very similar to those observed under temperate conditions : structural crusts and depositional crusts.

However, more specific crusts extensively developed on sandy soils. Six main types could be distinguished the coarse-textured topsoils (Fig. 2, Photos 3 and 4).

Drying crusts. When the soil was protected from raindrop impact by vegetation, surface structural changes were restricted to a slight cementation of the upper millimeters due to repeated wetting and drying cycles. However, crust strength remained weak and the process was revertible.

Layered structural crusts consisted of a layer of loose grains overlaying a plasmic seal (Photo 3). In the most advanced form, the structural crust exhibited three well-sorted layers: the uppermost was composed of loose, coarse grains, the middle one consisted of fine, cemented grains with vesicular voids (Photo 3) and the lower layer (plasmic seal) showed a higher content of fine particles with considerably reduced porosity (Valentin, 1981). A close time-dependent sequence of microscopic observations showed that structural crusts developed primarily as a result of waterdrop impact which formed micro-craters, the walls of which presented a clear, vertical sorting of particles. This suggested that the textural differentiation within the structural crusts mainly resulted from a mechanical sieving so that the finer the particles, the deeper they were deposited (Valentin, 1986). Moreover, the downward translocation of clay through the coarse-grained toplayer could be enhanced by the percolating water. Then, fine particles accumulated, probably due to entrapped air within the underlying layers (Collinet, 1988), and formed the plasmic seal (or "filtration pavement" according to Bryan, 1973).

Erosion crusts consisted of only one rigid, thin and smooth outcropping plasmic layer. Voids were generally restricted to some cracks and vesicles. Such plasmic seals outcropped where the coarse particles which formed the structural crust top layer were removed by wind or running water. Then, the winddrifted sand could be entrapped by the grass cover nearby and build up a drying crust again.

Runoff depositional crusts consisted of several alternate sorted microbeds, with a more or less interbedded orientation (Photo 4). These crusts, which could be few centimeters thick, particularly along the furrows, usually developed above the structural crusts. They resulted from deposition of soil particles in the running water layer : the sorting rate was controlled by the type of flow, turbulent or laminar (Mücher and De Ploey, 1977).

Sedimentation crusts consisted of densely packed and well-sorted particles, the size of which progressively increased with depth. The vertical particle size distribution with coarser particles at the bottom and finer particles at the top, was the reverse of that observed in the structural crusts described above. When dry, these crusts often broke up into curled-up plates. Sedimentation crusts formed in standing water and developed where surface flow was hindered. In puddles, the larger grains sank rapidly and formed the bottom layer, whereas the finer grains deposited at the top.

Pavement crusts. Desert pavement-like soil surfaces were commonly observed in arid and semi-arid areas. The soil top layer consisted of a gravel or pebble-size material embedded in a crust, the microstructure of which was very similar to the three-layered structural crust described above with a pronounced vesicular structure, especially below the pebbles (Fig. 2). Such pavement crusts often developed where the erosion crust and the top layers have been scoured by water erosion so that the gravelly B layers outcropped. Nevertheless, the formation processes of the crust embedding the coarse fragments are not yet fully documented. Some observations suggested that such a crust was mainly formed of wind-deposited particles which were subsequently subjected to similar processes to those described for the formation of the filtration pavement (Bryan, 1973). Provided the residual coarse fragments were sufficiently abundant, this typical surface seemed to have reached a steady state.

Crusting pattern. In clayey and silty arid soils, crusting followed the general pattern which was observed in the temperate areas : (i) sealing of the surface by a structural crust and (ii) development of a depositional crust. In the sandy arid soils, crusting followed a specific space- and time-dependent sequence (Fig. 2) which showed that the various types of crust were genetically related.

CONCLUSIONS

Our observations stressed the point that crust formation processes were very similar under temperate and arid conditions. In both climatic areas, three main stages could be observed : (i) the aggregate breakdown during wetting (structural crusts) ; *in situ* particle-size separation could occur (layered structural crusts and some temperate structural crusts), (ii) the particle detachment and transport by surface water flow or/and wind (erosion and pavement crusts), (iii) the depositional stage (depositional crusts, runoff depositional crusts, sedimentational crusts).

Even though this general crusting pattern was valid in both climatic areas, great differences were observed. Under temperate conditions, soil surface degradation was restricted to the structural and depositional crusts : no further stage was reached. In particular, erosion crust could not develop because : (i) no vertical textural differentiation could be observed in the structural crust, therefore scouring could not greatly change its morphology, (ii) crusting mainly occurred on seed-beds where surface roughness generally remained sufficient to hinder runoff along the slope, which limited the lateral differentiation in structural and depositional crusts, (iii) temperate crusts did not develop over a long time : they could be rapidly destroyed by faunal activity, cracking and tillage. By contrast, whole space- and time-dependent sequences (structural, erosion, runoff, depositional and sedimentation crusts) commonly occurred under arid conditions. Besides, the lateral differentiation was enhanced by wind which promoted the formation of erosion crusts surrounded by sandy micromounds capped with drying crusts.

Both the similarities and the differences stated above should lead to a better understanding of the mechanisms which govern soil surface crusting. Detailed study of the long-lasting structural stage in the temperate environment should provide some insight into the very fugacious processes involved in sealing under arid conditions. Conversely, the lateral differentiation described in the arid areas should help distinguish the various types of crust microhorizons in the temperate ploughed soils.

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SUMMARY

Both temperate loamy cultivated soils and variously textured arid pasture soils were studied. Field samples were observed at the successive stages of the crusting sequences, using macro- and micromorphological techniques. In temperate areas, two main crust types could be described : structural crust and depositional crust. In arid areas, similar crusts were observed on clayey and silty soils, and six specific types could be determined on sandy soils : drying crust, layered structural crust, erosion crust, runoff depositional crust, sedimentational crust and pavement crust. In both climatic areas, the crusting patterns were similar with three main stages : (i) aggregate breakdown during wetting with possibly *in situ* particle-size sorting, (ii) particle detachment and transport by surface water flow and/or wind, (iii) deposition stage. Nevertheless, the time-sequence was much more extended in the arid areas, and the lateral differentiation was much more marked. The micromorphological characteristics of the crusts suggest that the various mechanisms which are generally involved in soil crusting occurred in various ways according to space and time, and to soil and environment conditions.

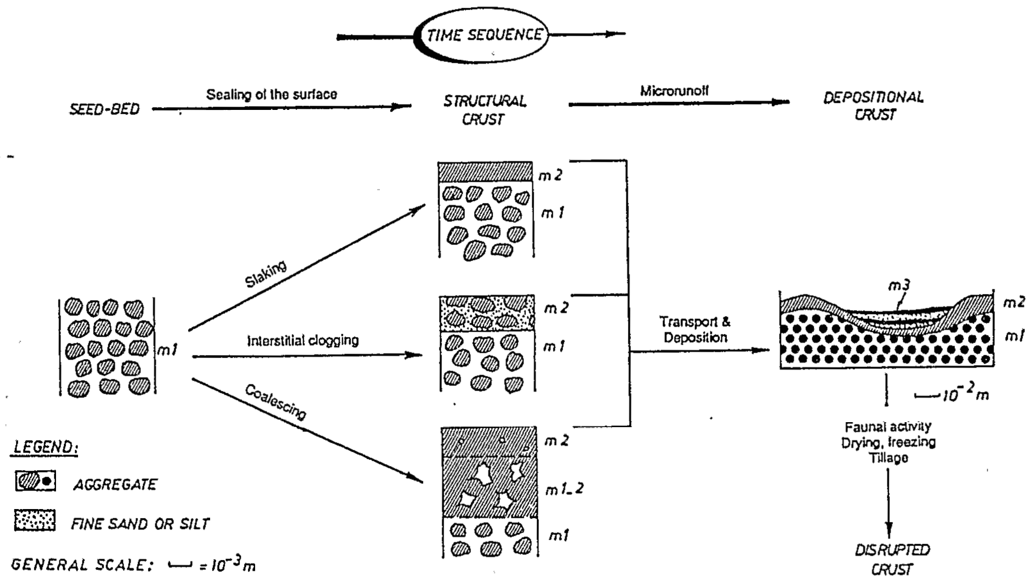
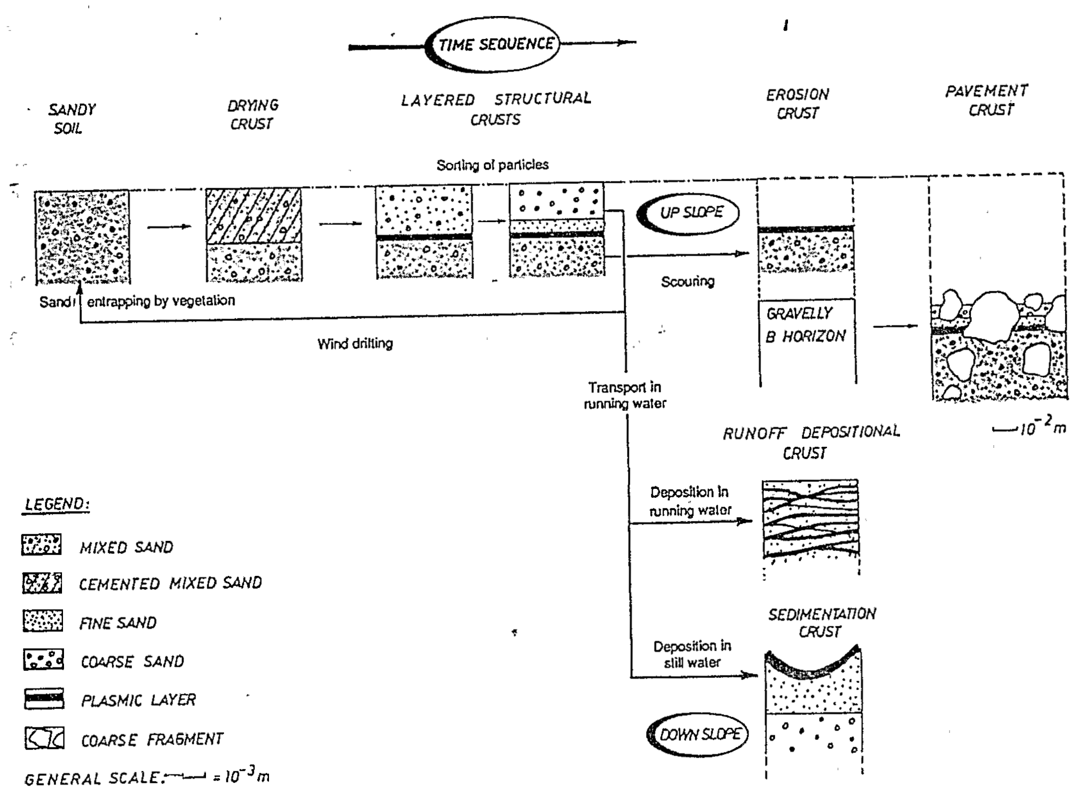


Fig. 1: Crusting pattern in temperate areas (loamy cultivated soils)

Fig. 2: Crusting pattern in arid areas: sandy pasture soils



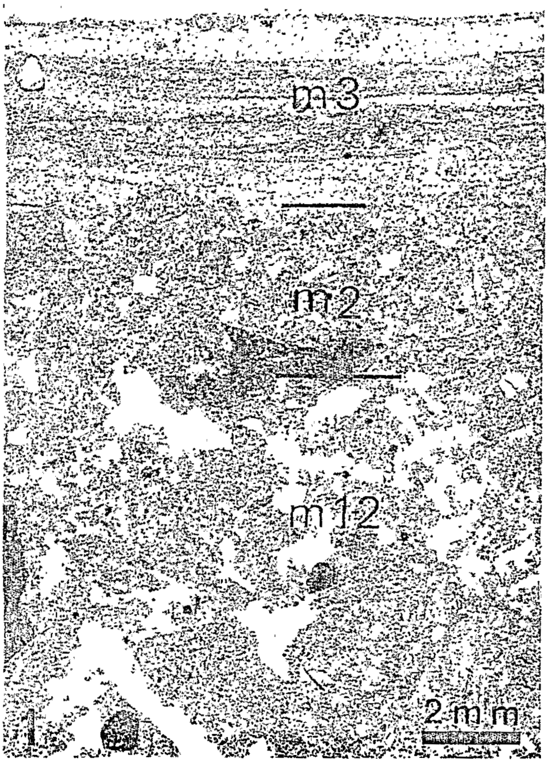


Photo 1: Temperate crust (depositional crust on a loamy cultivated soil). Microprofile with m3/m2/m1-2 microhorizons. M1-2 is more or less pedic, slightly packed, with large and 3-D continuous interconnected voids. M2 is apedic, dense, with isolated voids. M3 is microlaminated, with alternate clayey and silty microbeds (plain light).

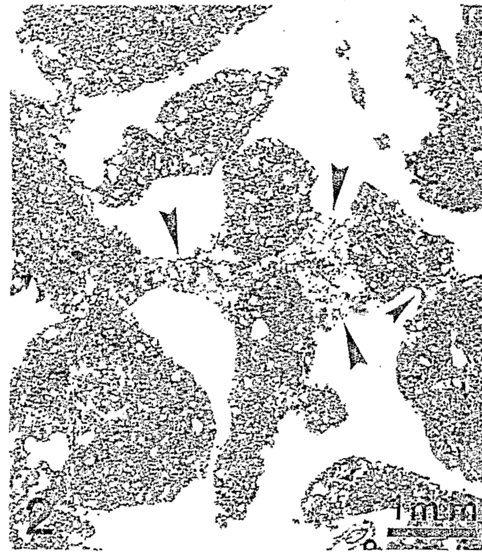


Photo 2: Temperate crust (structural crust on a loamy cultivated soil). Occurrence of illuvial silt bridges (arrows) between undisturbed peds 5 mm below the surface (plain light)

Photo 3: Arid crust (double-layered structural crust on a sandy pasture soil). *In situ* sorting of particles induced a sandy microlayer (s) at the top and a clayey microlayer (c) at the bottom just above undisturbed sandy material (u). Many vesicles (v) occurred in such a crust (S.E.M. with B.E.S.I. mode)

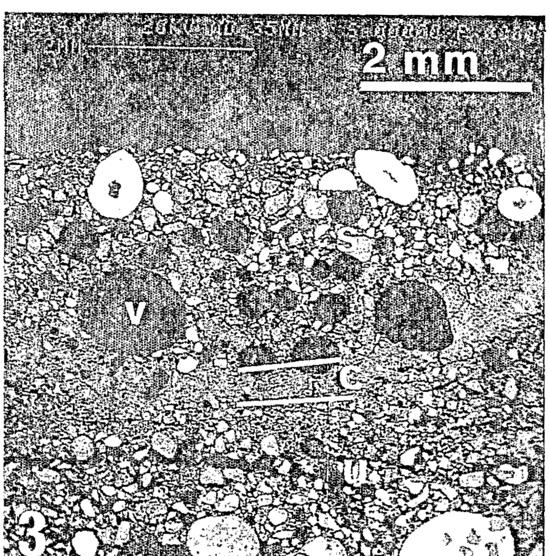


Photo 4: Arid crust (runoff depositional crust on a sandy pasture soil). Interbedding of alternate sandy and clayey microbeds (plain light).