The Soil Pore System as an Indicator of Soil Quality

Marcello Pagliai, Nadia Vignozzi

Istituto Sperimentale per lo Studio e la Difesa del Suolo

Piazza M. D'Azeglio 30 – 50121 Firenze (Italy)

Abstract

The need to reduce the environmental impact of agricultural activities and to control degradation of soil structure is one of the main aims of land management, especially in vulnerable environments. Intensive cultivation of some agricultural soils can lead to deterioration in soil structure and other physical properties of the soil and, consequently, decreased crop yields. The most important modifications of soil structure mainly involve changes in soil porosity. Therefore, measurements of this physical property can help to quantify the impact of management practices on 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.

Soil porosity is, therefore, 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 management practices. In this way, we can identify those management practices that are more compatible with environmental protection. Characterisation of the pore system provides a realistic basis for understanding the retention and movement of water in soil. 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. Soil porosity shows a strong correlation with penetration resistance: a decrease of porosity is generally associated with an increase of penetration resistance. The pore shape and size distribution are also strictly related to chemical, biochemical and biological properties, like enzyme activity, and root growth.

Key words: Soil Structure, pore size distribution, pore shape, pore continuity, image analysis.

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 (Ringroase-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., 1983, 1984). 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).

Quantification of the soil pore system

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.

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.

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., 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 at a particular moment in 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 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 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-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. The size depends on the kind of machines available; for porosity measurement a size larger than 6X6 cm is recommended. 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 are analysed with image analyzers (Murphy, 1977a, b; Pagliai et al., 1983, 1984). 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).

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.

Pore shape

The shape factors allow division of pores into different shape groups such as, for example, more or less rounded (regular), irregular and elongated pores (Bouma et al., 1977; Pagliai 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 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. 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 class (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).

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.

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, Figures 1 and 2 show highly significant correlations between elongated pores and hydraulic conductivity. Such correlations are more significant when the porosity formed by elongated pores is lower.

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.

Relationships between soil porosity and penetration resistance

Several studies of the effect of compaction caused by wheel traffic on porosity and structure of different types of soils have shown strong correlations between soil porosity and penetration resistance (Pagliai et al., 1992; Marsili et al., 1998). Fig. 3 shows a good correlation between porosity, measured by image analysis on soil thin sections, and penetration resistance in the surface layer (0-10 cm) of both compacted (porosity values below 10%) and uncompacted areas. The decrease of porosity in compacted areas was associated with an increase of penetration resistance.

Relationships between soil porosity and some chemical and biochemical properties

It is well known that soil structural quality depends strongly on interactions with organic matter. Micromorphological techniques can give useful contributions in studies dealing with interactions between organic matter and soil structure by means of the microscopic examination of soil thin sections. Fig. 4 shows the accumulation of organic matter distributed as coatings along the walls of elongated pores. These coatings 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. These observations illustrate the possibility of correlations between soil porosity and some chemical and biochemical soil properties. For example, Sequi et al. (1985) and Pagliai and De Nobili (1993) have found a linear correlation between soil porosity represented by pores ranging from 30 to 200 μm equivalent pore diameter, and the activity of soil enzymes, like urease (Fig. 5). Such relationships between pore size and enzyme activity were confirmed by Giusquiani et al. (1995) in soils treated with compost.

Relationships between soil porosity and root growth

Soil structure modifications such as the decrease of soil porosity and the increase of penetration resistance following compaction may hamper root growth besides reducing water infiltration. This aspect was studied in a grassed sandy loam soil in a peach orchard (Pezzarossa and Pagliai, 1990). The porosity and root density were measured down to a depth of 50 cm in the areas compacted by the continuous wheel traffic for all management practices (pesticide treatments, harvesting, etc.) and in the adjacent inter-row areas. Results are summarized in Fig. 6.

The large reduction of porosity in the 0-20 cm layer of the compacted areas is evident, while in the 20-30 cm layer porosity increased, even though its value remained lower than in uncompacted areas. The root density, measured by image analysis and expressed by root length per cm^3 of soil (Pezzarossa and Pagliai, 1990), showed the same trend: in the 0-20 cm layer of the compacted areas it showed a value about three times lower than in the same layer of adjacent uncompacted areas. In the 20-30 cm layer, where the effect of compaction was smaller, the root density increased showing approximately the same value as in uncompacted soil.

Similar results were obtained in a previous study where no-tillage and conventional tillage were compared in a clay loam soil under viticulture (Pagliai and De Nobili, 1993). The distribution of the roots in the Ap horizon showed a higher root density in the no-tilled soils than in those which were conventionally tilled, following the same trend of the distribution of elongated transmission pores (50-500 μm). This finding confirmed the importance of transmission pores for root development. Therefore for the soil examined in that investigation, no-tillage systems seemed to be more appropriate in maintaining favourable soil porosity by preserving the elongated transmission pores which facilitate good root development.

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 - 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

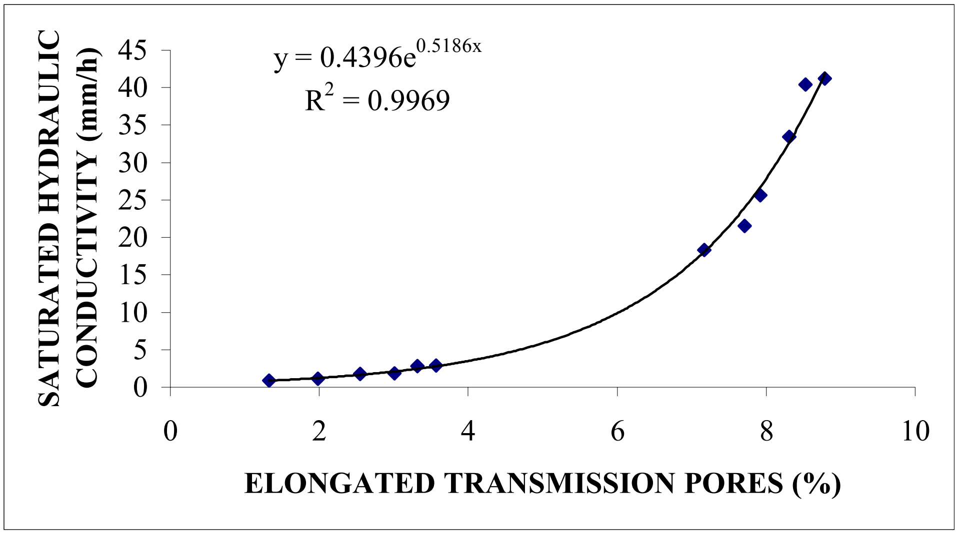

Fig.1 – Correlation between soil porosity, formed by elongated pores, and saturated hydraulic conductivity in the surface layer (0-10 cm) of compacted and uncompacted areas of a clay soil.

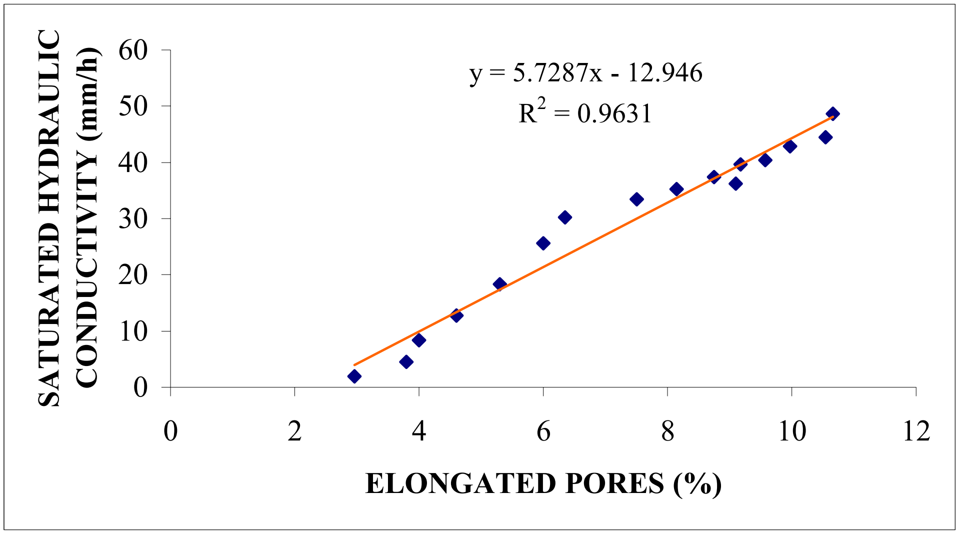

Fig. 2 – Correlation between soil porosity, formed by elongated pores, and saturated hydraulic conductivity in the surface layer (0-10 cm) of a loam soil cropped with maize.

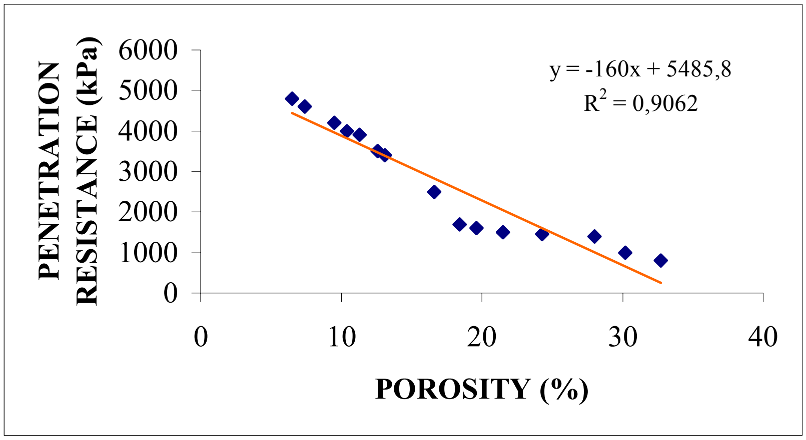

Fig. 3 – Correlation between soil porosity and penetration resistance in the surface layer (0-10 cm) of a clay loam soil.

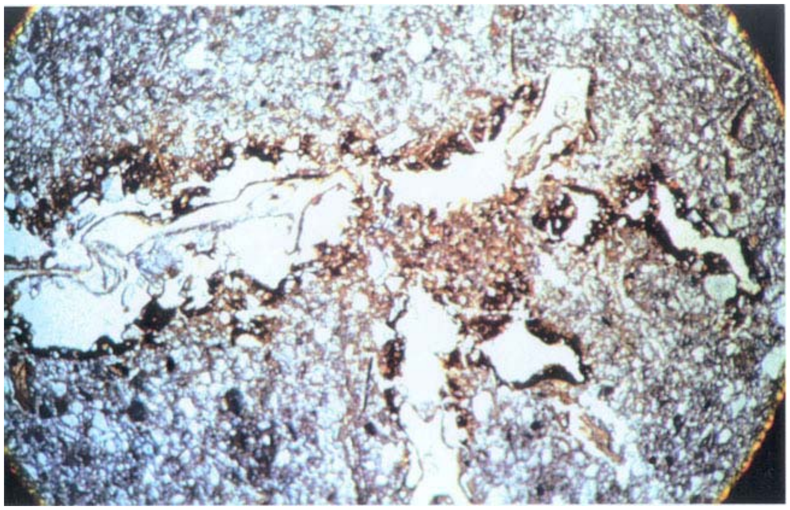

Fig. 4 – Macrophotograph of a vertically-oriented thin section. Organic materials can be seen clearly as coatings on pore walls. Plain light; pores appear white. Frame size 5 mm.

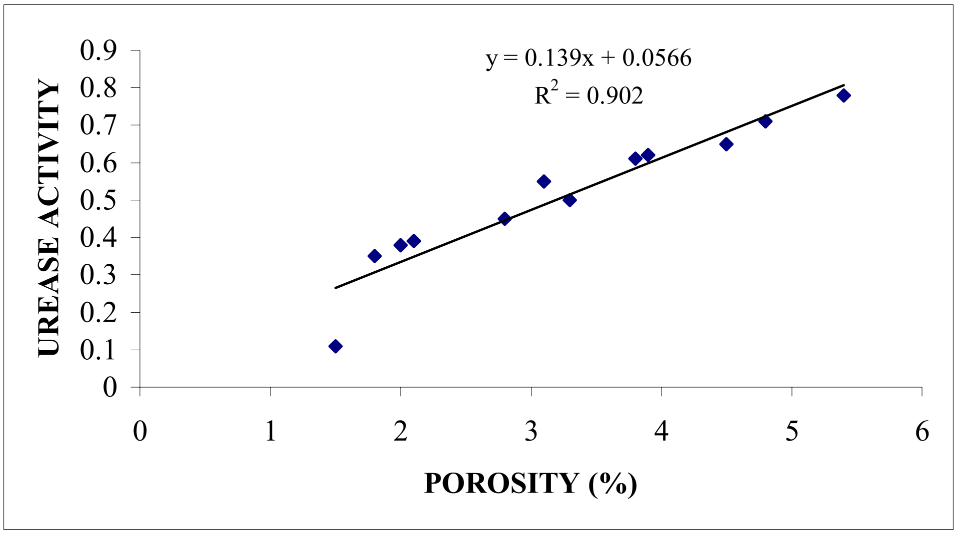

Fig. 5 - Correlation between soil porosity in the range 30-200 μm and urease activity (μmol ammonium release h^{-1} g^{-1} soil) in the surface layer (0-10 cm) of a clay loam soil.

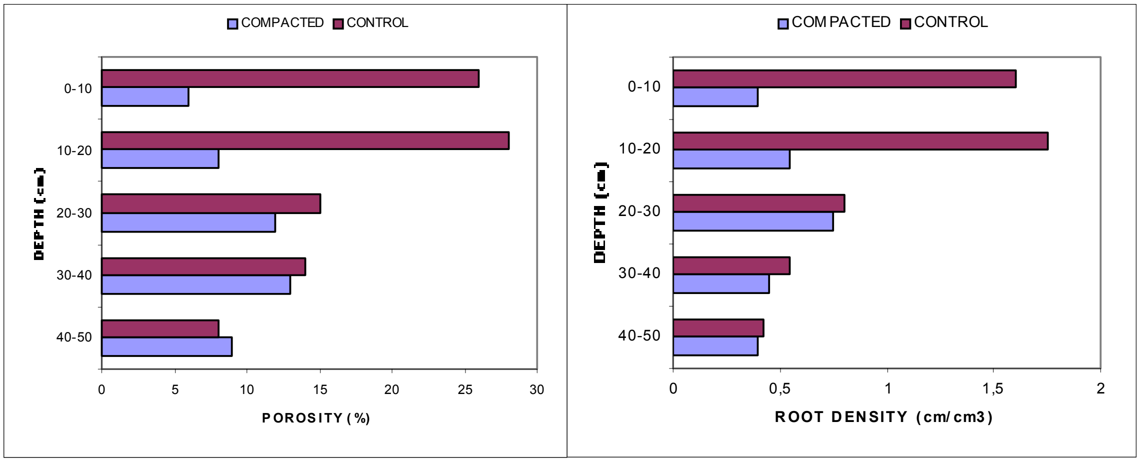

Fig. 6 – Effects of soil compaction, caused by wheel traffic of machines in a peach orchard, on soil porosity expressed as a percentage of the area occupied by pores larger than 50 μm per thin section (on the left) and on root density expressed as root length/cm^3 (right).