The Abdus Salam International Centre for Theoretical Physics

United Nations Educational, Scientific and Cultural Organization

IAEA International Atomic Energy Agency

2163-2

College on Soil Physics: Soil Physical Properties and Processes under Climate Change

30 August - 10 September, 2010

Soil Structure

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SOIL STRUCTURE

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Definition

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 developments 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.

Genesis of soil structure

Soil structure is a dynamic property and it is subjected to genesis and degradation processes. The main factors that affect the genesis of soil structure are represented by the effect of cations, by the interaction between clay particles under the influence of soil water content (wetting and drying cycles) and temperature, by the effect of organic matter, which is the main agent of aggregate stabilization, by root growth and by the action of soil macro and micro-organisms. Possible steps leading to the genesis of soil structure can be summarized as follows: flocculation of soil particles, microaggregation, aggregation and stabilization of aggregates. The main factors that affect the degradation of soil structure are the long-term intensive cultivations, which deplete the soil organic matter content, soil erosion, soil compaction, the formation of surface crusts and the formation of a compacted layer along the soil profile (e.g. ploughpan). Possible steps leading to the degradation of soil structure can be summarized as follows: destabilization or mechanical destruction of soil aggregates, disaggregation, microdisaggregation and dispersion of soil particles.

The genesis of soil structure depends on the presence of cementing substances, even though a structure can sometimes be recognized also in the absence of cementing substances

(Sequi, 1978). In many clay soils, for example, water can be naturally drained in the cracks formed during the drying processes following the shrinkage of the inorganic component of the soil and such cracks can never completely close during the year. However, the laboratory analysis of these types of soils reveals a low value of permeability. The alternation of wetting and drying cycles can be, therefore, an important mechanism of the genesis of soil structure also independently of the presence of cementing substances. Fig. 1 shows the quantification of the influence of wetting and drying cycles on soil porosity in different types of soils. In the sandy loam soil the total porosity showed a slight increase during the wetting and drying cycles. On the contrary, in the clay loam soil and in the silty clay soil the total porosity strongly increased until the 11th wetting and drying cycle, and at the end of the 16th it showed a slight decrease (Sartori et al., 1985; Pagliai et al., 1987). The micro and macroscopic observations revealed that the large degree of porosity was represented by intra-aggregate pores, which surrounded or separated the newly formed soil aggregates, thus confirming that wetting and drying cycles produce aggregation and this capacity is strongly related to the content of clay in soil. The slight decrease of porosity after the 11th cycle may be ascribed to a decrease of the microbial activity in soil during the continuous repetition of wetting and drying cycles. Utomo and Dexter (1982) demonstrated the importance of microbial activity in the formation of soil aggregates during wetting and drying cycles, and the formation of soil aggregates is related to soil porosity. However, the genesis of soil structure mainly depends on the presence of cementing substances. Organic matter is the main cementing substance and the main processes of soil aggregation are of a biological origin. In soils with an appreciable content of clay, the primary particles tend, under favourable conditions, to group themselves into structural units known as secondary particles or aggregates. Such aggregates are not characterized by any fixed size or stability. The visible aggregates, which are generally of the order of several millimetres to several centimetres in diameter, are often called peds or macroaggregates. The literature concerning the complex interrelationship of physical, biological and chemical reactions involved in the formation of soil aggregates is very wide; for example, the review of Harris et al. (1966) listed nearly four hundred references. Sequi (1978) summarized the main mechanisms involved in soil aggregation as the linkage between organic matter and mineral constituents, the adhesion of living organisms to mineral constituents, and physical actions of living organisms on inorganic constituents.

Linkage between organic matter and mineral constituents. - Organic matter is responsible for the formation of real bonds between organic and inorganic soil components and this is perhaps the most widely studied topic in soil aggregation (Greenland, 1965a,b; Oades, 1984). Authors often deal with organic matter without considering the presence of living organisms but this approach appears incomplete, except for peaty soils, where organic matter represents a very unusual pedological entity. Peat can be considered as a complex of mummified materials, like a transmission stage towards the formation of lignite and fossilization. However, living organisms represent a consistent percentage of soil organic carbon. Jenkinson and Powlson (1976) in their study on soil biomass determination showed that in several arable and uncultivated soils, containing from 0.84 to 3.49% of organic matter, the living organisms constituted from about a thirtieth to one fiftieth of the organic matter. Plant roots, in a broad sense, must be added to the soil biomass. Roots exert pressure which compresses aggregates. Water uptake by roots causes differential dehydration, shrinkage, and the opening of numerous small cracks. Moreover, root exudations and the continual death of roots and particularly of root hairs promote microbial activity which results in the production of humic cements. Since these binding substances are transitory, as they are susceptible to further microbial decomposition, organic matter must be replenished and supplied continually if aggregate stability is to be maintained in the long run. However, in some cases roots and rhizosphere organisms produce a range of acids that can stimulate the production of dispersible clay (Oades, 1984). Such an effect has been described by Reid and Goss (1982) and Reid et al. (1982), particularly for maize plants during the early weeks of growth. The acids produced could break organic matter-Fe, Al, Ca-clay bonds by lowering the pH and/or complexing the metal ions. Drying of the soil by plant growth or by air drying leads to an increase in the formation and stability of soil aggregates, presumably due to the increased sorption and effectiveness of organic binding agents, probably due to polysaccharides which are exuded from roots in addition to the soluble exudates (Oades, 1978).

Polysaccharides, among the many microbial products capable of binding soil aggregates, are prominent. Such materials are attached to clay surfaces by means of cation bridges, hydrogen bondings, van der Waals forces, and anion adsorption mechanisms. Polysaccharides, in particular, consist of large, linear, and flexible molecules capable of forming multiple bonds with several particles at once. The action of polysaccharides has been the subject of much research. Carbohydrates represent one quarter of soil organic matter and are essentially derived from plant polysaccharides in roots and plant debris. Other polysaccharides in soils are mucilages associated with roots (Oades, 1978), or microbial mucilages (Hepper, 1975). Cheshire et al. (1983) suggested that polysaccharides are the most important cements present in soils. It is widely demonstrated that the effectiveness of microbial polysaccharides in promoting soil aggregation is strictly correlated with their molecular weight. Pagliai et al. (1980) showed that microbial dextrans with a higher molecular weight appeared most efficient in improving pore size distribution and the stability of soil aggregates. Thus the molecular weight or length of the molecules is considered to be an important factor in improving the pore size distribution of a soil or the water stability of aggregates. The longer the molecules are the more able they are to link particles together in the walls of pores to stabilize the pores against the destructive forces of wetting.

Micromorphological techniques can give useful contributions in the studies dealing with the interaction of organic matter-soil structure by means of the microscopic examination of soil thin sections. Fig. 2 shows accumulation of organic matter distributed as a coat along the walls of elongated pores. These coats on pore walls can effectively seal pores from the adjacent soil matrix, thus stabilizing the pore walls against the destructive forces of water and assuring the functionality of the pores. These favourable conditions, with respect to soil structure, are not permanent. In fact, when the organic matter is totally decomposed and mineralized it loses its capability as a cementing substance, therefore the pore walls collapse and close the pore. This is the first step of soil structural degradation; to avoid this it is necessary to assure an adequate turnover of organic matter in soil. Pagliai and Vittori Antisari (1993) confirmed that the increase of micro and macro porosity and the improvement of soil structure in cultivated soils strictly depend on the addition of organic materials, including waste organic matter.

Because clays and organic materials are polyanions they can be bridged by polyvalent cations, such as Ca, Mg, Al, Fe. Soil organisms accumulate inorganic constituents as an essential part of their environment. Soil alkali-soluble organic matter itself contains large amounts, up to about 40%, of ash composed mainly of iron, aluminium and silica. Most of the iron is firmly bound to organic matter, as it is not removable by ion-exchange resins (Sequi et al., 1975). The main evidence for the role of cation bridges has been based on the increased disaggregation of soil after treatment with complexing agents or after treatments with acids (Hamblin and Greenland, 1977). The complexing agents most commonly used have been pyrophosphate and acetylacetone, which aimed particularly at Al and Fe. It has been shown consistently that pyrophosphate aids the disruption of aggregates beyond that due to saturation of the system with Na. Giovannini and Sequi (1976a, b) showed that treatments with acetylacetone in benzene, a reagent which essentially extracts metals bound to the organic matter, led to a substantial decrease in the water stability of soil aggregates. They suggested that metals can behave as bridges of nets composed of polymeric chains of soil organic matter.

Humification processes generally lead to a concentration of aromatic substances in soil organic matter. Such substances exert two main influences in soil. Firstly they complex, protect, and stabilize organic compounds in general (Haider et al., 1975). Griffiths and Burns (1972) showed that tannic acid stabilizes soil aggregates treated with polysaccharides. This effect can be due to the protection from microbial degradation by phenolic substances; the protective effect is general for most enzymes in soil (Sequi, 1978). The second influence depends on the hydrophobic nature of aromatic substances. The soil may be regarded as a system of hydrophilic components, with organic matter as unique hydrophobic constituent, due to its aromatic substances. Water repellency affects water infiltration, evaporation and water flow (Debano, 1975), and consequently influences soil structure. The commonly reported occurrence of water repellency in soil after fire (Giovannini and Lucchesi, 1987) is an interesting aspect of the same problem.

Adhesion of living organisms to mineral constituents. - The soil microflora can be regarded as aquatic and it is reasonable to regard bacterial cells as part of the colloidal system in soil (Oades, 1984). As is well known, microorganisms are not easily leached or washed out from soils, because they are attached to either clay or humic substances. The size of cells are on average similar to that of clay particles and these cells are ionogenic and in many cases amphoteric due largely to carboxyl and amino groups. Most microbial cells have a net negative charge at the pH of the soil. These negatively charged bioparticles can attract clay surfaces sufficiently close as to be adsorbed. Marshall (1971) showed the adhesion of microorganisms to clay particles including the fundamental forces of interaction between organisms and surface and the implications for the organisms involved and the surfaces acting as adsorbed.

Physical actions of living organisms on inorganic constituents. - Micro and macro living organisms can also cause mechanical actions on inorganic constituents in several ways. Unicellular organisms, during proliferation surround and link soil particles. Other filamentous growth forms, such as fungi hyphae, explore pores and entangle mineral constituents. Plant roots grow in the most favourable directions, forming a three dimensional net whose thickness is conditioned by physical and chemical fertility. Developing roots also compress the adjacent soil, so reducing the pore size. As the roots and hyphae decompose the fragments become the centre of water stable aggregates, because of mucilages produced during decomposition of the organic fragments interact with clay (Oades, 1984). Therefore, plant roots, such as fungal hyphae and bacterial colonies may well share physical actions with cementing properties of slime layers and exudates.

Organisms which have their own movement contribute to the migration of soil particles. In their movements these organisms abandon their catabolic residues in different places and this products can act as cementing substances.

Water adsorption by plant roots and other organisms causes a strong modification of the physical status of the adjacent soil and, for example, shrinkage phenomena can occur. Another important effect common to all living organisms, is their influence on the soil air composition. Such changes cause variations in oxidation potentials and redistribution by diffusion (Sequi, 1978).

Aggregate stability

As already said soil structure is a dynamic property and the degree of aggregation is a time-variable property, as aggregates form, degrade and reform periodically. A visible example of this cycle can be seen in cultivated soils where the granular or crumbly structure originated by the tillage operation visibly and rapidly deteriorates under destructive forces, such as, for example, rainfall impact (causing slaking, swelling, shrinkage, crusting and erosion) (Fig. 3). Therefore, soils vary in the degree to which they are vulnerable to externally applied natural or man-made destructive forces. Aggregate stability is a measure of such vulnerability and can be defined as the capacity of cohesive forces between soil particles to resist the externally applied destructive forces. The evaluation of aggregate stability and of the size of stable aggregates is important because it is the size of aggregates which determines their susceptibility to water erosion. Moreover, the size of aggregates determines the volume of pore space in soils.

Since the stability of aggregates and pores decreases on wetting dry soil, treatments in water are commonly used to determine the aggregate stability. Such treatments are mostly variations of the wet sieving method introduced by Tiulin (1933) and modified by several others (Kemper and Rosenou, 1986). In general, these methods consist in putting soil aggregates of a selected size onto a 0.2 mm mesh sieve which is moved mechanically in water. The dry weight of soil remaining on the sieve, expressed as a percentage of the original dry weight, is reported as aggregate stability. A deduction is made from both weights for sand grains too large to go through the sieve. Wet sieving is widely used for comparing effects of soil treatments and management practices on aggregate stability. To obtain reproducible results the method has to be rigorously standardized particularly as regards sample preparation, wetting procedure, and the handling and treating of wet aggregates. Slow wetting by capillarity from water under suction is commonly used to allow air to escape freely and so avoid explosive damage to weak aggregates. The aggregate stability is usually much lower when the samples are immersed rapidly.

Aggregate stability strongly depends on the soil organic matter. Its role ranges, as already said, from the production of cementing substances to the action of living organisms, roots, etc. Stability increases with a greater content of organic matter in the soils, especially among those with less than 2 per cent (Kemper and Koch, 1966). Iron and aluminium oxides can act alone or in combination with organic matter to stabilize aggregates. The clay content also plays a strong influence, since stability arises internally from bonds between clay plates, packets of clay plates (domains), and other particles. However, the presence of clay particles does not in itself ensure stability. Sodium in the exchange complex of the clay can make it quite unstable.

Soil Porosity

Soil porosity represents the liquid and gaseous soil phases and its relation with the solid phase is explained in the chapter on soil physical composition. 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. According to one of the most widely used classifications, that of Greenland (1977) reported in Table 1, 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 classe (Pagliai et al., 1981, 1983). 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).

A traditional method to determine pore size distribution is based on moisture retention data, using the concept of "equivalent" sizes derived from a capillary model. This model relates the height of capillary rise (h) to pore radius:

$$\rho gh=2\gamma\cos\theta/r$$

where ρgh is the suction (ρ is the density of water = 0.9982 Mg m^{-3} at 20 °C, g is the acceleration due to gravity = 9.80 m s^{-2}, and h is the height of capillary rise expressed in metres), γ the surface tension of water (72.75 mMm^{-2} at 20 °C), θ the solid-liquid contact angle which is here assumed to be zero, and r the radius of the capillary tube (m). This relationship can be pictured, for example, as a continuous graph, relating capillary diameter (2r) to corresponding negative pressure (suction) (Fig. 4). This figure illustrates that fine pores can exercise a larger pull than large pores. For example, a cylindrical pore diameter of 30 μm corresponds to a capillary rise of 1 m, (thus, suction of 1 m will withdraw water from pores with an effective diameter greater than 30 μm) and a diameter of 100 μm with a relatively low capillary rise of 0.28 m. On this basis, a moisture characteristic curve can be used to show the amount of pore space (as given by the water content on a volume basis) that has pores smaller than a given effective size.

However, for fine-textured soils the calculation of pore size distribution in this way is likely to be invalid, for two reasons. First, it is unlikely that the calculated pore size distribution represents the pore size distribution of the soil at all moisture contents. Secondly, during water desorption most fine-textured soils shrink and particle rearrangement takes place (Aylmore, 1961).

Pore size distribution can most rapidly be determined over a wide range (0.007 μm to 100 μm) by mercury intrusion porosimetry, i.e. measuring the pressure required to force mercury into the pores. Such a pressure depends on the contact angle, the pore shape and the surface tension of the liquid. For cylindrically shaped pores the relationship between pressure and the minimum pore diameter which may by intruded was given by Washburn (1921) as:

$$P=-4\gamma\cos\theta/d$$

where P is the required pressure, γ the surface tension of the liquid, θ the contact angle and d the diameter of the pores.

Experimentally, the method consists of the following steps: one applies an increment of pressure to a suitable apparatus (mercury intrusion porosimeter) in which mercury is permitted to intrude into the pores of a sample; the volume intruded is measured when the liquid ceases to flow; and then the process is repeated under successively higher pressures to the limit of the apparatus. The volume of mercury intruded in a given step is taken as the total volume of pores with equivalent diameters smaller than that corresponding to the pressure causing the flow. By adding the results of all of the steps a cumulative volume distribution with respect to pore diameters is built up.

One disadvantage of this method is that the pores must be empty of water at the start of the measurement. Diamond (1970) and Lawrence (1977) summarised the existing method of drying the soil for this kind of analysis.

Using 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., 1983, 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 in a particular moment of its dynamic evolution. For this analysis it is necessary to prepare thin sections of soil following a procedure which consists in taking undisturbed soil samples using appropriate implements, 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 alterating 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 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. The size depends on the kind of machines available; for porosity measurement a size larger tham 6X6 cm should be recommended. The 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), or plaster of Paris (FitzPatrick et al., 1985), or resin (Moran et al., 1989).

The soil thin sections or photographs (Pagliai et al., 1984) are analysed with image analyzers, such as the Quantimet (Murphy, 1977a, b; Pagliai et al., 1983, 1984). Two-dimensional images obtained have to be transformed into data representing three-dimensional area percentages that are representative for three-dimensional volumes. Stereology techniques have been recently applied to achieve this objective (Ringrose-Voase and Bullock, 1984; Ringrose-Voase and Nortclif, 1977). Basic measurements of image analysis on pores include number, area, perimeter, diameters, projections, etc., and these are supplemented by derived measurements such as shape factors, size distribution, continuity, irregularity and orientation.

The shape factors allow division of pores pore into different shape groups such as, for example, more or less rounded (regular), irregular and elongated pores (Bouma et al., 1977; Paglai et al., 1983). Pores of each shape group can be further subdivided into a select 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).

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 originated by the effect of soil tillage implements.

The elongated pores can be distinguished in two types, 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 already mentioned. An adeguate 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 these pores characterization by image analysis, besides the identification of their shape and width, must also determine 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 and, thus prevent 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 understable 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 radically change depending on whether a vertical or horizontal pore orientation is dominant.

Types of soil structure

In general, three broad categories of soil structure can be recognized: single grained, aggregates and massive. The definition of the several types of soil structure is fundamental for a first qualitative evaluation of soil physical fertility. 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 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. 5). Such a structure allows good soil aeration but the continuity of pores is limited. In the case of heavy rains ponding 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. 6). 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.

Effects of agricultural management practices and treatments on soil structure

Many anthropogenic activities affect soil structure. To evaluate the impact of management practices on the soil environment it is necessary to quantify the modifications of 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, irrigation and soil compaction by wheel traffic.

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 management 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., 1983; 1984; 1989; Shipitalo and Protz, 1987).

No-till management has been shown to increase the soil faunal populations (Barnes and Ellis, 1979) and this could ameliorate the detrimental effect of row crop production on soil structure. However, no-till management can not always be recommended because of reduced yields in some types of soil, probably due to the development of soil physical properties not conducive to plant growth (Pagliai and Pezzarossa, 1990). Therefore, the relationships between tillage practices, soil structure, and soil fauna are considered worthy of further investigation with the aim of preserving the soil environment.

Recent research has shown that management practices predominately affect soil porosity (Kooistra et al., 1990; Pagliai et al., 1989; Shipitalo and Protz, 1987). 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).

Tillage produces a loose and crumb structure with increased macroporosity which is dominated by large packing pores separating aggregates or clods. Such a crumb structure produced by tillage is very unstable, especially in the surface layer, and after the first rainfall and wetting and drying cycles can be transformed into a more compact structure, often associated with the presence of a surface crust. This transformation is strictly related to the type of soil, the organic matter content and the aggregate stability. During the cultural cycle the soil structure changes. Therefore, in order to study the modifications induced by different tillage treatments it is necessary to plan an appropriate sampling strategy during the crop cycle. A sampling in the period of crop ripening is particular important because at that time good soil conditions are critical for crop development (Pagliai et al., 1989). In the case of studying the effect of different tillage treatments on crusting soils a sampling before seedling emergence is very important.

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. 7 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). 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 the annual sampling in the period of corn ripening. Soil pore space significantly increased in all years, after treatment with all organic materials compared to treatment with chemical fertilization alone, irrespective of the sampling year.

Pore shape and size distribution were also affected by the application of organic materials. The proportion of storage (30-50 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. 8). 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. 9). The latter was associated with a lower water content in the surface soil and reduced root density. The larger amount of water applied in this system caused progressive soil compaction, resulting in decreased porosity and structural degradation.

Fig. 10 visually explains the results of Fig. 9: 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.

Soil compaction by wheel traffic. - Soil compaction is caused by a combination of natural and man-made forces. The latter are mainly related to vehicle wheel traffic and passage of tillage implements and generally have a much greater compactive effect than natural forces such as raindrop impact, soil swelling and shrinking and root enlargement especially because trends in agricultural engineering over the last few decades have resulted in machines of a greater size and weight.

Fig. 11 shows the results of an experiment dealing with the modifications of soil porosity and structure induced by tractor wheels in a clay sandy loam soil and for how long such modifications are apparent (Pagliai et al., 1992). In the compacted topsoil, porosity greatly decreased (3-4 times), particularly that of elongated pores. At the same time, the size of these pores was reduced and other observations indicated a modification of their orientation. This effect was even more evident in the case of several passes over the same area. Microscopic observation revealed that these elongated pores were thin fissures parallel to the soil surface, forming a platy structure, and had no vertical continuity (Fig. 12). As a consequence water infiltration was reduced, causing an increase of the risk of soil erosion. After seven months the modifications induced by compaction were still evident with respect to the uncompacted topsoil. Bullock et al. (1985b) also found that soil structure could regenerate after compaction in clay soils, although over a period of some years. Bresson and

Zambaux (1990) concluded that the noted decrease in the porosity of biopores and fissures due to compaction, associated with increased pH and decreased organic matter due to continuous cultivation, may alter the cohesion of the isotropic ultramicrofabric and make compaction irreversible. Coulon and Bruand (1989) confirmed that compaction modified the pore space geometry and fabric of the elementary particles.

The decrease of soil porosity causes, as already stated, strong structural modifications in the compacted areas, and it is strongly related to the cone penetrometer resistance. Fig. 13 shows a good correlation, in the surface compacted layer, between soil porosity and resistance to cone penetration.

The formation of compacted layers along the profile (ploughpans) - Continually ploughing the soil may cause the formation of a ploughpan (ploughsole) at the lower depth limit of cultivation (Fig. 14). Fig. 15 shows that the macroporosity, measured by image analysis, was high just above the ploughpan; decreased to a very low value in the ploughpan, and slightly increased in uncultivated soil below. In this case the ploughpan is only a few centimetres deep but other studies have shown that the ploughpan can reach a thickness of up to 10 cm. Fig. 15 also shows that other types of tillage such as the chiesel ploughing or minimum tillage could prevent or reduce the formation of the ploughpan. Microscopic observations revealed that in the first few centimetres of the ploughpan there were a few, very thin, elongated poroids parallel to the surface of the ploughpan. Some irregular pores were present in the lower part of the ploughpan. The presence of such dense layers at the lower depth limit of cultivation may greatly reduce water drainage and hamper root development at depth. Kooistra et al. (1984) observed that the continuity of large pores, made visible by stained channels, in thin sections of an undisturbed ploughpan in a sandy loam soil was greater than that in a ploughpan disturbed by deep rototilling, which had discontinuous (unstained) packing pores between the aggregates. This means that once the ploughpan is formed it is very difficult to recover a structure which allows good drainage.

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Table 1 - 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

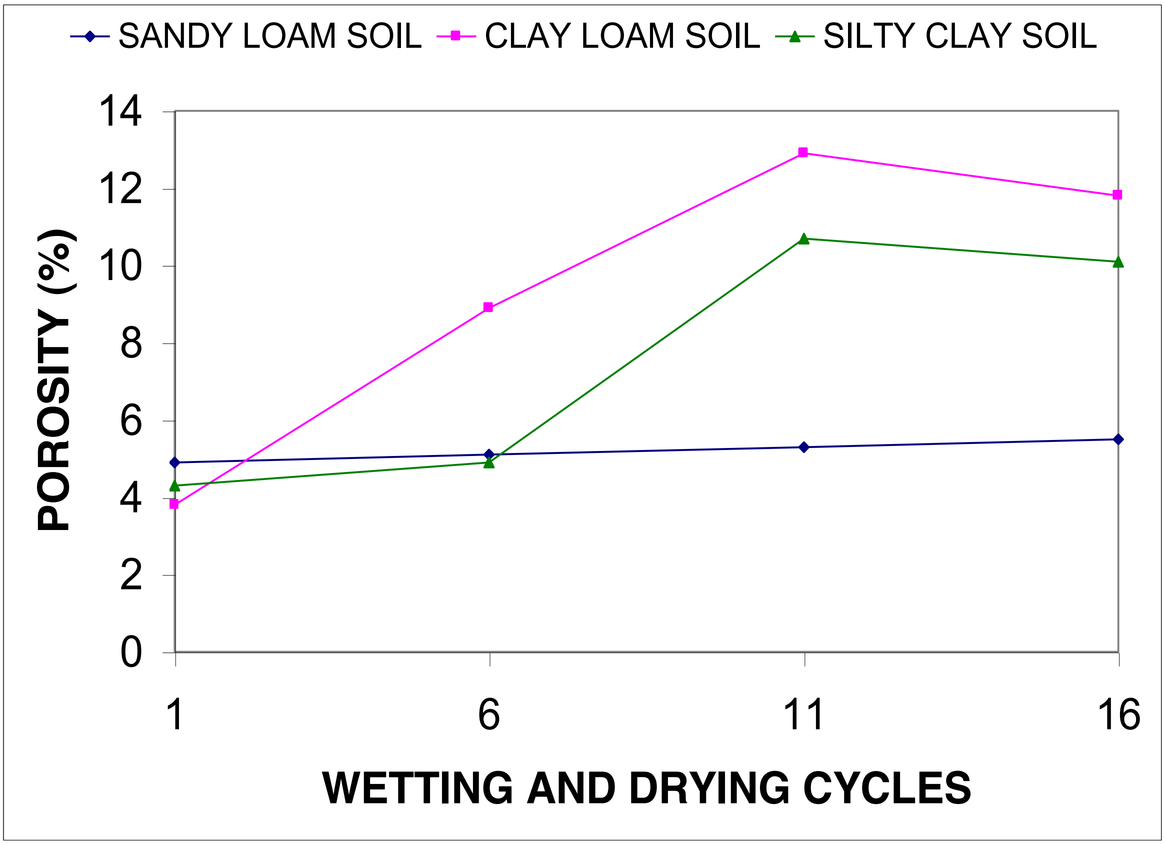


Fig. 1 - Influence of wetting and drying cycles on porosity formed by pores larger than 30 μm in three different soils. Modified by Pagliai et al. (1987).

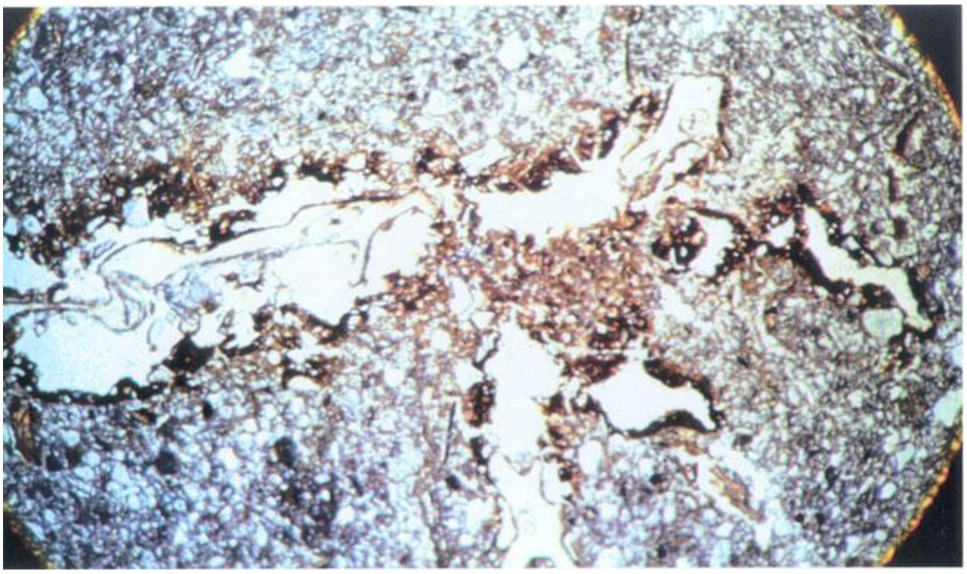
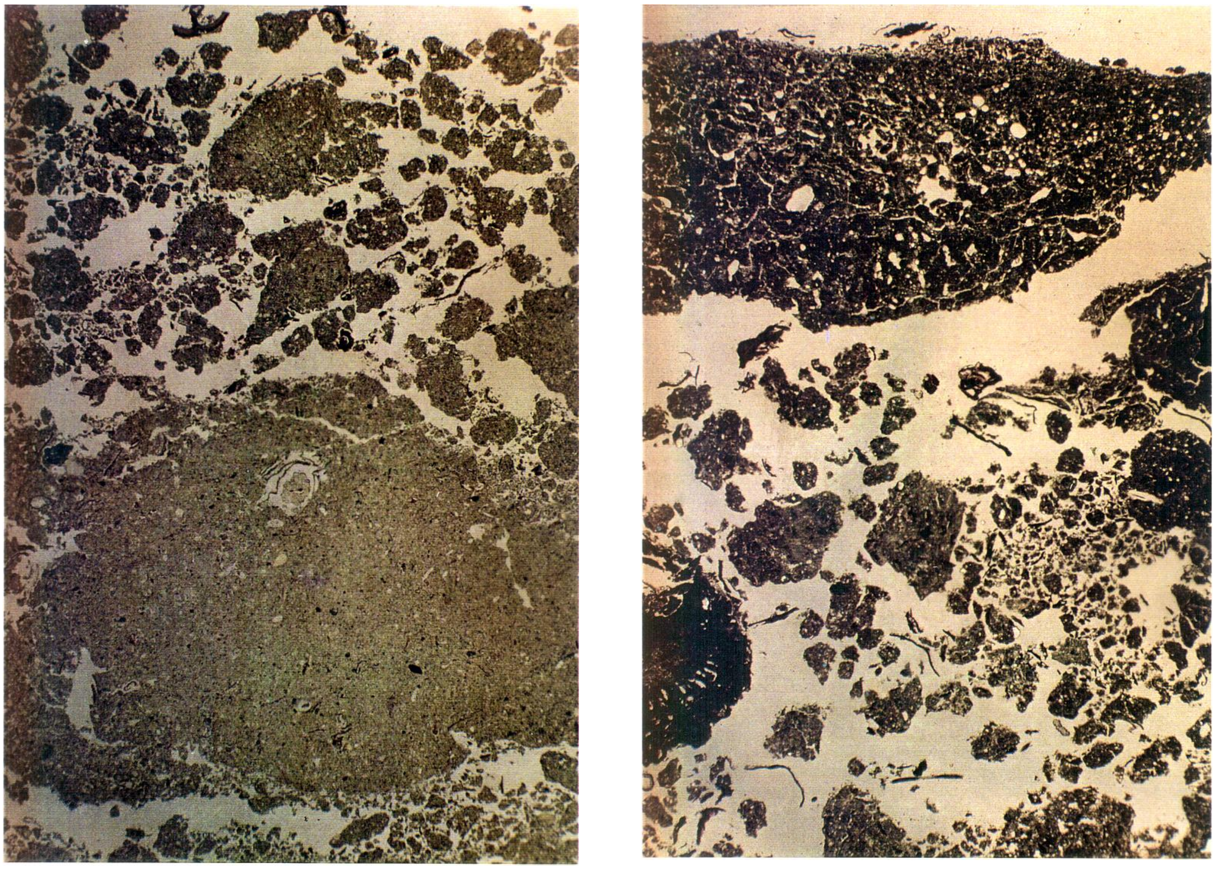


Fig. 2 - Microphotograph of a vertically oriented thin section from an undisturbed sample of a sandy loam soil showing the presence of organic matter (dark) as coats on pore (light) walls. Frame length 3×5 mm.



a b

Fig. 3 - Macrophotographs of vertically oriented thin sections prepared from undisturbed samples from the surface layer (0-10 cm) of a clay loam soil after the tillage (a) and after the first impact of rainfall and the following drying cycles (b). The transformation of a crumb/subangular blocky structure to a compact platy structure, associated with the presence of a surface crust, is evident. The rounded pores in the top layer in photo b are vesicles formed by entrapped air during the crusting processes. Frame length 3×5 cm.

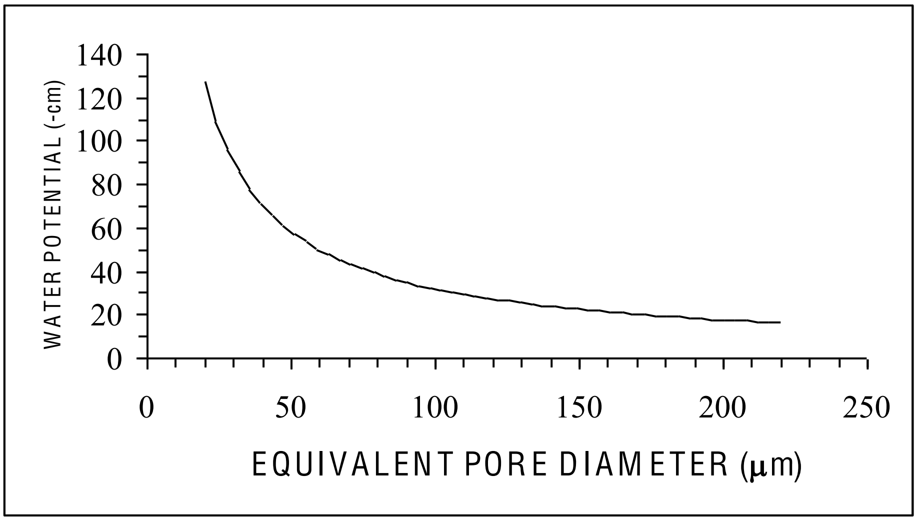


Fig. 4 - Example of relationships between pore size (equivalent diameter) and water potential in soil, according to the capillarity model.

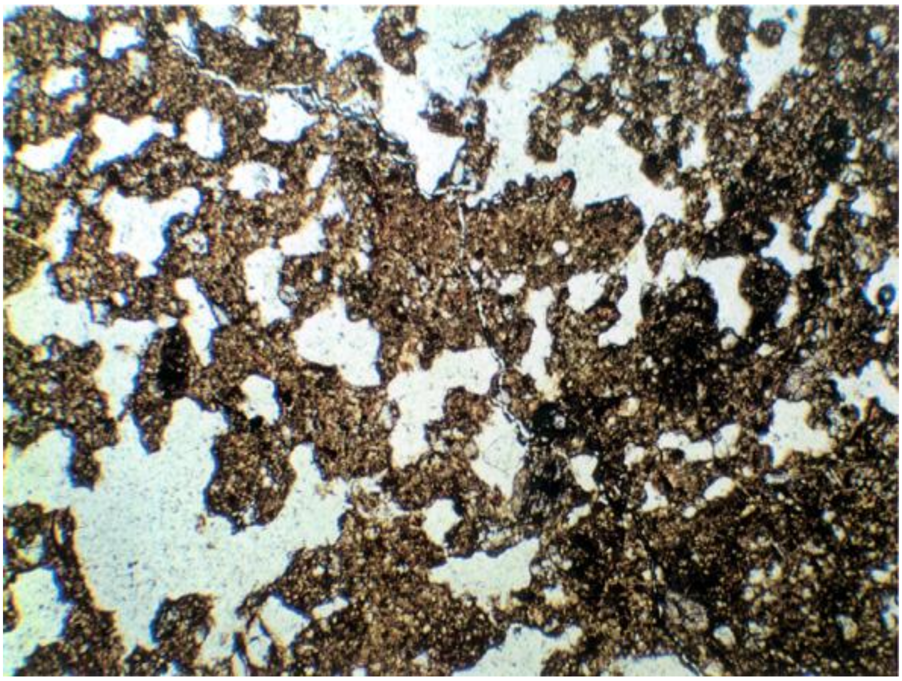


Fig. 5 - Microphotograph of a vertically oriented soil thin section showing an example of vughy structure. The white areas represent the pores. Frame length 3×5 mm.

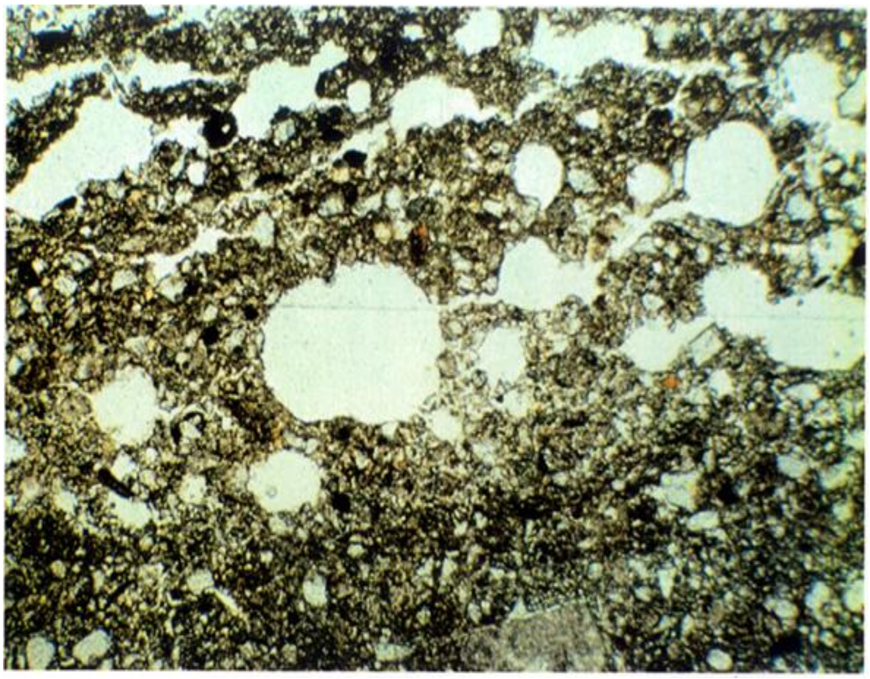


Fig. 6 - Microphotograph of a vertically oriented soil thin section showing an example of vesicular structure. The white areas represent the pores. Frame length 3×5 mm.

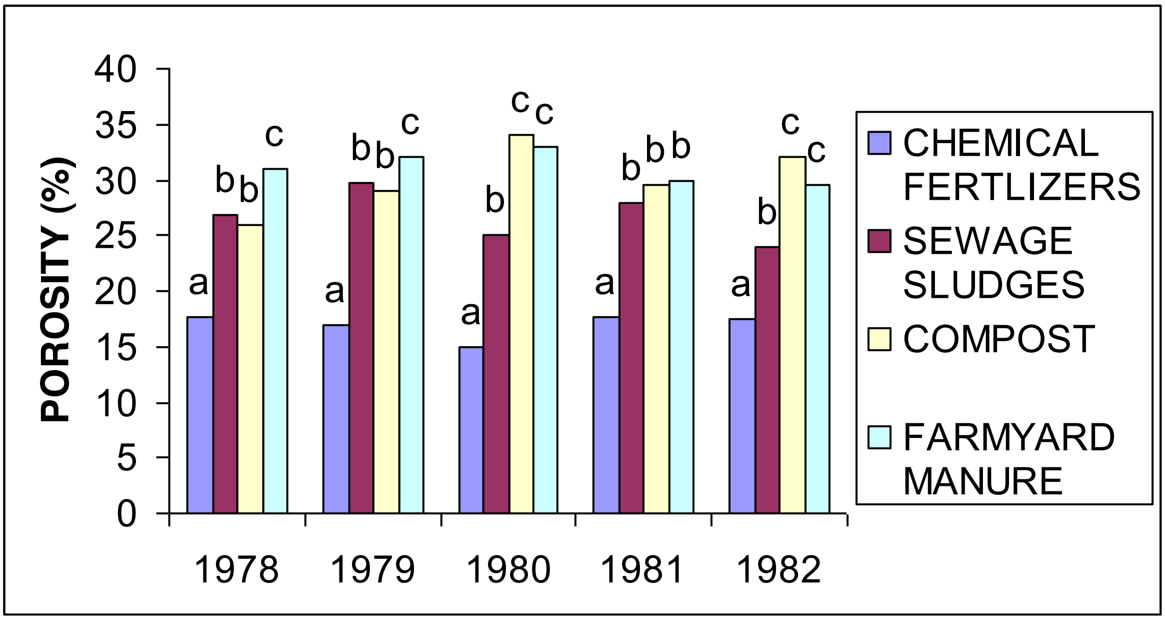
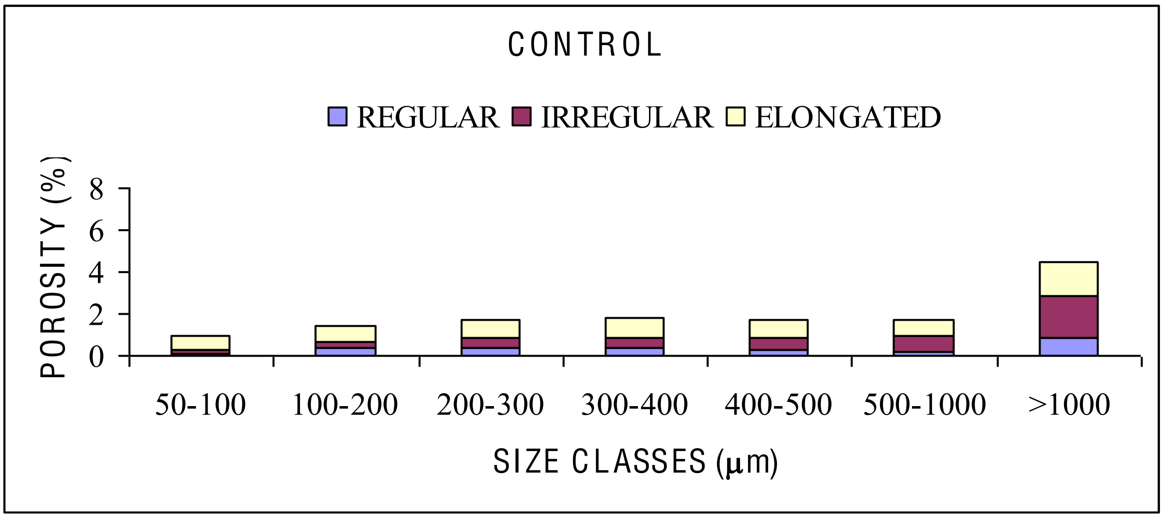


Fig. 7 - Effect of soil application of waste materials, farmyard manure and chemical fertilizers on soil porosity, expressed as a percentage of area occupied by pores per thin sections. Modified from Pagliai (1991).



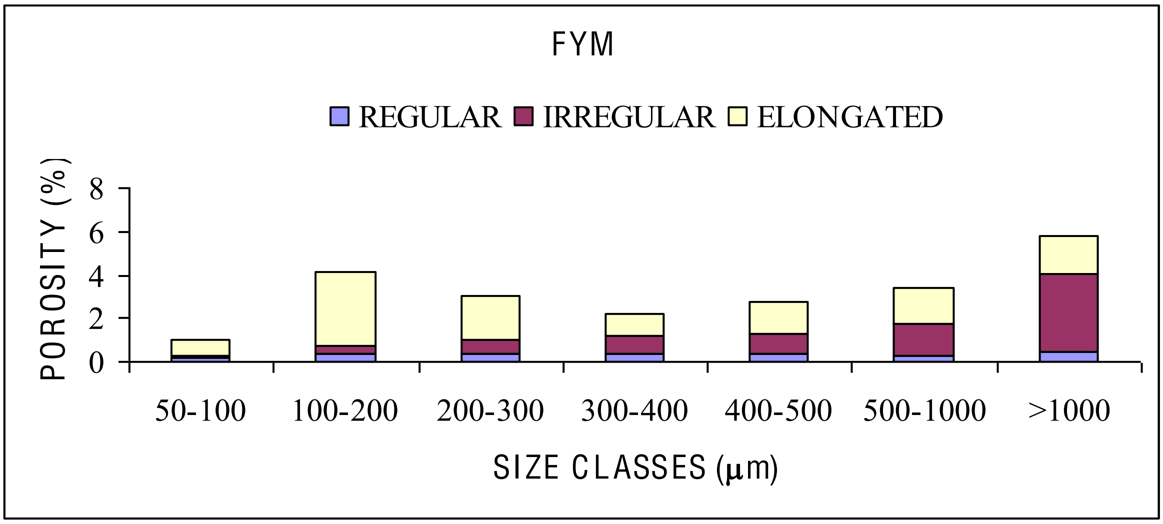


Fig. 8 - Pore size distribution according to the equivalent pore diamenter for regular and irregular pores and to the width for elongated pores in soil treated with farmyard manure in comparison with soil treated with chemical fertilizers.

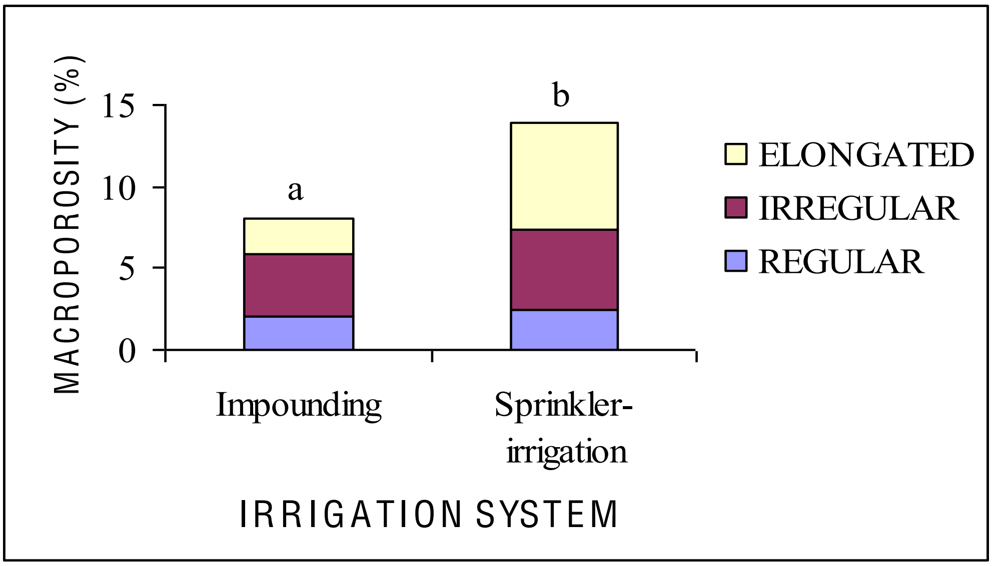
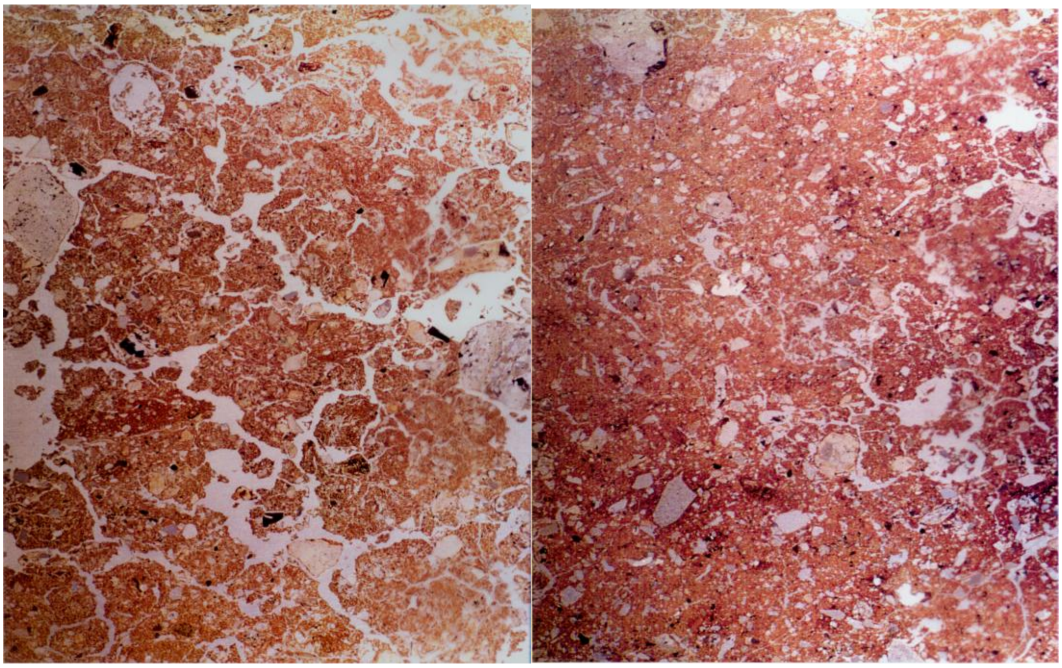


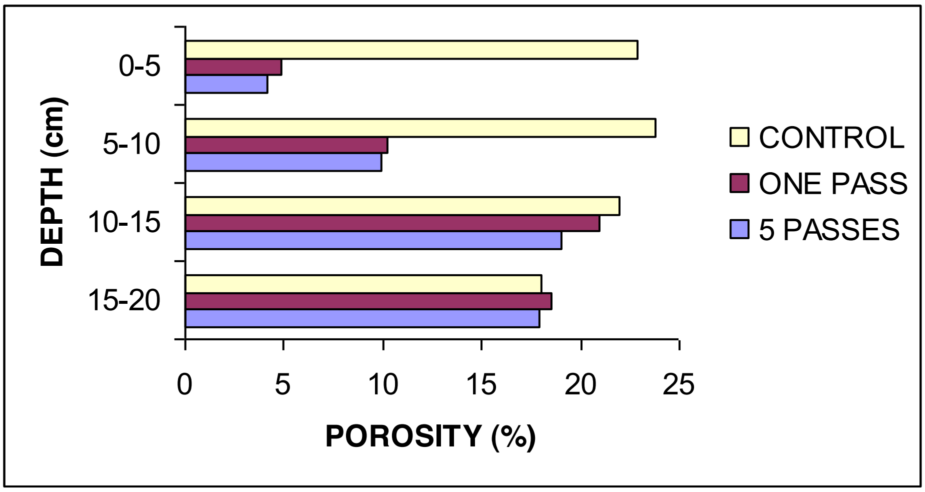
Fig. 9 - Pore size distribution according to the equivalent pore diamenter for regular and irregular pores and to the width for elongated pores, in the inter-row of a peach orchard sandy loam soil under two types of irrigation systems.



a) b)

Fig. 10 - 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 (a) and irrigated by impounding (b). 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.

A



B

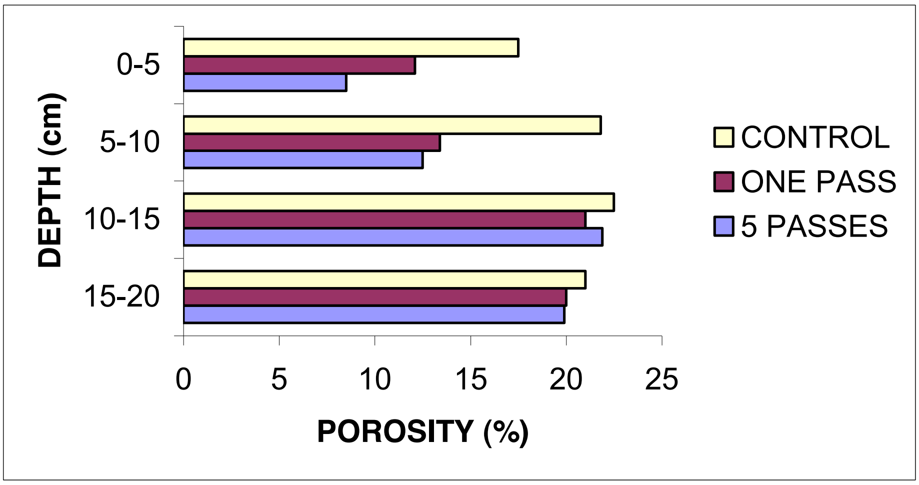
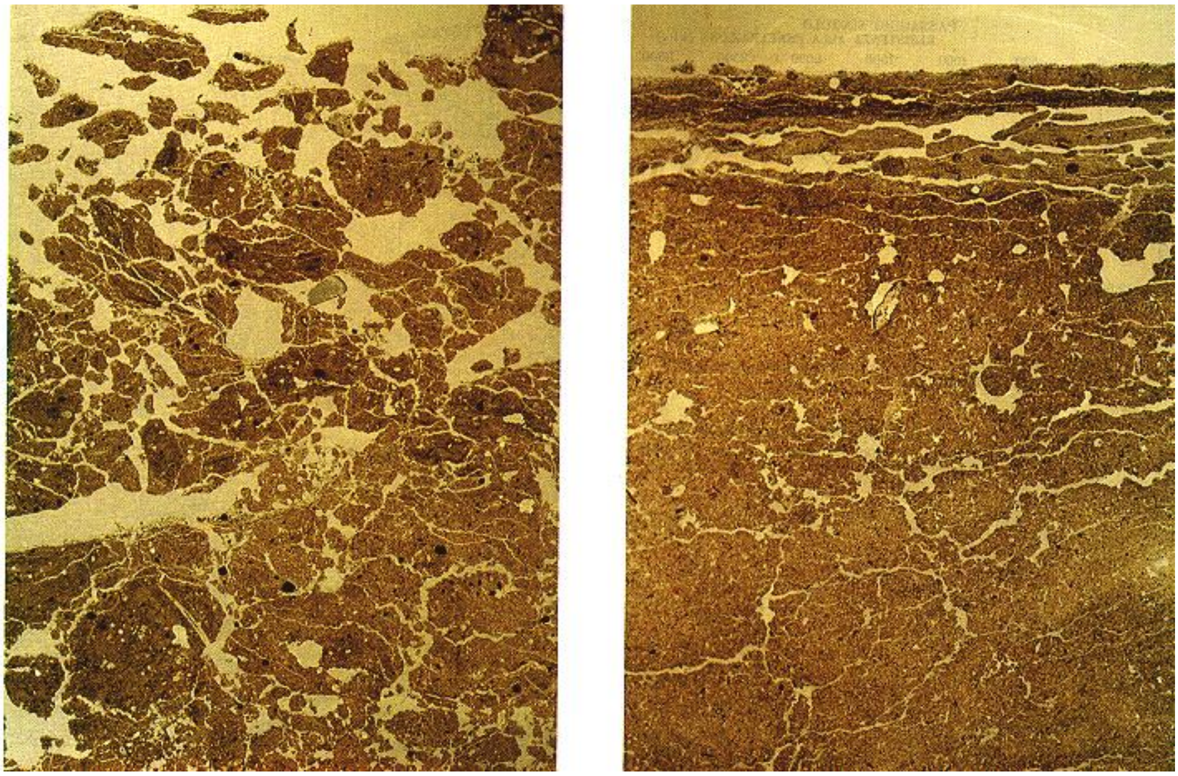


Fig. 11 - Porosity and pore shape distribution in a clay loam soil uncompacted (control) and compacted by one pass and five passes of wheel traffic at the time of compaction (A) and seven months later (B). Modified from Pagliai et al. (1992).



a) b)

Fig. 12 - Macrophotographs of vertically oriented thin sections prepared from undisturbed samples from the surface layer (0-10 cm) of uncompacted (a) and compacted (b) clay loam soil. The transformation from a subangular blocky structure of the uncompacted areas to a massive platy structure of the compacted areas. The interruption of pore continuity in the interface soil-atmosfere is also evident. Frame length 3×5 cm.

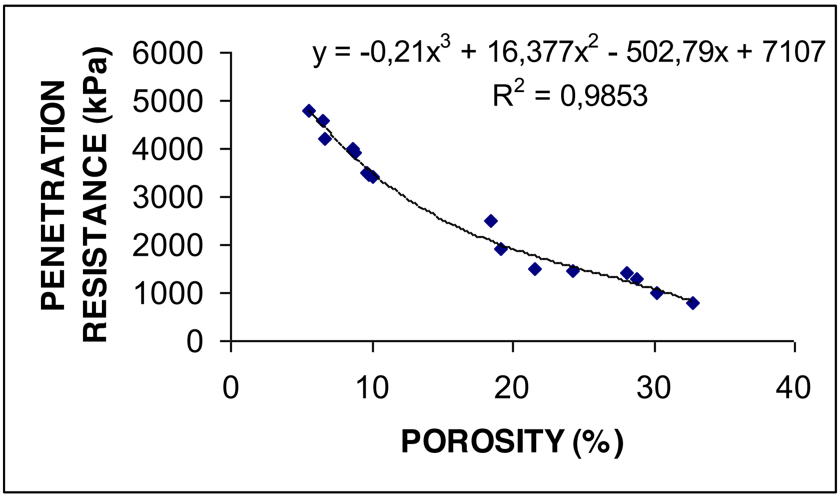


Fig. 13 - Correlation between soil porosity and resistance to cone penetration in the surface layer (0-10 cm) compacted by wheel traffic.

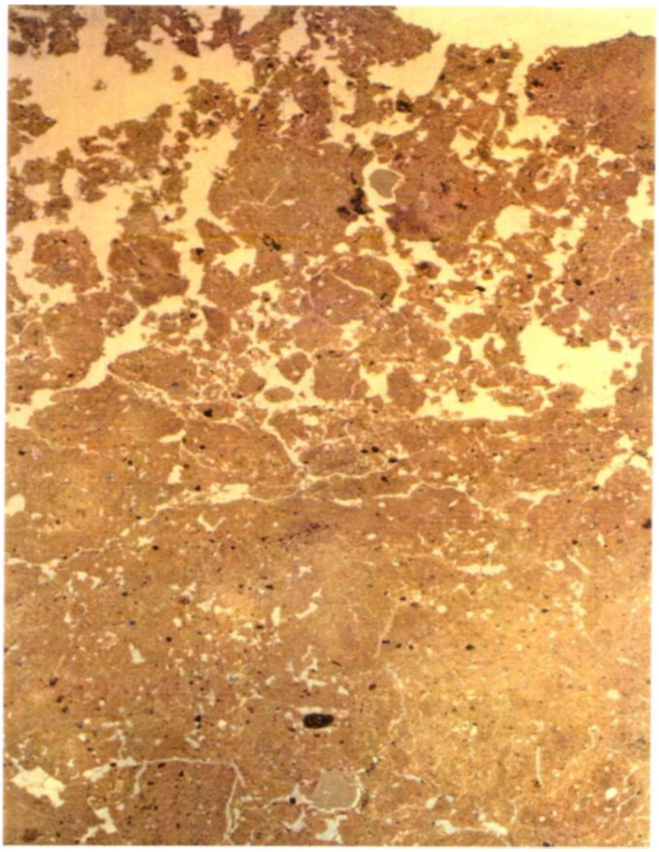


Fig. 14 - Macrophotographs of vertically oriented thin sections prepared from undisturbed samples from the 23-30 cm layer of a clay loam soil. The lower limit of cultivation (ploughpan) is visible. Frame length 3×5 cm.

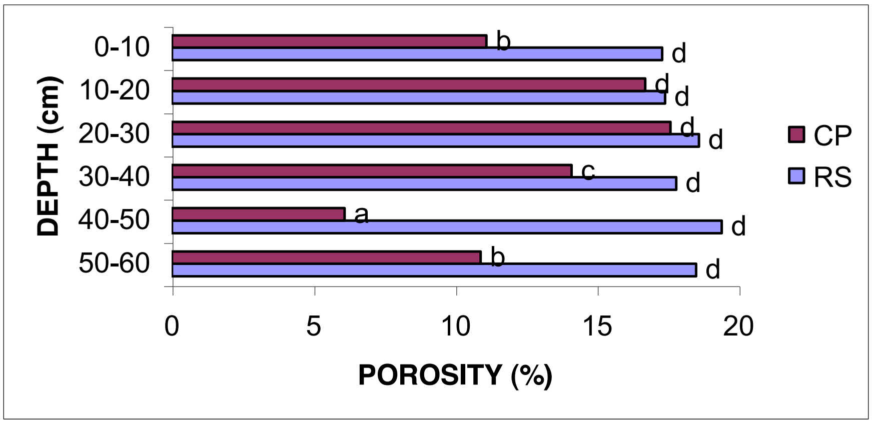


Fig. 15 - Example of variation of soil porosity along the cultural profile, measured by image analysis and expressed as a percentage of area occupied by pores larger tha 30 µm per thin section. CP = Conventional ploughing; RS = Ripper subsoiling.