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Image Analysis and Microscopic Techniques to Characterize Soil Pore System

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Abstract

Soil porosity is widely recognised to be the best indicator of soil structure quality. Quantification of the pore space in terms of shape, size, continuity, orientation and arrangement of pores in soil allows us to define the complexity of soil structure and to understand its modifications induced by anthropogenic activity. Characterisation of the pore system provides a realistic basis for understanding the retention and movement of water in soil. This is now possible because of the increasing use and availability of the technique of image analysis which makes possible the automated measurement of soil porosity on thin sections or impregnated soil blocks prepared from undisturbed soil samples. Significant correlations have been found between elongated continuous transmission pores and hydraulic conductivity that can be useful in the development and improvement of models for predicting water movement. The aim of this paper is also to discuss some examples of the application of soil micromorphology and image analysis to evaluate the impact of agricultural activities and to quantify some aspects of soil degradation through the complete characterisation of soil pore system.

Key words: Image analysis, pore size distribution, pore shape, pore continuity, soil structure.

Introduction

To evaluate the impact of management practices on the soil environment it is necessary to quantify the changes which occur in the soil structure. Soil structure is one of the most important properties affecting crop production because it determines the depth that roots can explore, the amount of water that can be stored in the soil and the movement of air, water and soil fauna. Soil quality is strictly related to soil structure and much of the environmental damage to intensively-farmed land such as erosion, compaction and desertification originate from soil structure degradation. To quantify soil structural changes following agricultural activities, besides traditional measurements such as aggregate stability and hydraulic conductivity, pore space measurements are being increasingly used. In fact, it is the size, shape and continuity of pores that affect most of the important processes in soils (Ringrose-Voase and Bullock, 1984). Detailed insight into the complexity of the pore system in soils can be obtained by using mercury intrusion porosimetry to quantify pores with equivalent pore diameter < 50 μm (micropores) within the soil aggregates (Fiès, 1992). Image analysis on thin sections prepared from undisturbed soil samples allows pores > 50 μm (macropores) to be quantified, which determine the type of soil structure (Pagliai et al., 1983b, 1984).

Soil Structure

Soil structure may be defined either as "the shape, size and spatial arrangement of individual soil particles and clusters of particles (aggregates)" or as "the combination of different types of pores with solid particles (aggregates)". Soil structure has generally been defined in the former way and measured in terms of aggregate characteristics. These can be related to plant growth only empirically. In fact, it is the pore shape, the pore size distribution and the pore arrangement which affect many of the most important processes in soil that influence plant development such as storage and movement of water and gases, solute movements and ease of root growth. For this reason measurements of pore space are increasingly being used to characterize soil structure. In fact, between the particles arranged singly or in aggregates, there is an intricate system of pore spaces on which plant roots, micro-organisms and soil fauna depend for the storage and movement of water and air.

Soil porosity represents the liquid and gaseous soil phases. To characterize the pore system it is necessary, first of all, to determine the size distribution and shape of pores because the agronomic functions of pores depend on their size and shape.

Soil thin section preparation

For image analysis it is necessary to prepare thin sections of soil following the techniques of soil micromorphology developed by Kubiena (1970). The procedure consists in taking undisturbed soil samples using appropriate tools, containers and techniques taking care that the interior structure of the soil samples remains undisturbed. Then the soil samples, carefully packed, are transported to the laboratory, dried to avoid pronounced shrinkage phenomena, using appropriate methods, e.g. acetone replacement of the water (Murphy et al., 1986), and impregnated, under vacuum, with a polyester resin, which has the characteristic of polymerising slowly at room temperature without altering in any way the structure of the soil. Practically, this resin fills the pores of the soil. When the soil samples are hardened (generally after 4-6 weeks) they are made into vertically- or horizontally-oriented thin sections by using appropriate machines (Murphy, 1986). Their thickness is about 30 μm so that they can be analysed by the microscope in transmitted light. Thin sections can be examined using a polarising microscope at low magnification to observe soil structure. The size depends on the kind of machines available; for porosity measurement a size larger than 6x6 cm is recommended.

Image analysis

The soil thin sections are analysed with image analysers (Murphy, 1977a, b; Pagliai et al., 1983b, 1984). With the technique of image analysis it is now possible to characterize soil structure by the quantification of soil porosity in all its aspects (pore shape, pore size distribution, irregularity, orientation, continuity, etc.) on thin sections, prepared from undisturbed soil samples (Bouma et al., 1977, 1982; Murphy et al., 1977a, b; Pagliai et al., 1983b, 1984; Pagliai, 1988). This morphometric technique has the advantage that the measurement and the characterization of pore space can be combined with a visual appreciation of the type and distribution of pores in soil at a particular moment in its dynamic evolution.

Technological and theoretical advances, regarding both sample preparation and image analysis, have improved the methods for direct quantification of soil pores. These methods allow the quantification of the effects of tillage practices on soil porosity and structure and in turn the definition of optimum tillage needs for sustainable agriculture (Mermut et al., 1992; Moran and McBratney, 1992).

Image analyzers perform light-electronic analysis of the image obtained using a macroepidiascope or light or electronic microscope (Pagliai et al., 1983a ; Bruand et al., 1992; 1996). The image is filmed with a videocamera and shown on a monitor; the video signal passes through a processor that transforms the image into pixels and analyzes them individually depending on the grey level in each. Pores are measured by programming the analyzer with their corresponding grey level detected on a scale of 256 levels. Basic measurements of image analysis on pores include number, area, perimeter, diameters, projections, etc., and these are supplemented by derived quantities such as shape factors, size distribution, continuity, irregularity and orientation (Pagliai, 1988).

To characterise the microporosity (pores less than 50 μm) the thin sections must be covered by a layer of carbon, in order to allow conductivity to the electron beam, and analysed by a scanning electron microscope (SEM) with a module for backscattered electron scanning images (BESI) (Pagliai et al., 1983a). The thin sections can be examined by the SEM at several magnification. For example, if the analysis in the image analyser starts with BESI taken at x400 magnification, the size of the pixel will be 0.2 μm, therefore pores in the range of the storage pores 0.5-50 μm can be measured from the back-scattered electron scanning images (Pagliai and Vittori Antisari, 1993).

To characterise the macroporosity the thin sections can be analysed by a macroepidiascope and the image analyser being set to measure pores larger than 50 μm.

Two-dimensional images obtained can be transformed into data representing three-dimensional area percentages that are representative for three-dimensional volumes. Stereology techniques have been applied to achieve this objective (Ringrose-Voase and Bullock, 1984; Ringrose-Voase and Nortcliff, 1987; Mele et al., 1999).

Image analysis can be used not only on soil thin sections but also on polished faces of large soil blocks impregnated directly in the field with (fairly cheap) materials such as paraffin wax (Dexter, 1988), plaster of Paris (FitzPatrick et al., 1985), or resin (Moran et al., 1989).

Soil porosity characterisation

Pore shape

The shape factors allow division of pores into different shape groups. For example, pore shape can be expressed by a shape factor [perimeter^2/(4π·area)] and pores divided into regular (more or less rounded) (shape factor 1-2), irregular (shape factor 2-5) and elongated (shape factor >5) (Pagliai et al. 1983b). These classes correspond approximately to those used by Bouma et al. (1977).

The regular pores are obviously those of a rounded shape and can be distinguished in two types according to their origin: the spherical pores formed by entrapped air during soil drying and the channels and chambers formed by biological activity (root growth and movement of soil fauna). Their distinction on soil thin sections is very evident because spherical pores (vesicles, according to Brewer, 1964) have very smooth walls, while channels, even though cut in a transversal way on thin section, present rough walls with deposits of insect escrements or root exudates. The presence of many spherical pores of the first type (vesicles) creates a vesicular structure typical of soils with evident problems of degradation.

The irregular pores are the common soil voids with irregular walls (vughs, according to the micromorphological terminology of Brewer, 1964) and can be isolated (packing voids) or interconnected. The dominant presence of these pores produce the typical vughy structure (Bullock et al., 1985). In cultivated soils these pores can be produced by the action of soil tillage implements.

Two types of elongated pores can be distinguished, i.e., cracks and thin fissures (planes). The former are typical of clay soils with a depleted soil organic matter content and they are visible at the surface when the soil is dry and has shrunk. The thin fissures are the most important, especially from an agronomic point of view, in fact, they are the typical transmission pores. An adequate proportion of this type of pore (over 10% of the total porosity) generally creates an angular to subangular blocky structure of good quality. Obviously for this to be true it is necessary for these pores to be homogeneously distributed in the soil matrix. In fact, for the characterization of these pores by image analysis, it is necessary to determine not only their shape and width, but also their length. With the same procedure of width determination it is also possible to determine the length of these elongated pores, which may reflect their continuity, and it is well known that the flow of water through soil depends on the continuity of large pores. Therefore the analysis of pore patterns allows the characterization and prediction of flow processes in soils.

For root growth and water movement not only the size and continuity of elongated pores are important but also their irregularity and orientation. The ratio convex perimeter/perimeter or convex area/area of elongated pores gives information about their irregularity, tortuosity and re-entrancy. As regards water movement, for example, the very regular and the moderately regular elongated pores play a different role. The very regular elongated pores are flat and smooth pores with accommodating faces, which tend to seal when the soil is wet, thus preventing water movement. In contrast, the moderately regular elongated pores have walls which do not accommodate each other. Therefore, these pores permit water movement even when the soil is wet and fully swollen (Pagliai et al., 1984). The ratio vertical/horizontal dimensions gives the orientation of elongated pores (Pagliai et al., 1984). It is easily understandable that many soil processes such as water movement, leaching, clay migration, etc., are strongly related to the orientation of pores in soil and these processes change radically depending on whether a vertical or horizontal pore orientation is dominant.

Pore size distribution

As already said, to characterize the pore system it is necessary, first of all, to determine the shape and size distribution of pores because the agronomic functions of pores depend not only on their shape bur also on their size.

The pore size distribution is a dynamic property. It is dependent upon the water content especially in fine textured soils subjected to swelling and drying (Kutilek and Nielsen, 1994). There are a lot of studies that show the changes of pore size distribution in Vertisols at different water content, i.e. when they are water saturated after the rain and the cracks are closed due to saturation and when they are dried and the cracks are open (Schweikle, 1982; Kutilek, 1983). The changes of pore size distribution are strictly correlated with the changes of hydraulic conductivity (Kutilek, 1996).

By means of image analysis pores of each shape group can be further subdivided into a selected number of size classes according to either the equivalent pore diameter for rounded and irregular pores or the width for elongated pores. The equivalent pore diameters are calculated from the area of regular and irregular pores, while the width of elongated pores is calculated from their area and perimeter data using a quadratic equation because it is assumed that elongated pores are long narrow rectangles (Pagliai et al., 1984).

Table 1 reports the most frequently used classification scheme of pore size distribution proposed by Brewer (1964). Detailed information about the applicability of hydraulic equations in the different classes of pores are reported in Kutilek and Nielsen (1994).

According to another of the widely used classifications, that of Greenland (1977) reported in Table 2, the very fine pores less than 0.005 μm, called "bonding pores", are critically important in terms of the forces holding domains and aggregates of primary particles together; pores of less than 0.5 μm are the "residual pores" for the chemical interactions at the molecular level; pores which have an equivalent pore diameter ranging from 0.5 to 50 μm are the "storage pores", i.e. the pores that store water for plants and for micro-organisms; and the pores ranging from 50 to 500 μm are those called "transmission pores" in which the movements of water are important for plants, and, moreover, they are the pores needed by feeding roots to grow into. The water content when pores larger than 50 μm have drained, corresponds to the field capacity of the soil. The wilting point commences when most pores larger than approximately 0.5 μm have emptied.

Pores larger than 500 μm can have some useful effects on root penetration and water movement (drainage), especially in fine-textured soils. However, a high percentage of this latter type of pore (above 70-80% of the total porosity) in soils is usually an index of poor soil structure, especially in relation to plant growth. This is because surface cracks, which develop after rainfall, when the stability of soil aggregates is poor, belong to this size class (Pagliai et al., 1981, 1983b). Until now the necessary proportion of large pores for air and water transmission and easy root growth has generally been inadequately defined. In fact, adequate storage pores (0.5-50 μm) as well as adequate transmission pores (50-500 μm) are necessary for plant growth (Greenland, 1981).

Characterization of the soil pore system by image analysis of thin sections can give detailed information about soil structural conditions, moreover if climate, agronomic and management data are known, an evaluation of soil physical vulnerability is possible. Hence, the soil pore system can be considered a good indicator of soil quality, nevertheless, as for other indicators, threshold values have to be known.

According to the micromorphometric method, a soil can be classified as follows where the total porosity represents the percentage of area occupied by pores larger than 50 μm per thin section (Pagliai, 1988):

Soil very compact	when total porosity is	<5%
Soil compact	when total porosity is	5-10%
Soil moderately porous	when total porosity is	10-25%
Soil highly porous	when total porosity is	25-40%
Soil extremely porous	when total porosity is	>40%

A total macroporosity of 10% is considered to be the lower limit for good soil structural condition, anyway, only the complete evaluation, both quantitative and qualitative, of the soil pore system can produce exhaustive information on actual soil quality.

Types of soil structure

According to the definition of soil structure the different types of structure are originated by the combination and the spatial arrangement of different types of pores and aggregates. The definition of the several types of soil structure is fundamental for a first qualitative evaluation of soil physical fertility. The microscopic examination of soil thin section, by a polarizing microscope at low magnification, allows such a definition.

In general, three broad categories of soil structure can be recognized: single grained, aggregates and massive. According to Bullock et al. (1985) the main types of soil structure can be summarized as follows:

Single grain structure. - Typical of sandy soils; the quartz (sand-sized) grains are completely loose and the fine materials in the intergranular spaces are very rare. The porosity is represented by packing voids delimitated by quartz grains. When these grains are of a more or less uniform shape and size a rather compact grain structure can be originated.

Bridged/pellicular grain structure. - The sand-sized grains are bridged or coated by fine materials, usually clay, which can cement some grains to each other, so originating microaggregates.

Vughy structure. - There are no separated aggregates and the mass is broken up by scattered but not interconnected irregular pores, "vughs", and occasional channels and chambers (Bullock et al., 1985) (Fig. 1). Such a structure allows good soil aeration but the continuity of pores is limited. In the case of heavy rains pounding water can be present in the soil profile with consequent collapse of the soil structure. Such a type of structure is, therefore, unstable and transitory.

Vesicular structure. - There are no separated aggregates and the mass is broken up by rounded pores, "vesicles" (Bullock et al., 1985), originated by entrapped air during drying processes (Fig. 2). This kind of structure is an indicator of degraded soils.

Crumb structure. - The soil aggregates are more or less rounded, often rugose, well separated from each other and rather compact inside. The porosity is represented by pore space (packing voids) which separates the aggregates. This type of structure is often originated by anthropogenic activities (soil tillage).

Subangular blocky structure. - The soil aggregates are separated by elongated continuous pores (planes), are of different sizes and can be rather porous inside. Aggregate faces largely accommodate each other. From an agronomic point of view, this is the best type of soil structure because the continuity of elongated pores allows good water movement and facilitates root growth. Moreover, it is a rather stable soil structure.

Angular blocky structure. - The soil aggregates have angular edges and are separated by elongated pores of a regular shape. Aggregate faces normally accommodate each other. This is a typical structure of clay soils and it less stable than the subangular blocky structure because during the wetting process the soil swells and pores, which have accommodating walls, tend to seal up, thus, prevent water movement, resulting in soil degradation.

Platy structure. - The thin and flat soil aggregates are separated by elongated pores oriented parallel to the soil surface and, therefore, not continuous in a vertical sense. This leads, as a consequence, to a drastic reduction of water infiltration capacity. Soils with this type of structure are subject to water stagnation or runoff and erosion depending on their slope. The platy structure is typical of compact soils.

Prismatic structure. - The soil macroaggregates are divided into prisms separated by vertically oriented elongated pores with accommodating walls. Also this type of structure is typical of clay soils, especially in the B horizon, and is not very stable because the swelling of the soil when wet causes the closing of pores.

Massive structure. - The soil material is very compact, there are no visible separated aggregates. The porosity is very low and represented by small pores isolated in the soil matrix. This type of structure represents a bad "habitat" for plant development and is common in degraded soil with a low content of organic matter.

Complex structure. - The soil presents two or more types of soil structure.

Relationships between soil porosity and water movement

The relationships between pore size distribution and soil water content are expressed by the capillary model, while the relationships between pore size distribution and water movement at specific water potentials have been developed in terms of several physical equations and models (Marshall, 1958; Childs, 1969).

The main limitation of these models is due to the assumption of the cylindrical shape of pores or the spherical shape of soil particles. The development of micromorphological techniques together with image analysis allow the improvement of such models. For example, Bouma et al. (1977) developed a method based on the preparation of undisturbed soil columns, saturated and then percolated with a 0.1% solution of methylene-blue that is adsorbed by the soil particles on the pore walls. Then vertical and horizontal thin sections are prepared. Pores are divided into three shape groups as already explained and then the pore size distribution is determined. For the planar elongated pores the total area, the area of the blue-stained pore walls, and their lengths, and the spatial distribution of the widths and lengths of the pores with blue-stained walls are determined. Particular attention should be paid to the measurement of the width of the necks of elongated pores because the hydraulic conductivity is determined by the necks in the flow system. Following this procedure the hydraulic conductivity (K_{sat}) can be calculated as proposed by Bouma et al. (1979). Further studies of Bouma (1992) confirmed that morphological information on the soil pore system is essential for the realization of water flux models.

The evolution of software for image analysis, that enables the acquisition of precise information about shape, size, continuity and arrangement of pores in soil, permit the simplification of the modelling approach. For example, Fig. 3 shows highly significant correlations between elongated pores and hydraulic conductivity.

Combined with image analysis, the use of fractal and fractal fragmentation models can help to characterize the geometry of a porous medium in relation to transport process (Kutilek and Nielsen, 1994). For example, the model of fractal fragmentation leads to a better understanding of relationships between aggregation, n-modal porosity and soil hydraulic properties.

Evaluation of the impact of agricultural management practices on soil structure

Many anthropogenic activities affect soil structure. Parameters such as pore size distribution, pore shape, pore continuity and relative position of aggregates and pores are very important for evaluating induced modifications of soil structure, e.g., by different management practices such as soil tillage, application of manures and irrigation.

Soil tillage

Long-term intensive arable cultivation has negative effects on soil physical properties, particularly on soil structure, with resulting effects on soil erodibility and crop yields. The need to check the degradation of soil structure has caused farmers to consider no-till and minimum tillage as an alternative to conventional tillage. Abandoning traditional farming rotations and adopting intensive monocultures, without applications of farmyard manure or organic materials to the soil, has decreased the soil organic matter content with evident degradation of soil structure. The resulting soil porosity conditions are often unfavorable for crop growth (Pagliai et al., 1983b; 1984; 1989; Shipitalo and Protz, 1987).

Long-term field experiments in different types of soils, representative of the typical pedological environments, have shown that alternative tillage systems, like minimum tillage, ripper subsoiling, etc., improve the soil pore system increasing the storage pores (Fig. 4) and the amount of the elongated transmission pores (Fig. 5) with respect to the continuous conventional ploughing. The resulting soil structure is more open and more homogeneous, thus allowing better water movement, as confirmed by the higher values of hydraulic conductivity measured in minimally tilled soils (Pagliai et al., 2000). Also the water content is generally higher in reduced tilled soils. The continuous conventional tillage, moreover, causes a decrease of soil organic matter content that is associated to a decrease of aggregate stability, leading, as a consequence, to the formation of surface crusts, with an increase of runoff and erosion risks, and compact structure.

Management practices can also affect biological activity and can therefore affect both the formation and preservation of biopores, important for water movement and root development (Kooistra, 1991; Pagliai and De Nobili, 1993).

The fractal parameters of pore surfaces as derived from micromorphological data can be useful to evaluate the impact of long-term management practices on soil structure (Pachepsky et al., 1996).

Applications of manures

The application of organic materials to the soil has also been shown to enhance both soil porosity and pore size distribution. Fig. 6 summarizes results obtained in a long-term field experiment on a sandy loam soil in which annual application of sewage sludges and composts from urban refuse were compared to the applications of farmyard manure or chemical fertilizers (Pagliai et al., 1981; 1983a; Pagliai and Vittori Antisari, 1993). The application rates were calculated on the organic carbon basis and were equivalent to 50 metric tons/ha of manure. The soil was planted to corn and the tillage was the same for all treatments, i.e., conventional ploughing to a depth of 25 cm. Data refer to a sampling in the period of corn ripening. Soil pore space (microporosity and macroporosity) significantly increased after treatment with all organic materials compared to treatment with chemical fertilization alone.

Pore shape and size distribution were also affected by the application of organic materials. The proportion of storage (0.5-50 μm) and transmission pores (elongated pores, 50-500 μm) was greater in soil treated with any type of organic material than in soil treated with chemical fertilizers only (Fig. 7). Similar results were obtained with the application of pig slurry to a silty clay soil. In this experiment, a positive relationship between the rate of application and the increase of soil porosity was found. It also emerged that the time of application was important, with the best results being obtained for spring applications (Pagliai et al., 1983a; 1985). The increase of pore space and the modification of the pore system in soil treated with these organic materials was associated with an increase of aggregate stability (Pagliai et al., 1981). Thus, from these cited data there is clear evidence that sludges, composts and livestock effluents can improve the physical properties of soil in a similar way to manure.

Irrigation

Intensive continuous cultivation is not the only cause of soil structure degradation; other management practices like irrigation are also important, especially in the longer term. Mathieu (1982) showed that after 15 years of impounding irrigation in clay soils, the structural conditions appeared greatly changed: massive structure, modification of the pore shape and pore size distribution, increased migration of clay particles from the ploughed horizon Ap to the B horizon. Pezzarossa et al. (1991) found that in a peach orchard near Verona (Italy) soil porosity of the surface layer decreased during the irrigation season and that the decrease was significantly greater when irrigation was by impounding rather than under sprinkler-irrigation, due to a reduction in elongated pores (Fig. 8). The latter was associated with a lower water content in the surface soil and reduced root density. The larger amount of water applied with this system caused progressive soil compaction, resulting in decreased porosity and structural degradation.

Fig. 9 visually explains the results of Fig. 8: in fact, in the sprinkler-irrigated soil a subangular blocky structure can be observed, while in the soil irrigated by impounding the structure was more compact, rather massive, with drastic reduction of both the total amount and the size and continuity of elongated pores. This caused decreased water infiltration and, under these conditions, 30% of applied water was lost by run-off. It is clearly intuitive that run-off along the interrow transported nutrients, particularly nitrogen and potassium. For example, results reported by Pagliai (1992) showed that the losses of potassium amounted to 25% of the quantity applied as fertilizer (150 kg/ha/year of K_2O).

Sprinkler irrigation consumes only half the amount of water needed for impounding and causes no evident damage to soil structure, so the loss of water by run-off is negligible but, unfortunately, this method is more expensive and complicated for the farmer. However, for the real conservation of environmental resources and over all to reduce risks of soil structure degradation, erosion and pollution, it is necessary to consider and rationalize all the management practices.

Quantification of some aspects of soil degradation

Soil Compaction

Soil compaction is another of the most important factors responsible for environmental degradation. It causes strong modifications to soil structure and reduces soil porosity. Soil compaction is caused by a combination of natural forces, which generally act internally, and by man-made forces related to the consequences of soil management practices. The latter forces are mainly those related to vehicle wheel traffic and tillage implements and have a much greater compactive effect than natural forces such as raindrop impact, soil swelling and shrinking, and root enlargement. This is because trends in agricultural engineering over the last few decades have resulted in machines of a greater size and weight. Therefore, soil compaction has become one of the most significant aspects of soil degradation and problems of finding tyres, inflation pressures, etc., able to reduce soil compaction are far from being solved. It is therefore fundamental to evaluate the impact of wheel traffic on soil structure and porosity measurements can help to quantify the degradation effects of compaction. Results showed that compaction, both in agricultural and forestry soils, not only reduces total soil porosity but also modifies the pore system. In fact, the proportion of elongated pores, useful for water movement and root growth is strongly reduced in compacted soil. The modifications to the pore system also changes the type of soil structure: the platy structure is a common feature in compacted cultivated soil (Fig. 10). Results also showed that the reduction of porosity and of elongated pores following compaction, is strictly related to the increase of penetration resistance and to the decrease of hydraulic conductivity (Fig. 11) and root growth (Marsili et al., 1998; Richard et al., 2001). Soil regeneration after compaction depends on the type of soil and on the degree of damage to the soil (Bullock et al., 1985).

The formation of compacted layers along the profile (ploughpans)

Soil compaction is not only caused by wheel traffic but also to the shear strength of tillage implements, like the compact layer (ploughpan) formed at the lower limit of cultivation in continuous ploughed soils (Fig. 12). As already said, Fig. 5 shows the strong decrease of elongated transmission pores and over all of hydraulic conductivity, respectively in the 40-50 cm layer in conventionally tilled soil (Pagliai et al., 2000). Subsoil compaction is strongly under evaluated, even though such a ploughpan is largely widespread in the alluvial soils of the plains cultivated by monoculture and it is responsible of the frequent flooding of such plains in occasion of heavy rains concentrated in a short time (rainstorm), because the presence of this ploughpan strongly reduced drainage. Alternative tillage practices, like ripper subsoiling, are able to avoiding the formation of this compact layer.

Soil crusting

Surface crusts are another of the dangerous aspects of soil degradation, and are formed by raindrop impact, which causes the mechanical destruction of soil aggregates. The dispersed particles, that can be also translocated by runoff, in the following drying process their deposition causes the formation of a compact layer of horizontally oriented plate-like particles at the soil surface. This compact layer contains few, if any, large pores. Generally the surface crusts are formed by several thin layers of fine particles. These are intercalated by thin elongated pores parallel oriented to soil surface, not continuous in a vertical sense (Fig. 13), or by rounded pores (vesicles) formed by air trapped during drying. The presence of such pores in the topsoil formed a vesicular structure that can be regarded as an indicator of an unstable and transitory structure induced by poor stability of soil aggregates. Soil crusting reduces seedling emergence, soil-atmosphere gas exchange, water infiltration and increases surface runoff. Results showed that addition of organic materials to soil and reduced tillage practices are able to prevent crust formation. In intensively cultivated soils the surface aggregates are less rain-stable. The decrease of soil porosity and particularly of elongated transmission pores in conventional ploughed soils, as reported in Fig. 5, can be ascribed to the presence of the surface soil crusts that negatively affect the hydraulic conductivity (Pagliai et al., 2000). Such crusts were less developed in soil under minimum tillage and ripper subsoiling (Fig. 13).

Conclusions

The characterisation of the soil pore system gives essential indications about soil quality and vulnerability in relation to degradation events mainly connected with human activity. Such a characterisation is especially useful in the study of the relationships between soil physical, chemical and biochemical properties and provides a realistic basis for understanding water retention and water movement in soil. In fact, the quantitative evaluation of water movement and solute transport along the macropores opens new horizons in the modelling of these phenomena. This is one of the new approaches in the study of soil, since up to now water movement in macropores has not been adequately considered. Some traditional concepts of soil physics need to be reconsidered or modified: for example, the concept of available water for plants should be associated with the concept of accessible water.

The characterisation of soil pore system, by means of image analysis on thin sections, can provide basic information for the study of soil. The major disadvantage of this technique is that the preparation of soil thin sections is both difficult and time consuming. However, many public and private laboratories are now equipped for the preparation of soil thin sections and the development of improved computer software has made the analysis of the images easy.

When the obstacle of the acquisition of soil thin sections is overcome, it will be possible to benefit from the full potential of this technique, most importantly to quantify the changes in soil structure following human activities. Therefore, on the basis of the acquired experience, it is possible to go deep into the analysis of soil thin sections in relation to aspects of water movement. The quantification of the size, continuity, orientation and irregularity of elongated pores allows the modelling of water movement and solute transport, or, at least, allows the prediction of the changes which can be expected following soil structural modifications, or following soil degradation due to compaction, formation of surface crusts, etc. The quantification of the damage caused by degradation processes also makes it possible to predict the risk of soil erosion.

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Table 1 - Morphologic pore size classification according to Brewer (1964).

Class	Subclass	Class limits (Equivalent diameter μm (10^{-6}m))
Macropores	Coarse	above 5000
	Medium	2000-5000
	Fine	1000-2000
	Very Fine	75-1000
Mesopores		30-75
Micropores		5-30
Ultramicropores		0.1-5
Cryptopores		less than 0.1

Table 2 - Classification of soil pores according to their size. Modified from Greenland (1977).

Equivalent diameter μm (10^{-6}m)	Water Potential (bar)	Name
<0.005	>-600	Bonding space
0.005 - 0.5	-600 / -6	Residual pores
0.5 - 50	-6 / -0.06	Storage pores
50 - 500	-0.06 / -0.006	Transmission pores
>500	<-0.006	Fissures

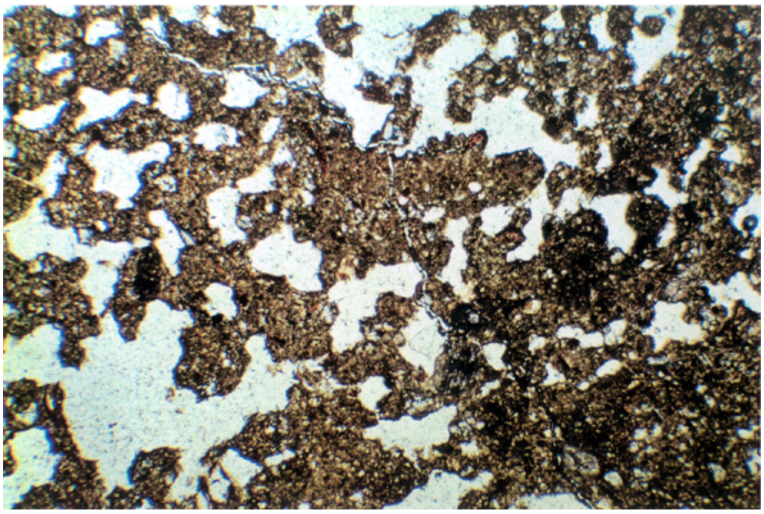


Fig. 1 - Microphotograph of a vertically oriented soil thin section showing an example of vughy structure. The white areas represent the pores. Frame length 3×5 mm.

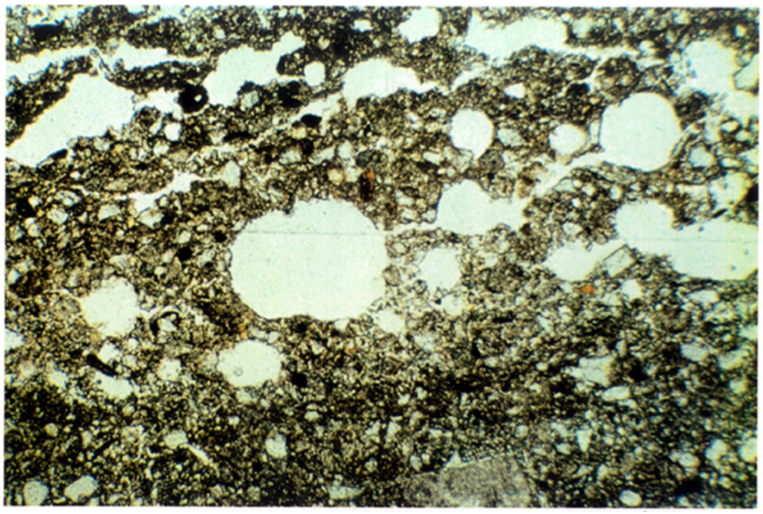


Fig. 2 - Microphotograph of a vertically oriented soil thin section showing an example of vesicular structure. The white areas represent the pores. Frame length 3×5 mm.

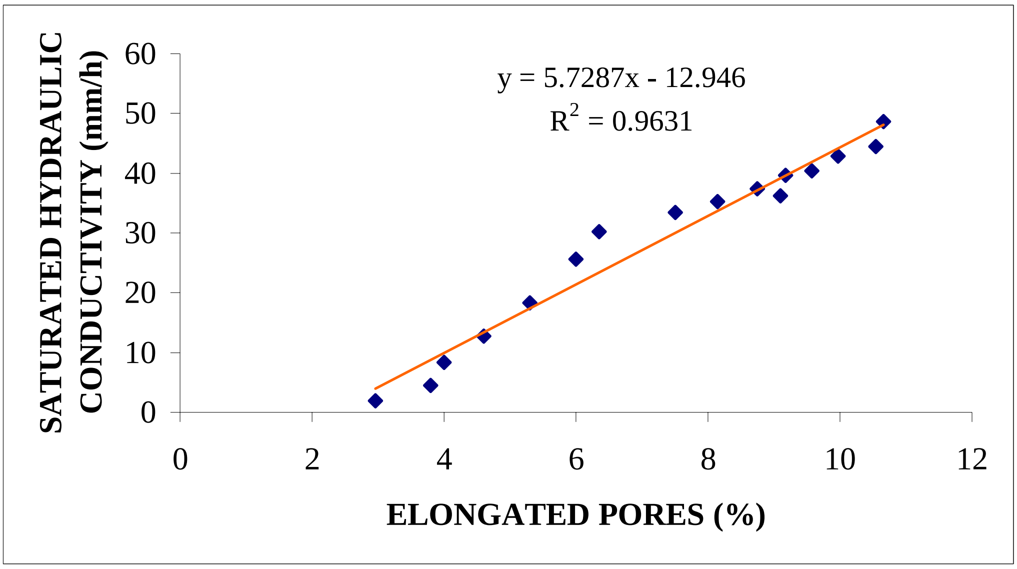


Fig. 3 – Correlation between soil porosity, formed by elongated pores, and saturated hydraulic conductivity in the surface layer (0-10 cm) of a loam soil cropped with maize.

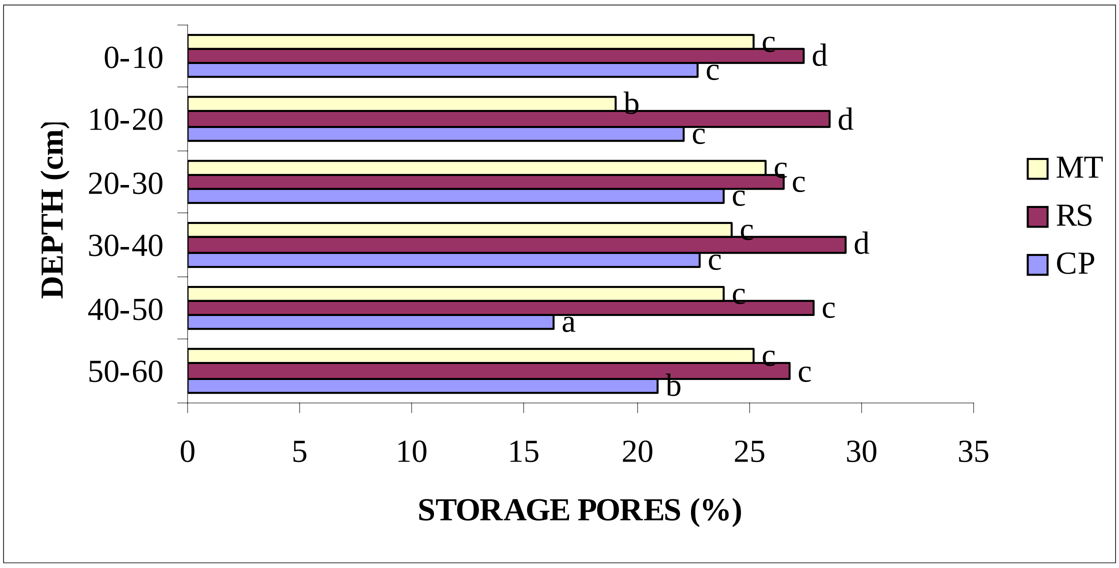


Fig. 4 – Effects of tillage systems on storage pores inside the aggregates measured by mercury intrusion porosimetry along soil profile (MT: minimum tillage; RS: ripper subsoiling; CP: conventional deep ploughing). Values differ significanly when followed by different letters at $P \leq 0.05$.

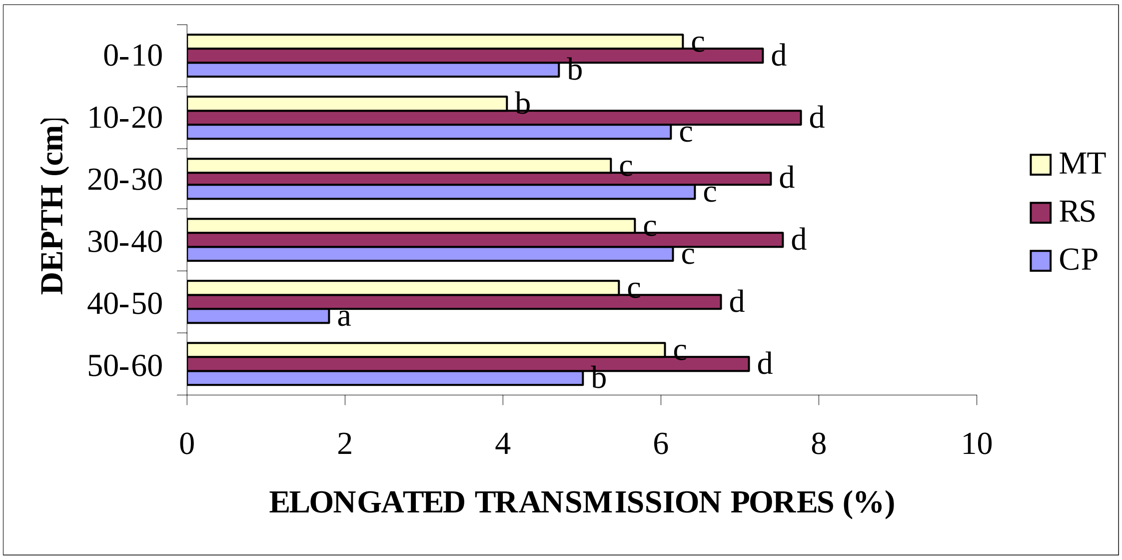
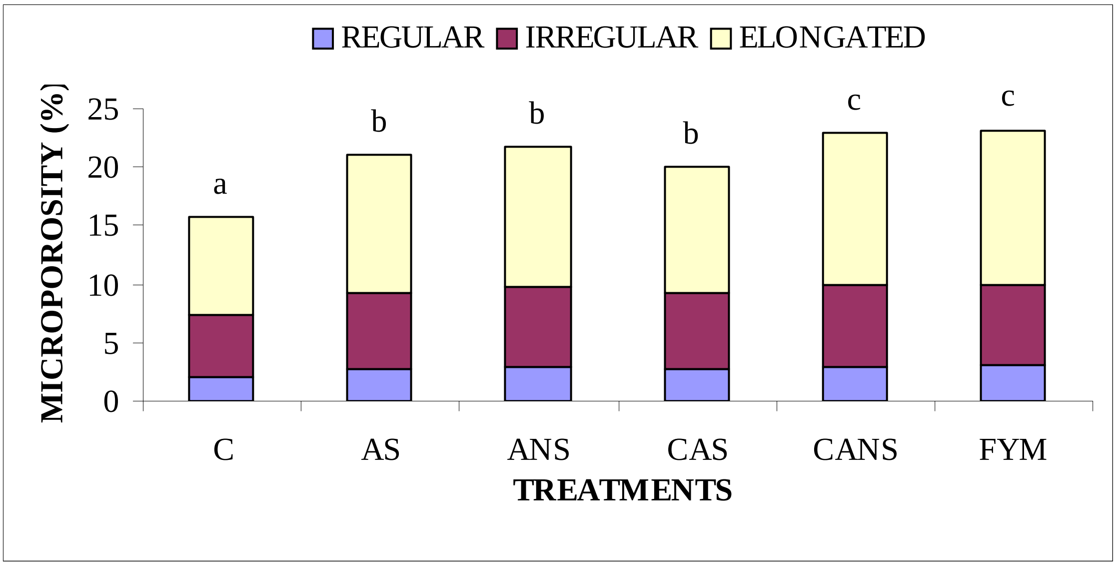


Fig. 5 – Effects of tillage systems on elongated transmission pore distribution along soil profile expressed as a percentage of total area occupied by pores ranging from 50-500 μm per thin section (MT, minimum tillage; RS, ripper subsoiling; CP: conventional deep ploughing). Elongated transmission pore values differ significantly when followed by different letters at P ≤0.05 employing the Duncan's Multiple Range Test. (Modified from Pagliai et al., 2000).



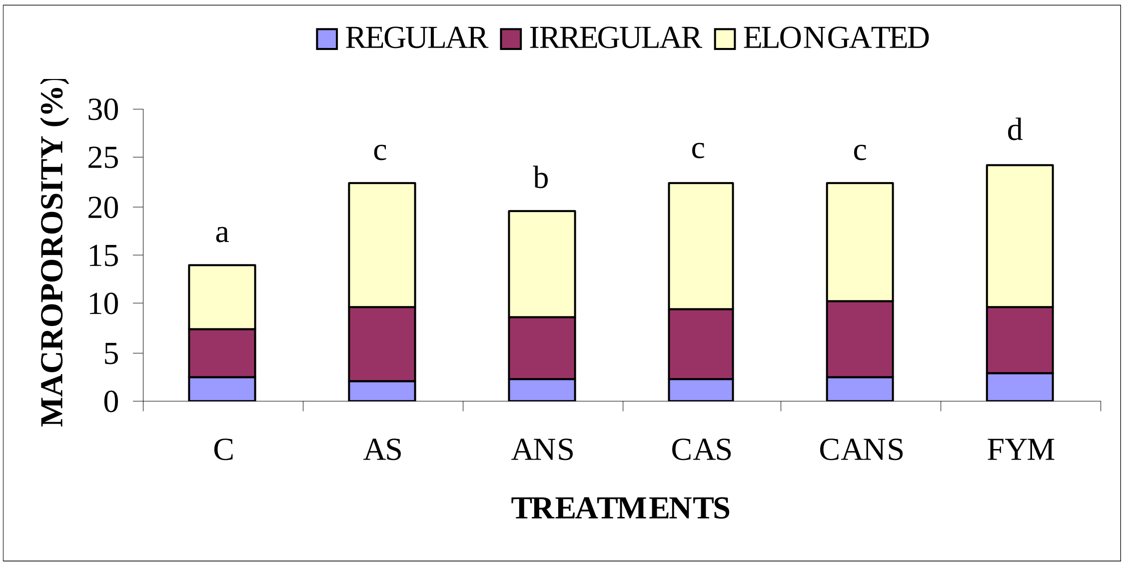


Fig. 6 – Effect of surface application of sludges, composts and farmyard manure (C: chemical fertilsation; AS: aerobic sludges; ANS: anaerobic sludges; CAS: compost of aerobic sludges and the organic fraction of urban refuse (40:60%); CANS: compost of anaerobic sludges and the organic fraction of urban refuse (20:80%); FYM: farmyard manure) on soil microporosity (0.5-50 μm) and macroporosity (>50 μm) of a sandy loam soil expressed as a percenatage of total area of pores per thin section; mean of six replicates. Total porosity values followed by the same letter are not significantly different at the 0.05 level as determined by Duncan's multiple range test. (Modified by Pagliai and Vittori Antisari, 1993).

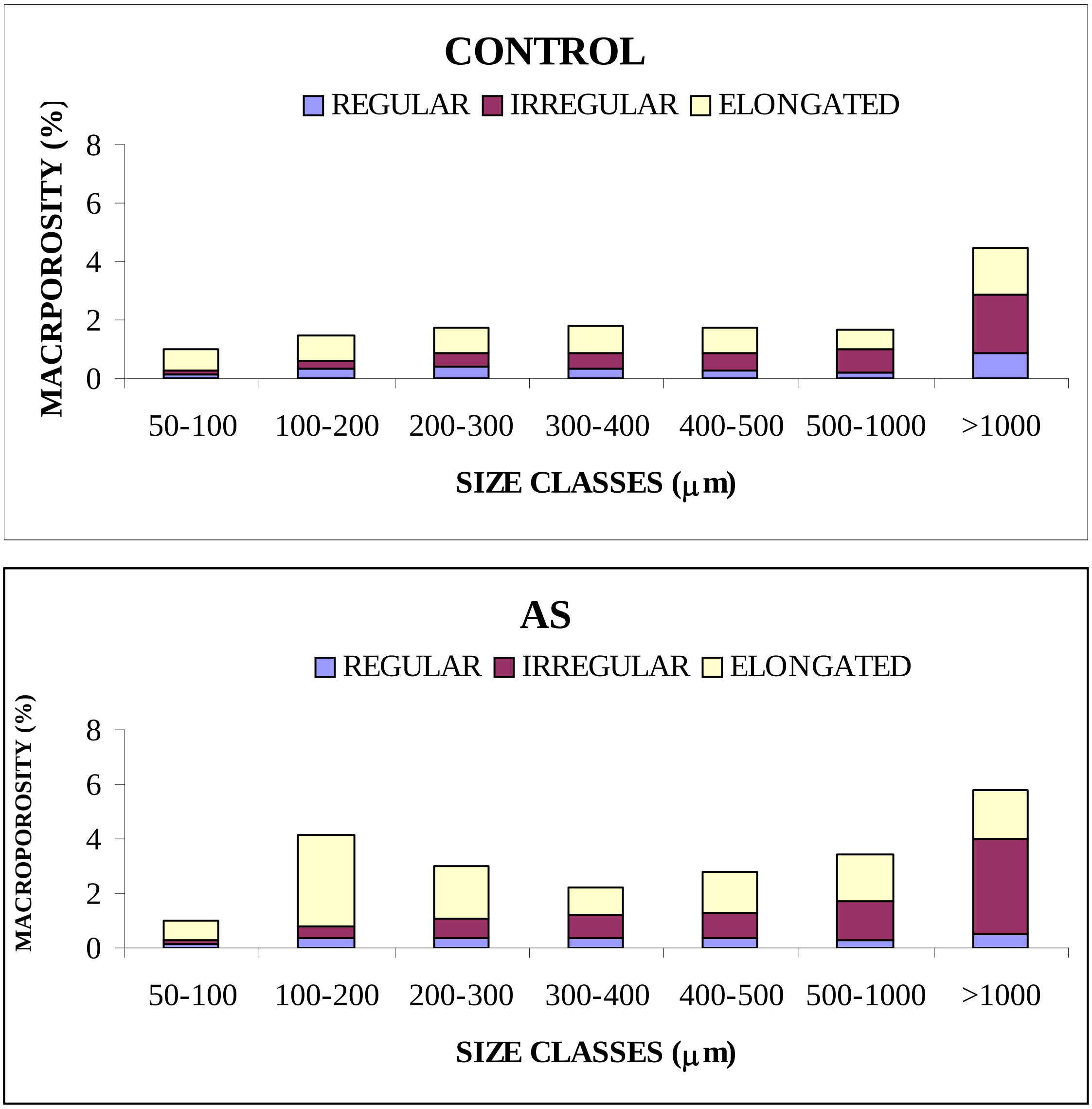


Fig. 7 – Pore size distribution of pores larger than 50 μm, according to the equivalent pore diameter for regular and irregular pores and width for elongated pores, in the control plots of a sandy loam soil and in those treated with aerobic sludges.

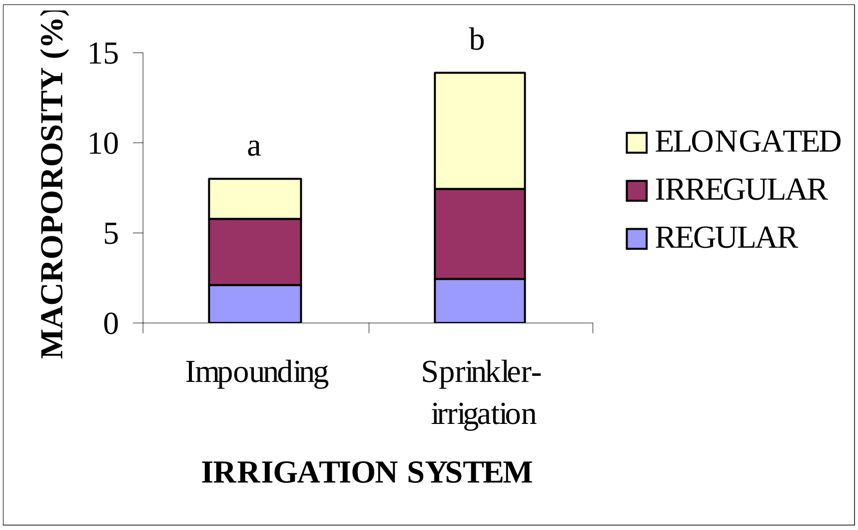


Fig. 8 – Effect of two irrigation systems on soil macroporosity (>50 μm) of a peach orchard sandy loam expressed as a percenatage of total area of pores per thin section; mean of six replicates. Total porosity values followed by the same letter are not significantly different at the 0.05 level as determined by Duncan's multiple range test. (Modified by Pagliai, 1992).

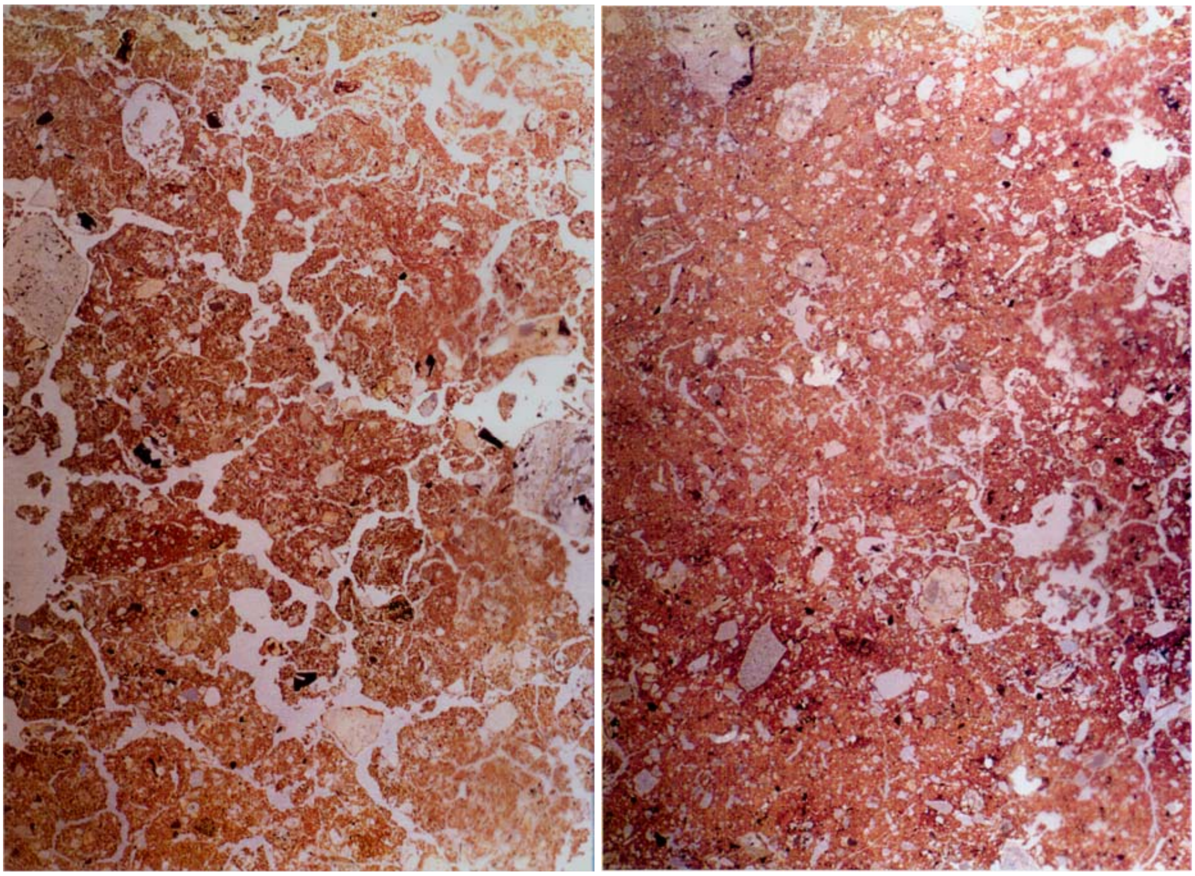


Fig. 9 – Macrophotographs of vertically oriented thin sections prepared from undisturbed samples from the surface layer (0-10 cm) of a peach orchard sandy loam under sprinkler irrigation (left) and irrigated by impounding (right). The transformation from a subangular blocky structure in sprinkler-irrigated soil to a rather massive structure in soil irrigated by impounding is very evident. Frame length 3×5 cm.

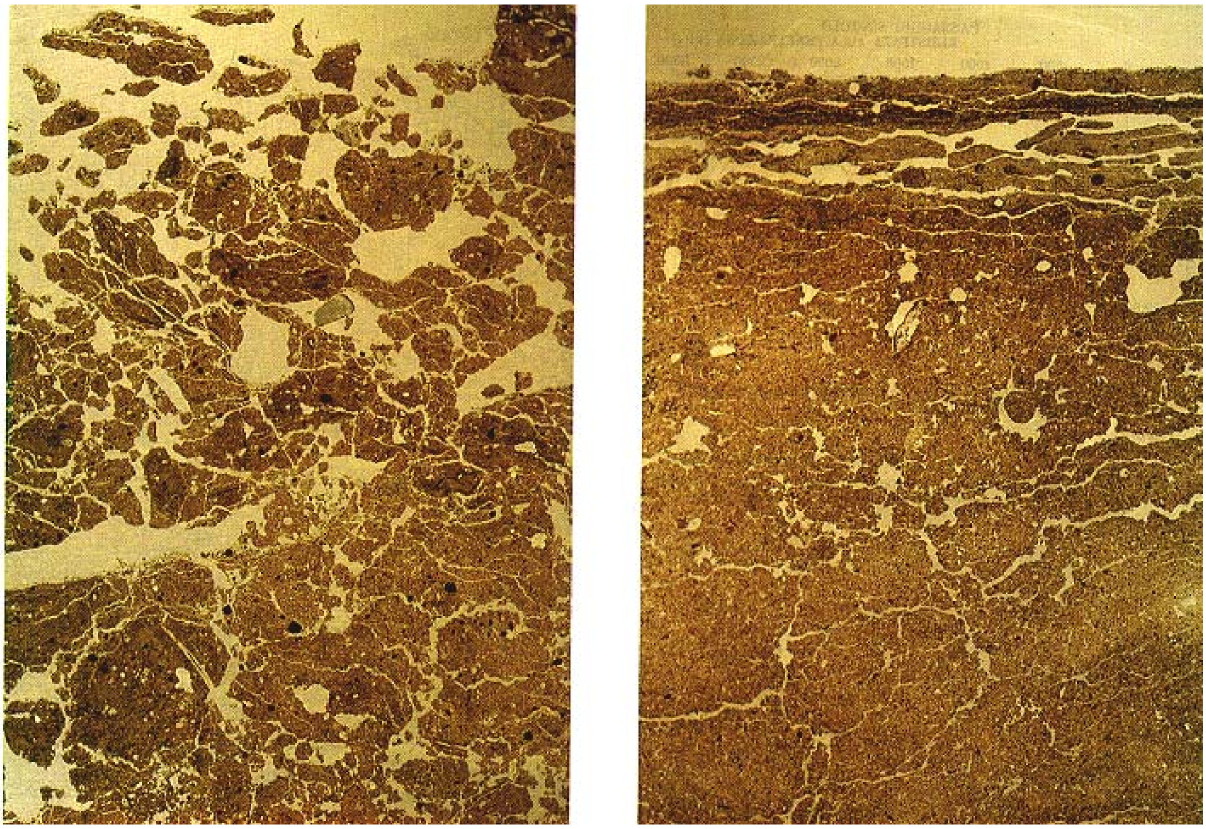


Fig. 10 – Macrophotographs of vertically oriented thin sections from the surface layer (0-5 cm) of the uncompacted (left) and compacted areas (right) of a loam soil. Plain polarized light. Pores appear white. The change of the subangular blocky structure of the uncompacted areas into a massive platy structure of the compacted areas is very evident. Frame length 3 cm.

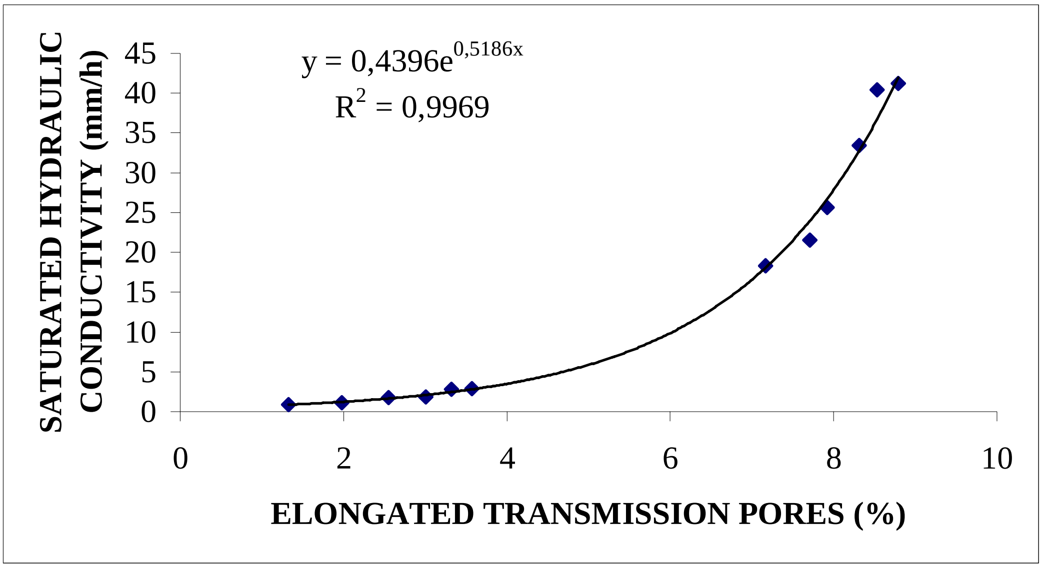


Fig. 11 – Exponential correlation between soil porosity formed by elongated pores and saturated hydraulic conductivity in the surface layer (0-10 cm) of the compacted (elongated pores less than 4%) and uncompacted areas (elongated pores greater than 7%).

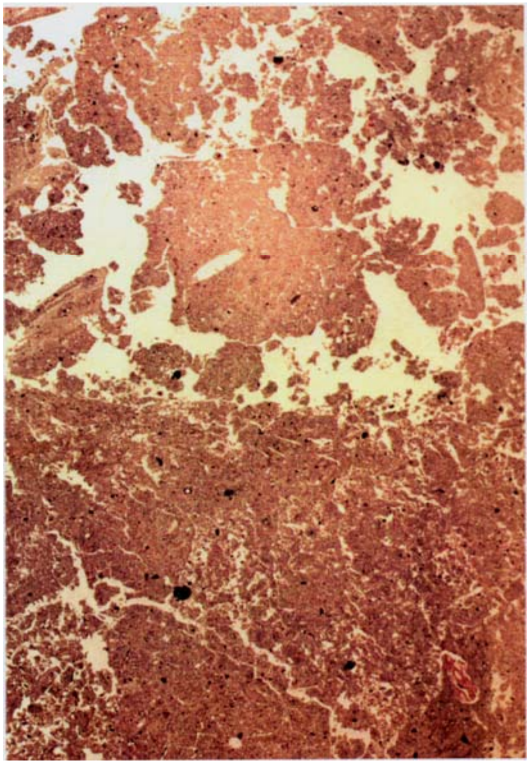


Fig. 12 - Macrophotographs of vertically oriented thin sections prepared from undisturbed samples from the 40-50 cm layer of a clay loam soil tilled by continuous deep ploughing. The lower limit of cultivation (ploughpan) is visible. Frame length 3×5 cm.

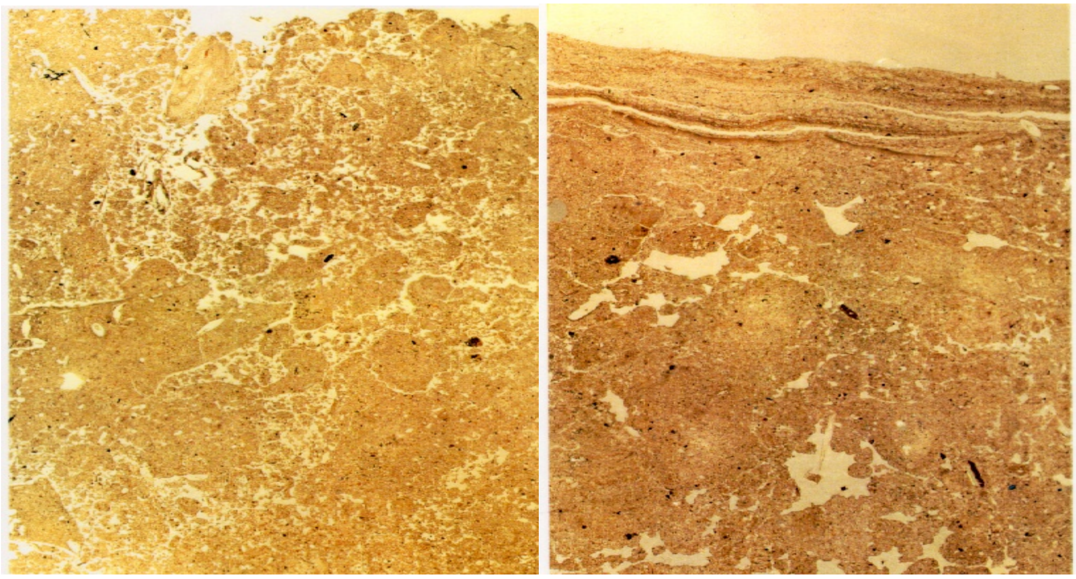


Fig. 13 – Macrophotographs of vertically oriented thin sections from the surface layer (0-5 cm) of the minimum tilled (left) and deep ploughed (right) soils. Plain polarized light. Pores appear white. The change of the subangular blocky structure of the MT soil into a platy structure of the DP soil, due to the surface crust, is very evident. Frame length 3 cm.