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Soil surface sealing and crusting 2

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SOIL CRUSTING

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INTRODUCTION

Soil crusts are specific modifications in the top soil caused by natural events such as raindrop impact and the following drying process. They consist in the formation of hard thin layers at the soil surface and are widespread especially in the soils of arid and semiarid regions. Their thickness usually ranges from less than 1 mm to 5 cm (Evans and Boul, 1968). When dry, these features are more compact, hard and brittle than underlying soil materials and not only decrease both the size and the number of pores, but also modify the arrangement of the pore system (Pagliai *et al*., 1983a; Bresson and Boiffin, 1990; Norton, 1987; Valentin and Ruiz Figueroa, 1987; West *et al*., 1992).

In temperate areas, surface crusts mainly develop on unstable loamy soils (Mucher and De Ploey, 1977), especially when cultivated (Pagliai *et al*., 1983b; Pagliai, 1987; Norton and Scrhoeder, 1987). In tropical areas, soil crusting occurs on a wider range of soils and is serious not only in the drier regions, but throughout the range of climatic regimes. In humid areas, intensive cultivation results in exposure, for some time, of the soil surface to the destructive effect of high energy rains. At the same time, the loss of organic matter content is very rapid. In these fragile environments the extent of bare areas increases, and the sustainment of biomass production is reduced (Valentin and Janeau, 1989).

From the agronomic point of view the most important disadvantages of soil crusts are the influences they have on seedling emergence and water infiltration.

The effect on seedling emergence is important for many cultures, especially for those with small seeds and when the time of emergence is critical for climatic or marketing reasons. In some cases expensive replanting is necessary.

The decrease of water infiltration in crusted soils produces serious problems for irrigation especially where the shortage of water reduces the possibility of large scale use, obliging the farmers to adopt a policy of rational consumption. Moreover the reduction of water infiltration consequently increases the surface run-off causing both erosion problems and environmental risks due to the pollution of surface waters following the possible nutrient losses by the increased run-off. Also the reduced soil-atmosphere gaseous interchanges contribute to decrease crop yields.

Epstein and Grant (1973) found that soil erodibilty is a function of the rate and extent of crust formation, noting that soil loss reached a maximum during the initial 10 min of rainfall, then decreased to a constant. It is well known that during crust-forming rainfall events, water infiltration decreases to a constant with time, creating a concomitant inverse increase in run-off volume. Increased run-off, coupled with an enhancement of rainsplash energy due to the presence of overland flow, implies that the overall erosivity of the crust-forming event will increase to a maximum with time. Therefore, the observed decreases in soil erosion that accompany increases in water erosivity suggest a decreasing soil erodibility associated with crust formation (Moore and Singer, 1990).

MECHANISMS OF CRUST FORMATION

Crusting takes place mainly in the soils where the stability of surface aggregates is low. The following mechanisms are presumed to play an important role in the formation of soil crusts (McIntyre, 1958; Robbins *et al.*, 1972):

1) mechanical destruction of soil surface aggregates by raindrop impact;

2) leaching of fine particles and their subsequent deposition in the underlying pores ("washing in");

3) compaction of the soil surface to form a thin film which restricts both the further entry of water and the movements of fine particles in the soil pores.

4) cementation of the slaked soil at the soil surface due to the drying and reorientation. Upon drying, in fact, the orientation of the particles would contribute to the rigidity of the soil crusts (Ferry and Olsen, 1975).

The crusts formed as a result of the above described mechanisms of formation are called "structural crusts". Sometimes the crusts can also be formed by translocation of fine soil particles, deriving from the destruction of surface soil aggregates, and their deposition at a certain distance from their original location. In this case they are called "depositional crusts" (Chen *et al*., 1980).

SOIL PROPERTIES RELATED TO CRUST FORMATION

The susceptibility of soils to crusting not only depends on the external factors such as raindrop impact, which acts according to the above described mechanisms, but also on the following intrinsic soil factors:

Soil texture - Soil particle size distribution, particularly clay, affects soil crusting. A high clay content generally favours aggregation and reduces the rate of crust formation, although clay mineralogy and exchangeable cation composition can modify this generalisation. Medium-textured soils (<20% clay) are usually very susceptible to crusting. In extremely sandy soils the amount of clay, once dispersed, is probably not sufficient to clog the conducting pores at the soil surface. Coarse fragments seem to protect the smaller surface aggregates from raindrop impact - in the same way as a mulch does - thus increasing infiltration and reducing erosion (Collinet and Valentin, 1984).

Clay mineralogy - Generally if the dominant clay mineral of the clay fraction is kaolinite, crusting should be less serious, while soils containing smectite, illite and micaceous minerals are most prone to crusting (Miller, 1987; Collinet, 1988).

Organic matter content - It is well known that organic matter is one of the most important aggregate-stabilising agents in soil. The effects of organic matter on aggregate stability have been widely studied on various soil types. When soils are intensively cultivated, the susceptibility to crusting is increased and this can be related to the progressive decrease of organic matter content.

Sesquioxide content - The stabilising effect of Fe and Al hydrous oxides are commonly regarded as an important factor in aggregate formation.

Exchangeable cations - Saturating cations also play a leading role in crust formation due to their ability to disperse and flocculate the colloidal materials. It is well known that a high percentage of exchangeable sodium (high ESP) and in some cases exchangeable Mg, favours clay dispersion, with resulting effects on the increase of crusting.

Soil water content - Aggregates "explode" more easily when they are initially dry and then wetted suddenly. Therefore, slaking and dispersion occur more rapidly when rain falls on a dry soil, compared to soil that is already wet (Valentin, 1986). In fact, when the rainfall suddenly covers a dry aggregate its periphery is wetted and water moves into the aggregate compressing the air ahead of it. As the wetted zone is weakened by swelling and the pressure of entrapped air increases in proportion to its compression, the aggregate is shattered and air bubbles out (air slaking). The final result is the overall collapse of the shattered aggregate. Therefore, the raindrop impact can cause the mechanical destruction of soil aggregates because of its kinetic energy and because of the air slaking process.

METHODS USED IN SOIL CRUSTING INVESTIGATION

A fundamental contribution to the study of crust formation and problems related to the presence of a crust is given by the observations of crust morphology, which may range from the field or plot scale using the unaided eye or a low power lens to the micrometer scale using optical and scanning electron microscopes. Each scale of observation offers unique information concerning processes important to the development of surface crusts. The scale of observation used to describe crust morphology depends on the objective of the study, equipment available, and skills of the researcher, but integration of observations at all scales is needed to achieve a complete understanding of crust formation. In fact, macro-scale observations generally cannot be used to resolve microfabric alteration, microfeatures and porosity within a crust that indicates processes that have been important in its development. To describe these features, observations at a higher magnification using an optical or electron microscope are needed.

Use of optical or electron microscopes has allowed observations of changes in amount, shape, size and arrangement of pores, changes in ratios of groundmass (coarse particles) to micromass (fine particles), particle orientation, microlayering, and other microfeatures that have been associated with processes of crust formation. Optical (petrographic) microscope observations have been made on thin sections prepared from undisturbed samples taken from the surface of a crusting soil following the methods for thin section preparation used in soil micromorphology (Murphy, 1986). The combination of optical and electron microscopes and image analysis has allowed the quantification and characterisation of porosity in soil crusts, which is very important as regards water infiltration and seedling emergence (Pagliai *et al*., 1983a, b; Pagliai, 1987; Norton, 1987; West *et al*., 1992; Bresson and Valantin, 1994). The time and specialised equipment needed for thin section preparation and observation, however, limits the universal application of this technique for descriptions of crust morphology.

Surface crusting is a dynamic process strongly related to the amount and intensity of rains and to the pedological characteristics of soils. For a detailed study of this phenomenon in relation to spatial variability and its evolution the use of a rainfall simulator, in which it is possible to establish the rainfall rate, the drop size and its kinetic energy, is very appropriate (Norton, 1987; Moore and Singer, 1990). This apparatus is fundamental to the study of the relationships between crust formation, surface run-off and soil erosion.

In order to study the negative effects of soil crusts on seedling emergence the measurement of crust resistance to penetration is useful. This can be done with the pocket penetrometer (Hadas and Stibbe, 1977).

To determine the main chemico-physical properties of the crusts it is fundamental to measure the water infiltration rate, the soil sodicity and electrolyte concentration, and the organic polymers (Shaimberg and Singer, 1985).

EFFECTS OF SOIL MANAGEMENT ON THE FORMATION, PREVENTION AND CONTROL OF SURFACE CRUSTS

Among soil management practices soil tillage has the strongest influence on soil crusting. The main aims of soil tillage are seedbed preparation and weed control. The conventional tillage contributes materially in obtaining good tilth, i.e., a crumbly to granular structure typical of ploughed soils (Figure 1). Such a kind of soil structure is not stable, in fact the long-term intensive cultivations cause a decrease of organic matter content, also because, in modern agriculture, there is a strong reduction in the application of organic materials to the soil, due to the severe shortage of farmyard manure. Associated with a decrease of organic matter content there is also a strong decrease in the living organism population. Consequently the soil aggregate stability strongly decreases and in the soils susceptible to crusting a single rainfall event is sufficient to form the surface crust. Figure 2 represents an example of field conditions after surface crust formation. The crust mainly occurs when the soil is bare and the surface aggregates are subjected to the direct action of raindrop impact, i.e., after seedbed preparation and during seedling emergence, just when good soil conditions are critical for crop development.

Figure 3 represents a typical and detailed example of a surface structural crust of a cultivated sandy loam soil. At the surface there is a thin layer of horizontally oriented plate-like particles. This compact thin layer contains few, if any, large pores. In fact, in this crust the porosity is represented by few very thin fissures (planar pores) oriented parallel to the soil surface without continuity in a vertical sense and, therefore, of no use for water infiltration. Figure 4 represents another typical surface crust of the same sandy loam soil. In this case the crust is formed by a very thin layer of fine materials, particularly strongly oriented and cemented clay ("sealing crust"). Just below this layer spherical pores, called vesicles (Brewer, 1964; Bullock *et al*., 1985), are banded and distributed parallel to the soil surface and they are caused by air entrapped during drying processes that occur after a heavy rainfall. Such a pattern, typical of a wide range of cultivated soil types, is an index of poor aggregate stability because the vesicular structure is unstable and transitory (Brewer, 1964; Kemper and Miller, 1974).

In cultivated soils depositional crusts are also very common. In fact, after the mechanical destruction of soil aggregates the dispersed particles can be transported by run-off. In the following drying process their deposition can take place on a previously formed crust, giving a layer of different texture (Pagliai and La Marca, 1979).

Figures 5 and 6 show other examples of typical crusts of loam soils under continuous conventional tillage (ploughing). Figure 5 shows a surface crust formed by compacted layers intercalated by thin planar pores oriented parallel to the soil surface and not interconnected in a vertical sense. In this type of crust the reduction of porosity, with respect to the soil material just beneath it, is very evident. In the type of crust represented in Figure 6 such a reduction of soil porosity is less evident. In fact, this crust shows a more complex porosity pattern: there are many planar pores, some also large, oriented parallel to the soil surface not vertically interconnected, giving a platy structure (Bullock *et al*., 1985). Moreover there are the vesicles formed by entrapped air. Bresson and Boiffin (1990) reported gradual alteration of polyconcave pores with rough walls in unaffected soil to smooth-walled convex vesicles near and in the surface crust.

Porosity is now considered the best indicator of soil structure conditions and its characterisation provides a realistic basis for understanding water movement in soil; to assess the suitability of soil for root growth; to study the activities and movement of soil organisms; etc.

A reduction in porosity from 30 to 90% resulting from formation of structural crusts has commonly been reported (Pagliai *et al*., 1983a; Pagliai and Guidi, 1986; Norton, 1987; West *et al*., 1992). Associated with the porosity decrease in structural crusts is a reduction in the mean size of pores (Pagliai *et al*. 1983a; Bresson and Boiffin, 1990; West *et al*., 1992). As already said, the depositional crusts show a more complex soil porosity pattern. In most studies the fine-grained microlayers have been reported to have few or no pores larger than a few micrometers in diameter. These microlayers are intercalated by coarse-grained layers that generally have a greater total porosity than the fine-grained microlayers. However, a reduction of both total porosity and pore size has also been demonstrated in depositional crusts with respect to uncrusted soils (Kooistra and Siderius, 1986; Pagliai, 1987; Valentin and Ruiz Figueroa, 1987; Arshad and Mermut, 1988). However, for a thorough characterisation of soil crusts, especially in relation to their hydraulic properties, data on total porosity and pore size distribution are important but not sufficient. Parameters such as pore shape, pore continuity and the relative position of aggregates and pores are very important for evaluating the interactions of soil crust-water infiltration-crop development. The spherical pores (vesicles) present in the crusts are completely isolated in the soil matrix, and the planar pores oriented parallel to the soil surface not interconnected in a vertical sense are of no use for water infiltration and seedling emergence. The reduction of water infiltration demonstrated in crusted soil depends on this porosity pattern. Such porosity information, which cannot be obtained with the commonly used methods such as calculation from bulk density, mercury intrusion, water retention, and nitrogen sorption, can be supplied by the micromorphometric method, i.e., image analysis on thin sections prepared from undisturbed soil samples (Pagliai *et al*., 1983a,b; Murphy, 1986; Norton, 1987; Ringrose-Voase, 1987).

As already said, continuous conventional tillage is the most responsible for crust formation. Many experiments have shown that conservation tillage practices such as zero tillage, minimum tillage, surface mulching, contour ploughing, etc., reduce run-off, soil loss and are best suited to preventing and controlling crusting. Pagliai *et al*. (1983b) and Pagliai and Guidi (1986) found that, in a clay loam soil planted to grapevines under zero tillage versus conventional tillage, the formation of surface soil crusts was strongly reduced in no-tilled soil with respect to conventionally tilled soil. The soil porosity in conventionally tilled soil showed a strong reduction in the surface layer (0-2 cm) affected by the crust with respect to the layer below 5 cm, while in no-tilled soil the porosity did not show significant differences between the surface layer and the layer below 5 cm (Figure 7). Thin sections of samples from no-tilled soil showed that the layer of oriented particles were absent and pores were present even from the soil surface (Figure 8). A factor that contributed to the prevention of soil crust in no-tilled soil, was the remains of grass plant killed by the herbicide (in no-tilled soil the weed control was carried out by using herbicides) on the soil surface. Such grass remains acted as a mulch, while in the conventionally tilled soil a large number of surface soil aggregates were subjected to the direct action of raindrop impact. Similar results were also obtained in a loam soil cultivated to grow autumn-sown wheat under different tillage practices (Pagliai *et al*., 1989; Pagliai *et al*., 1995). Surface crusts, like those represented in Figures 5 and 6, formed frequently in ploughed plots, while in plots under no-tillage, minimum tillage and chisel ploughing the surface crusts were absent or strongly reduced (Figure 8) and this indicates that ploughing forms surface soil aggregates which are less rain-stable than after no-tillage, minimum tillage or chisel ploughing. Also in this soil the porosity was more homogeneously distributed along the cultural profile under reduced tillage, while in the ploughed soil there were significant differences between the surface layer (0-2 cm) and the layer below 5 cm (Figure 7). Therefore, the adoption of reduced tillage practices and the reintroduction of the traditional farming rotations, instead of the continuous monocultures, should be strongly reconsidered by farmers in order to prevent soil degradation and, therefore, also soil crusting (which is an aspect of soil degradation) and consequently to reduce surface run-off and soil erosion. Run-off is the main phenomenon responsible for the pollution of surface water, because it can transport, for example, a great amount of nutrients added to soil by chemical fertilisation.

Another important management practice for the prevention of crust formation is the application of organic materials to the soil. Such organic materials can carry out their beneficial action in two ways: one due to chemico-physical action of organic matter that increases the stability of soil aggregates and so rendering them more rain-stable; the second due to the mechanical action of the organic materials. In fact, the adhesion of soil particles to the organic materials can cause the formation of vertical cracks and microcracks in the layers forming a crust (Figure 9) and these are of importance for improved water infiltration. Pagliai *et al*. (1983a) found that the addition of farmyard manure, sewage sludges, compost and livestock effluents to a sandy loam soil and a silty clay soil played an important role in the prevention of soil crust formation. Some details of the variations of soil porosity in these soils following the application of organic materials are reported in Figure 10. In untreated soils where the surface crust was well developed the porosity was lower.

The addition to soil of gypsum/phosphogypsum is another important practice to combat crust formation especially when sodicity is high or electrolyte concentration is very low (van der Watt and Claassens, 1990; Borselli *et al*., 1996).

Irrigation management can also strongly influence crust formation. The chemical composition of irrigation water and the kinetic energy of water applied by overhead irrigation are the most important factors to consider in the case of irrigation of soils susceptible to crusting.

Many studies have clearly demonstrated that the use of synthetic soil conditioners, such as dextrans, polyvinyl alcohol, polyacrylamide, etc., increase the aggregate stability of soils. Therefore, such conditioners can be useful and efficacious in the prevention of crust formation (Oades, 1976; Pagliai and La Marca, 1979). The limitation of the use of these conditioners on a large scale depends on their cost.

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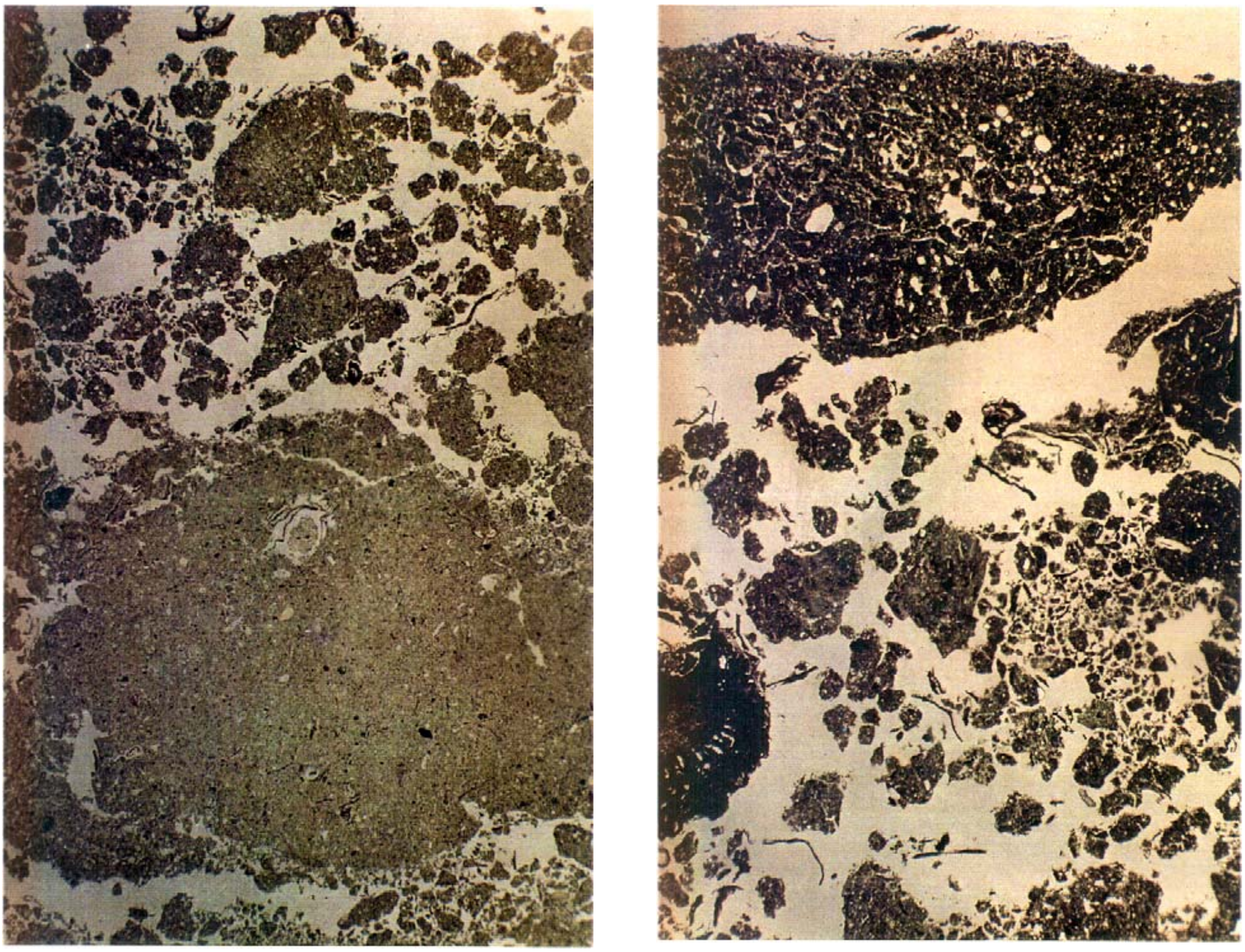


Figure 1 - Macrophotograph of a vertically oriented thin section from undisturbed samples of the surface layer (0-5 cm) of conventionally tilled loam soil collected one week after tillage and before any rainfall events (Left) and after the first rainfall event (a rain of 40 mm) (right). A crumbly to granular structure created by the tillage is evident (Left). At the surface a compacted layer originated by the mechanical destruction of the aggregates can be noticed (right). The decrease of soil porosity with respect to the soil beneath this layer is very evident. Picture taken under a macro-epidiascope with plain polarised light (the white areas represent pores). Frame length 3 cm.

Figure 2 - Example of field conditions after the formation of surface crust.

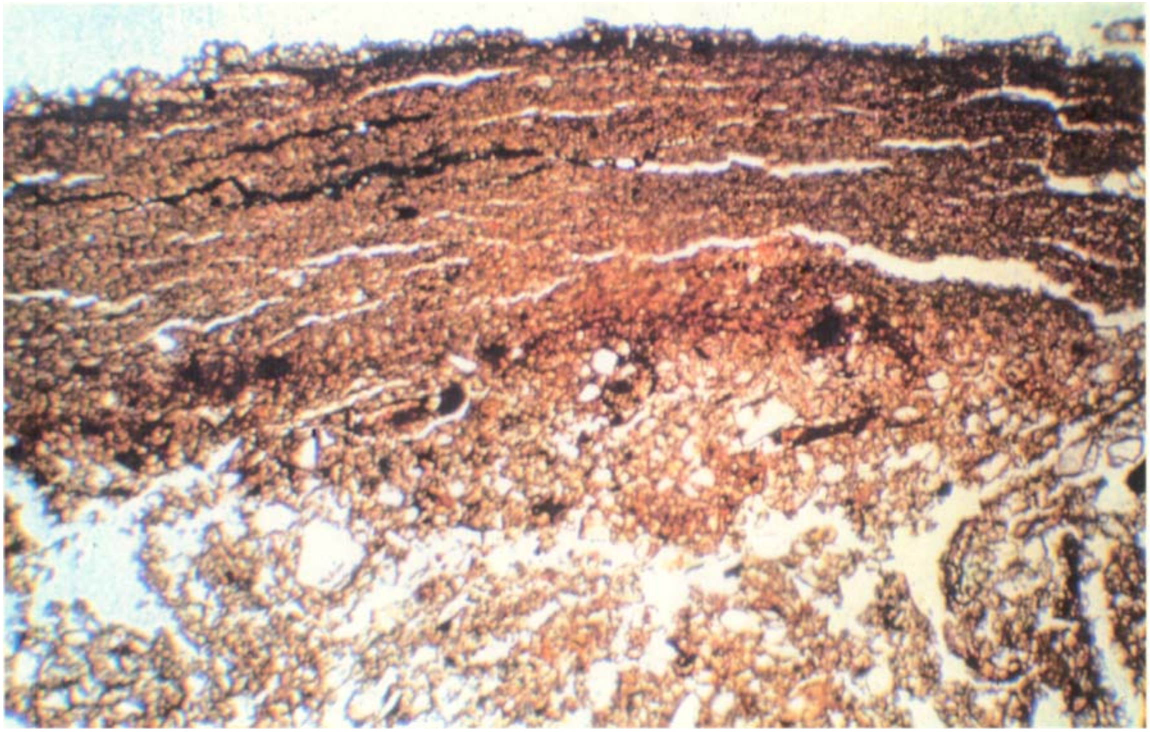


Figure 3 - Microphotograph of a vertically oriented thin section from undisturbed surface samples of a cultivated sandy loam soil. The fine-textured layer at the surface represents the soil crust. The porosity in this layer is very low and formed only by thin planar pores oriented parallel to the soil surface and not interconnected in a vertical sense. It is easy to understand that these pores are of no use for water infiltration. When dry this layer is very hard and, therefore, represents a great obstacle for seedling emergence. Picture taken under a microscope with plain polarised light. Frame length 5 mm.

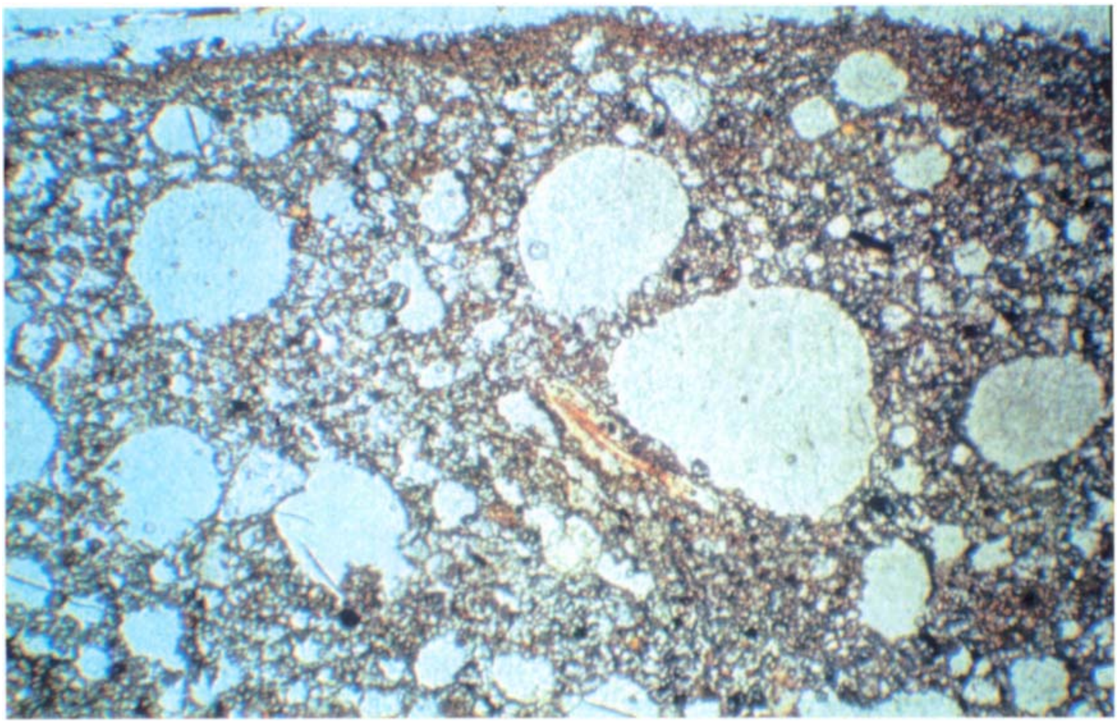
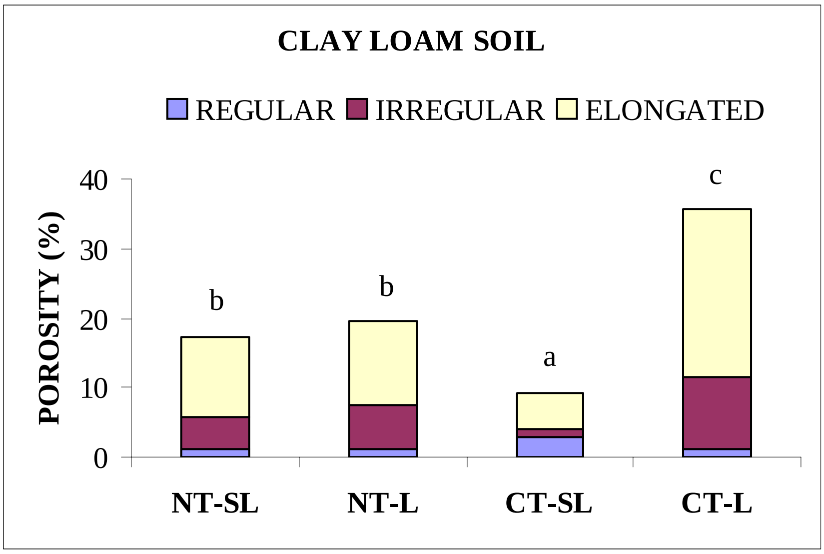


Figure 4 - Microphotograph of a vertically oriented thin section from undisturbed surface samples of a cultivated sandy loam soil. This type of crust can be called "sealing crust", in fact, at the soil surface a very thin layer of fine particles is rapidly formed during the drying process. This thin layer interrupts the soil-atmosphere gaseous exchange and the spherical pores (vesicles) with a banded distribution pattern parallel to the soil surface are formed by entrapped air. Picture taken under a microscope with plain polarised light. Frame length 5 mm.

Figure 5 - Macrophotograph of a vertically oriented thin section from undisturbed samples of the surface of conventionally ploughed loam soil. The presence of a surface crust, formed by a compacted layer intercalated by planar pores oriented parallel to the soil surface, can be noticed. Picture taken under a macro-epidiascope with plain polarised light. Frame length 3 cm.

Figure 6 - Macrophotograph of a vertically oriented thin section from undisturbed samples of the surface of conventionally ploughed loam soil. In this case the crust appears thicker than that represented in Figure 5. The porosity is also higher but formed by some "vesicles" and planar pores, some also large, oriented parallel to the soil surface. The continuity in a vertical sense is practically absent. Picture taken under a macro-epidiascope with plain polarised light. Frame length 3 cm.



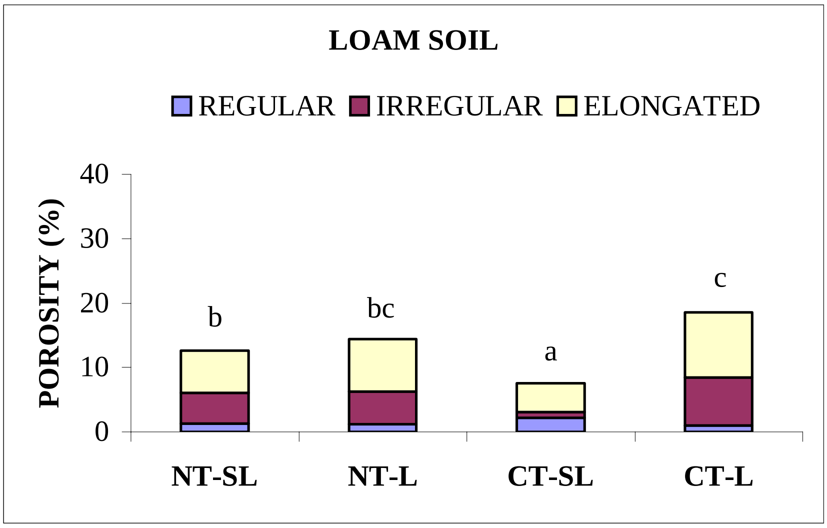


Figure 7 - Effects of different management practices (NT: no-tillage; CT: conventional tillage) on soil porosity measured on thin sections from undisturbed samples by image analysis and expressed as a percentage of the total area occupied by pores larger than 30 μm per thin section, in the surface layer (0-2 cm) affected by the crust (SL) and in the layer below 5 cm (L). This is the first step of porosity characterisation. The pore size distribution and the orientation of elongated (planar) pores can also be easily measured by image analysis. The low porosity value in the crust layer of the tilled loam soil clearly illustrates that this soil is more susceptible to crusting than the clay loam soil. Total porosity values followed by the same lower case letter are not significantly different employing Duncan's Multiple Range Test.

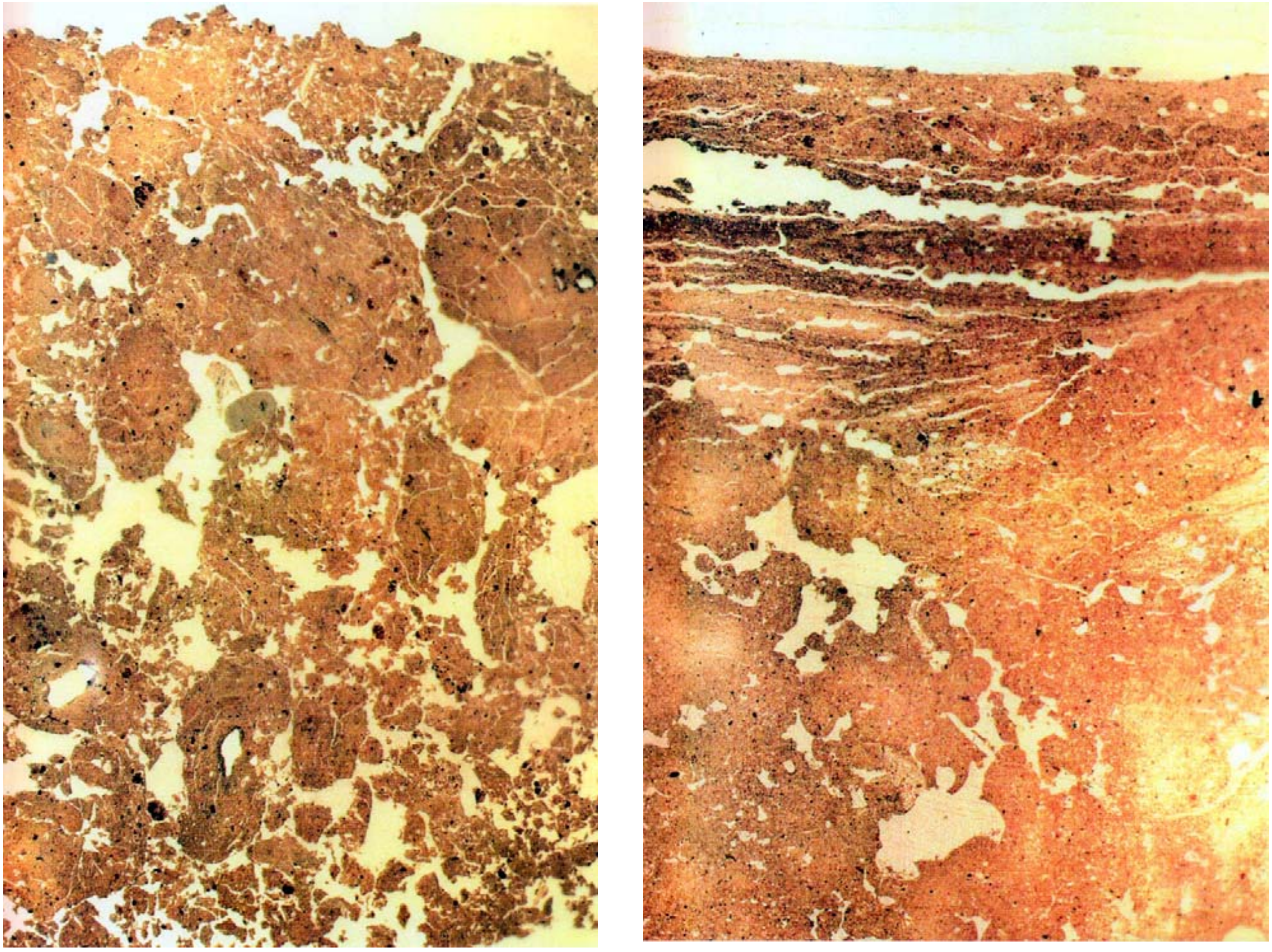


Figure 8 - Macrophotographs of vertically oriented thin sections from undisturbed surface samples of a loam soil under minimum tillage (left) and conventional tillage (right). This is another good example of absence of surface crust in minimum tilled soil where a subangular blocky structure is present throughout the surface layer, while the crust is very pronounced in conventionally tilled soil. Picture taken under a macro-epidiascope with plain polarised light. Frame length 3 cm.

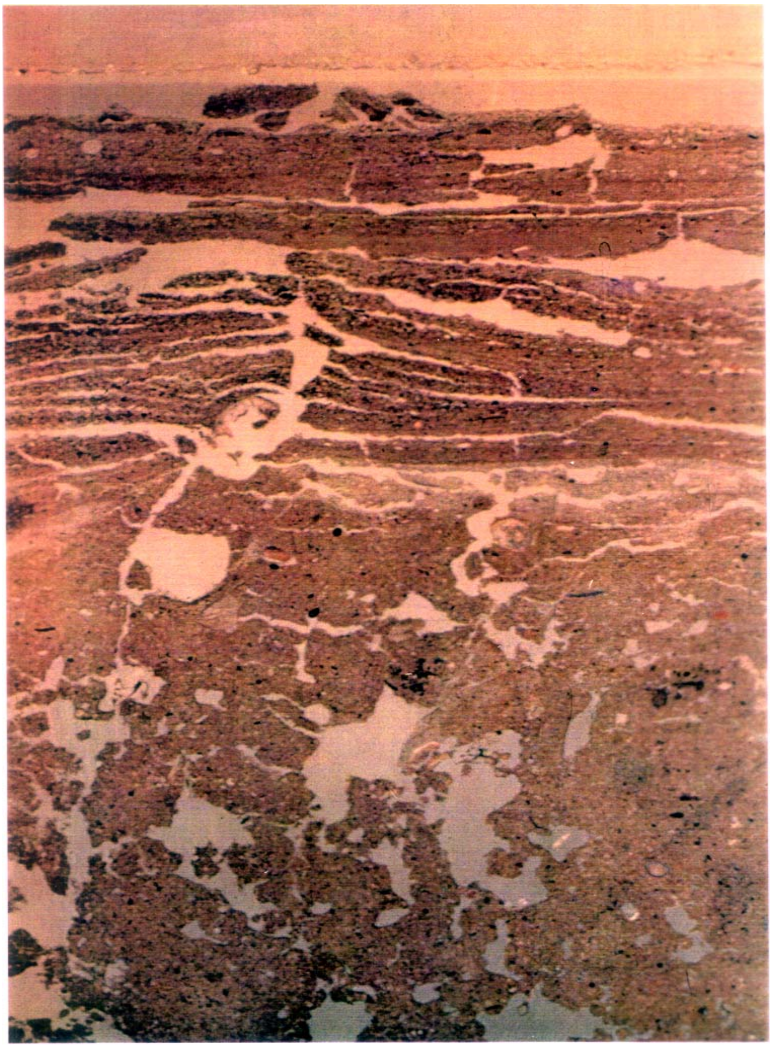
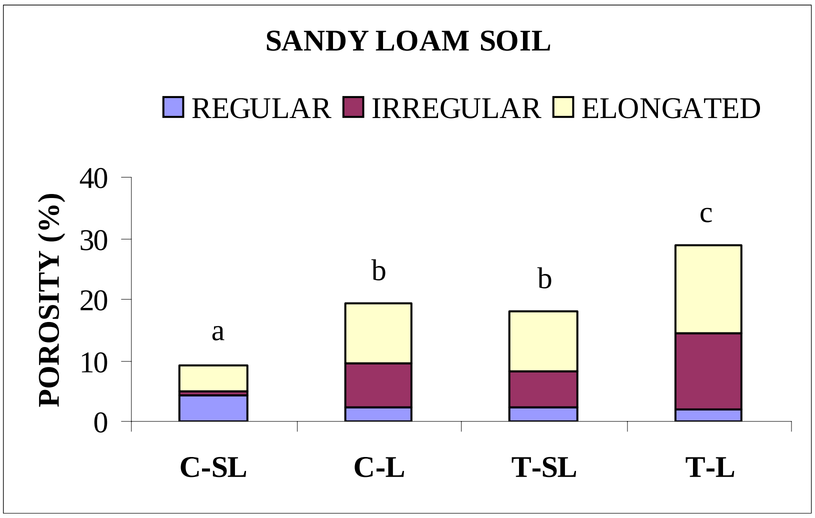


Figure 9 - Macrophotograph of a vertically oriented thin section from undisturbed surface samples of a cultivated loam soil. The presence of a very thick surface crust is very evident. However, the presence of organic material can cause vertical cracks in the compacted layers, thus creating the continuity in a vertical sense very important for water infiltration and seedling emergence. Picture taken under a macro-epidiascope with plain polarised light. Frame length 3 cm.



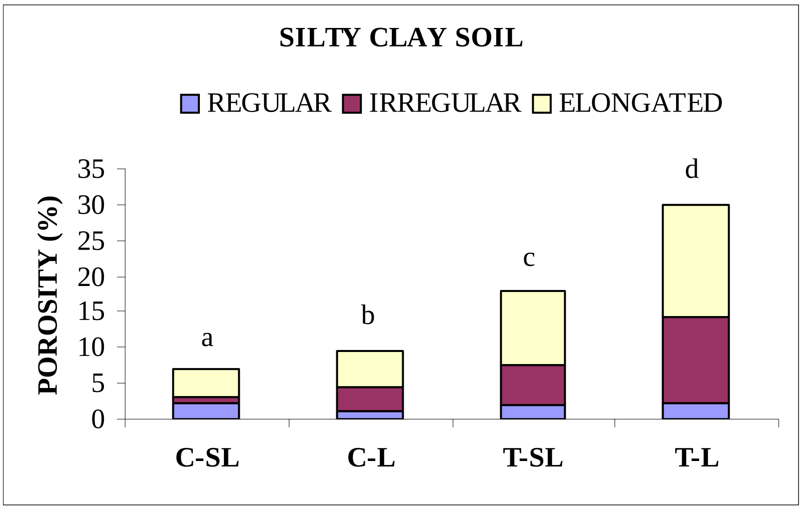


Figure 10 - Effects of the addition of organic materials (C: control; T: treated with compost) on soil porosity measured on thin sections from undisturbed samples by image analysis and expressed as a percentage of the total area occupied by pores larger than 30 μm per thin section, in the surface layer (0-2 cm) affected by the crust (SL) and in the layer below 5 cm (L). Total porosity values followed by the same lower case letter are not significantly different employing Duncan's Multiple Range Test.