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CHANGES OF PORE SYSTEM FOLLOWING SOIL COMPACTION

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Abstract

Soil compaction is one of the most important factors responsible for environmental degradation. It causes strong modifications to soil structure and reduces soil porosity. Therefore the measurements of such a physical property can help to quantify the effects of compaction. This is now possible because of the increasing use and availability of the technique of image analysis allowing the measurement of soil porosity on thin sections or impregnated soil blocks, prepared from undisturbed soil samples.

Results showed that compaction 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 soil. 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 and root growth. Soil regeneration after compaction depends on the type of soil and on the degree of damage to the soil.

Introduction

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 environmental 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 compaction and soil structure degradation.

To evaluate the impact of management practices on the soil environment it is necessary to quantify the modifications to 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 in intensive arable lands 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 many 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., 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 (McBratney et al., 1992; Mermut et al., 1992; Moran and McBratney, 1992).

Methods

The pore system was characterised by image analysis on thin sections from undisturbed soil samples to measure pores >50 μm (macroporosity) and by mercury intrusion porosimetry to measure pores <50 μm (microporosity).

For the image analysis, at the least six undisturbed samples must be collected in the surface layer (0-10 cm) and at selected depths along the profile and at selected times in the compacted areas and in the adjacent areas (control). Samples are dried by acetone replacement of water (Murphy, 1986), impregnated with a polyester resin and made into 6×7 cm, vertically oriented thin sections (Murphy, 1986). Such sections are analysed by means of image analysis techniques (Pagliai et al., 1984), using a PC-IMAGE software produced by Foster Findlay Associates (London). Total porosity and pore distribution are measured according to their shape and size. The instrument is set up to measure pores larger than 50 μm. Pores were measured by their shape, which is expressed by the shape factor [perimeter^2/(4π·area)] and divided into regular (more or less rounded) pores (shape factor 1-2), irregular pores (shape factor 2-5) and elongated pores (shape factor >5). These classes correspond approximately to those used by Bouma et al. (1977). Pores of each shape group can be further subdivided into size classes according to either the equivalent pore diameter, for regular and irregular pores, or the width, for elongated pores (Pagliai et al., 1983, 1984). Thin sections are also examined using a Zeiss "R POL" microscope at 25x magnification to observe soil structure.

For mercury intrusion porosimetry, six undisturbed samples can be collected in the areas adjacent to those sampled for thin section preparation. Aggregates with a volume up to 4 cm^3 are air-dried and degassed prior to analysis using a mercury intrusion porosimeter (Carlo Erba WS Porosimeter 2000) equipped with a Carlo Erba 120 macropore unit. The porosity and pore size distribution are determined within the range 0.007-50 μm.

Other methods for assessing the effect of soil compaction can be the measurement of penetration resistance by standard cone penetrometer and the comparison of results between compacted and uncompacted soil.

The effects of soil compaction can be reflected in water movement which can be assessed by infiltration measurements in the field. Such a measurement is time consuming and complicated. The laboratory measurement of saturated hydraulic conductivity may be useful in evaluating the effect of compaction on water flow. For this it necessary to collect undisturbed cores (5.68 cm diameter and 9.5 cm high) from the compacted and uncompacted areas. The samples are slowly saturated and the saturated hydraulic conductivity can be measured using, for example, the falling-head technique (Klute and Dirksen, 1986).

Soil porosity

Fig. 1 shows the results of an experiment dealing with the modification of soil porosity, expressed as a percentage of area occupied by pores larger than 50 μm per thin section, induced by tractor wheels in a loam soil (Pagliai et al., 1995). Results show that porosity significantly decreased (until three times with respect to the control) in the surface layer (0-10 cm) just after a single pass. Such a decrease still increased after four passes, even though not significantly when compared to the single pass. A new recent experiment on the same type of soil confirmed that the compaction caused a four times decrease in soil porosity between the wheel tracks and a six times decrease under the wheel tracks compared to the adjacent uncompacted soil (Pagliai et al., 1998). The compacting effect of wheel traffic, in this type of soil with a water content at the time of compaction of 0.16 m^3m^{-3}, seemed to be limited to the surface layer: in fact, the porosity in the 10-20 cm layer did not show significant differences between uncompacted areas and those compacted by one and four passes of the tractor.

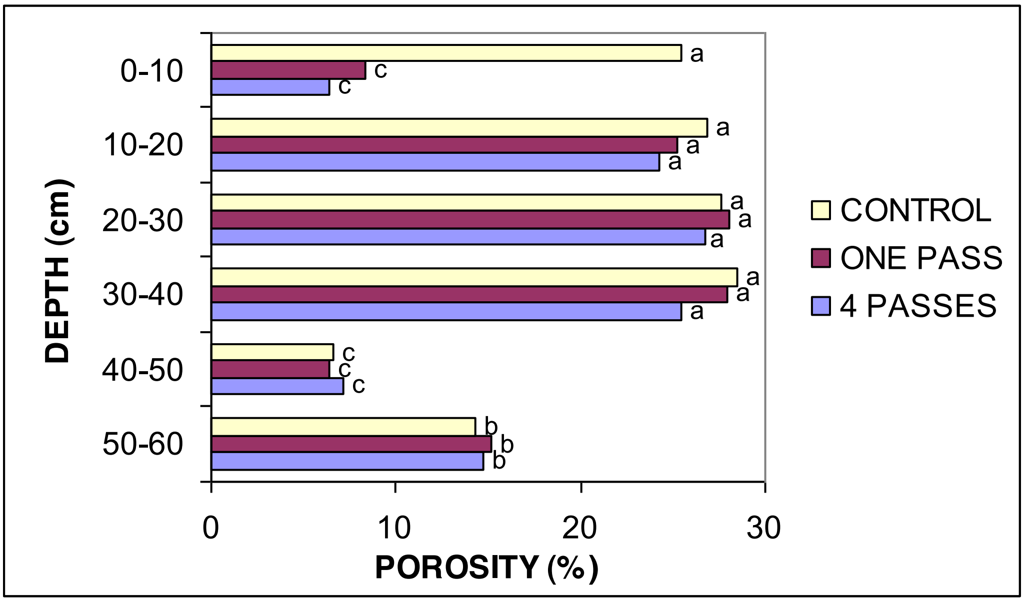


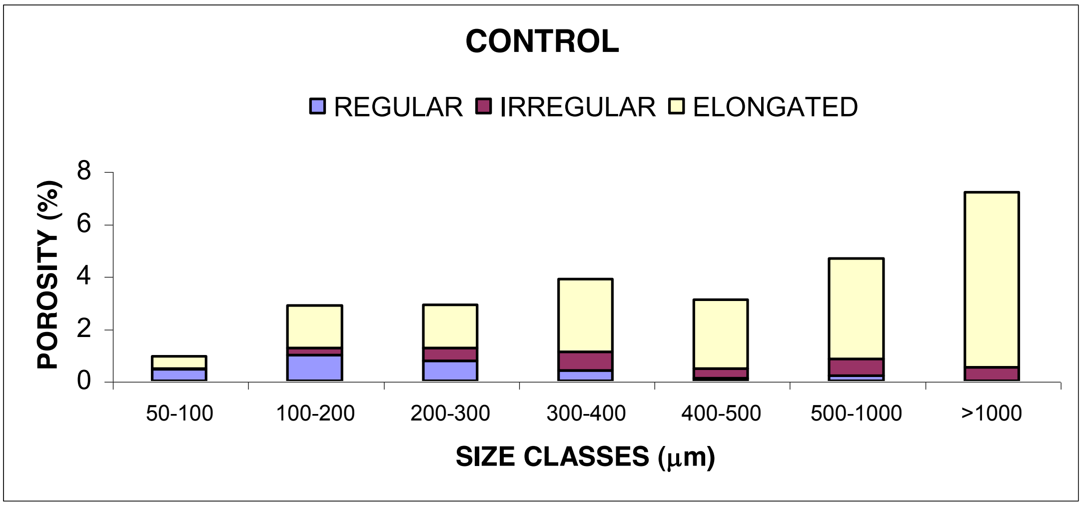
Fig. 1 – Effects of soil compaction, caused by one and four passes of tractors, on soil porosity expressed as a percentage of area occupied by pores larger than 50 μm per thin section. Mean of six replications. Values followed by the same letter are not significantly different at the 0.05 level employing Duncan's Multiple Range Test.

In the 40-50 cm layer the porosity drastically decreased from over 25% of the upper layer to 6-7% due to the formation of a ploughpan at the lower cultivation limit. The investigated soil was, in fact, cultivated to maize and ploughed to a depth of 40 cm. The adoption of alternative tillage systems such as ripper subsoiling may remove or prevent the formation of this compact layer (Pagliai et al., 1998).

For a better interpretation of this data it could be stressed that according to the micromorphometric method, a soil is considered dense (compact) when the total macroporosity is less than 10%, moderately porous when the porosity ranges from 10 to 25%, porous when it ranges from 25 to 40% and extremely porous over 40% (Pagliai, 1988). The soil of this study, in the surface layer, can be considered as moderately porous and the compaction is significant because it decreased the porosity below 10%.

For a thorough characterization of soil macropores, the main aspects to be considered are not only the pore shape but also the pore size distribution, especially of elongated continuous pores, because many of these pores directly affect plant growth by easing root penetration and storage and transmission of water and gases. For example, according to Russell (1978) and Tippkötter (1983), feeding roots need pores ranging from 100 to 200 μm to grow into. According to Greenland (1977), pores of equivalent pore diameter ranging from 0.5 to 50 μm are the storage pores, which provide the water reservoir for plants and micro-organisms, while transmission pores ranging from 50 to 500 μm (elongated and continuous pores) are important both in soil-water-plant relationships and in maintaining good soil structure conditions. Damage to soil structure can be recognized by decreases in the proportion of transmission pores.

The soil compaction following the wheel traffic of the tractors not only reduced the total porosity but also modified the pore system in soil, i.e., modified the shape and the size distribution of pores. Pore shape and size distribution in the 0-10 cm layer of the areas compacted by the passes of the tractors showed large differences compared with uncompacted areas (Fig. 2). The reduction of porosity following the compaction of one and four passes of the tractors was due to a reduction of all larger pores but mainly the elongated pores which can negatively affect water infiltration. Such pores are the most important, because, as already said, many of these pores directly affect plant growth by easing root penetration and storage and transmission of water and gases.



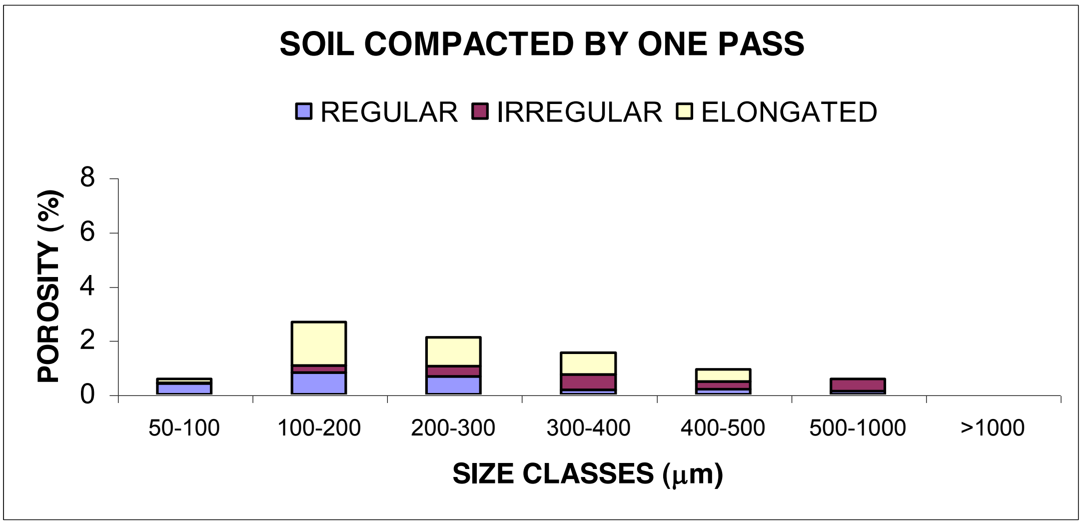


Fig. 2- Pore shape and size distribution, according to the equivalent pore diameter for regular and irregular pores, or the width for elongated pores, in the surface layer (0-10 cm).

Similar results in changes of macroporosity and pore shape and size distribution following compaction were also obtained in a sandy loam soil (Pagliai et al., 1988; 1992) and in a clay soil (Marsili et al., 1998). In these experiments the effect of compaction due to wheel traffic with different types of tyres used at two inflation pressures (Pagliai et al., 1992) and tractors with rubber and metal tracks (Marsili et al., 1998) was also studied. The former experiment showed that the tyres with a narrower section caused a more pronounced compaction effect than those with a wider section, while the different inflation pressures did not seem to cause significant differences on soil compaction effect. The latter experiment revealed that tractors with rubber tracks caused a more pronounced compaction effect than tractors with metal tracks. In this case the decrease of soil porosity after one pass was not significant compared to uncompacted soil.

Total pore volume measured by the mercury intrusion porosimetry inside the aggregates of the 0-10 cm layer was lower in the compacted areas than in the adjacent control soil. This decrease in compacted soil was mainly due to the reduction of volume of storage pores (0.5-50 μm). However, such a decrease was not so pronounced as was the case of macroporosity.

Soil structure

The variations in porosity, pore shape and size distribution following compaction by wheel traffic were reflected in the type of soil structure. Microscopic examination of thin sections revealed that in the uncompacted areas an angular to subangular blocky structure was homogeneously present down the 0-40 cm layer (Fig. 3), while in compacted areas the structure was massive in the 0-10 cm layer and only in the surface layer (0-5 cm) the thin elongated pores were oriented parallel to the soil surface, thus originating a platy structure typical of compacted soils (Fig. 3). Therefore, the few elongated pores were not vertically continuous and practically useless for water infiltration, thus increasing the water stagnation or the surface runoff and, as a consequence, the risk of soil erosion depending on the soil slope.

The wheel traffic may also cause damage, in terms of soil porosity, in sandy soil. Fig. 4 shows a sandy forestry soil with high interconnected porosity and accumulation of organic matter mixed by biological activity. The wheel traffic of machines reduced the porosity causing a compaction of organic materials and a packing of quartz grain. Such a condition may hamper the root growth (Pagliai et al., 1993). The decrease of porosity, even though in this case the continuity in a vertical direction was not interrupted, may however reduce the water infiltration in case of heavy rains with the increase of risk of surface runoff.

Correlation between soil porosity and penetration resistance

In studies on the effects of compaction caused by different types of tyres on porosity and structure of a sandy loam soil Pagliai et al. (1992) showed a strong correlation in the surface layer (0-10 cm) between soil porosity and penetration resistance.

The same results were obtained in the previously mentioned experiment on a loam soil (Pagliai et al., 1995) where the decrease of porosity in compacted areas was associated with an increase of penetration resistance. Fig. 5 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. These results confirmed previous findings on the same type of soil which showed a significant increase of penetration resistance after the tractor passes (Bazzoffi and Chisci, 1986).

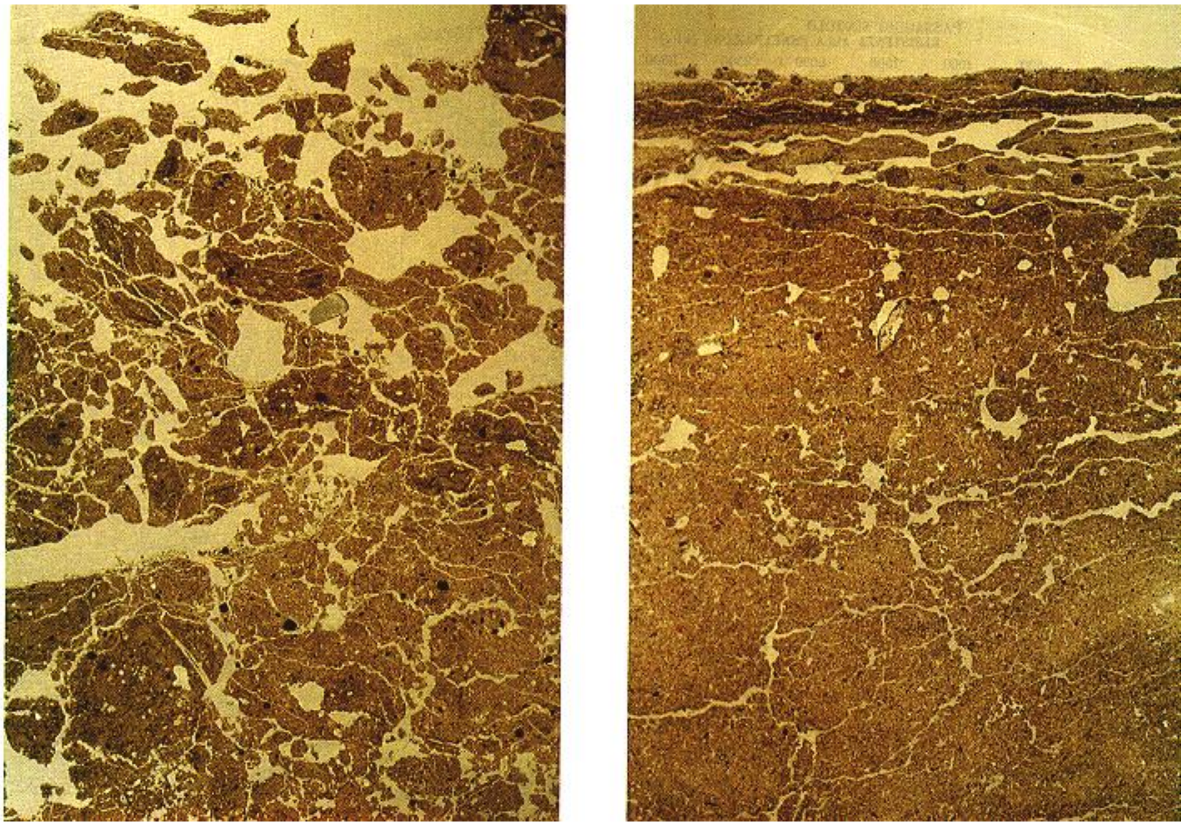


Fig. 3 – Macrophotographs of vertically oriented thin sections from the surface layer (0-5 cm) of the uncompacted (left) and compacted areas (right) of a loam soil. Plain polarized light. Pores appear white. The change of the subangular blocky structure of the uncompacted areas into a massive platy structure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

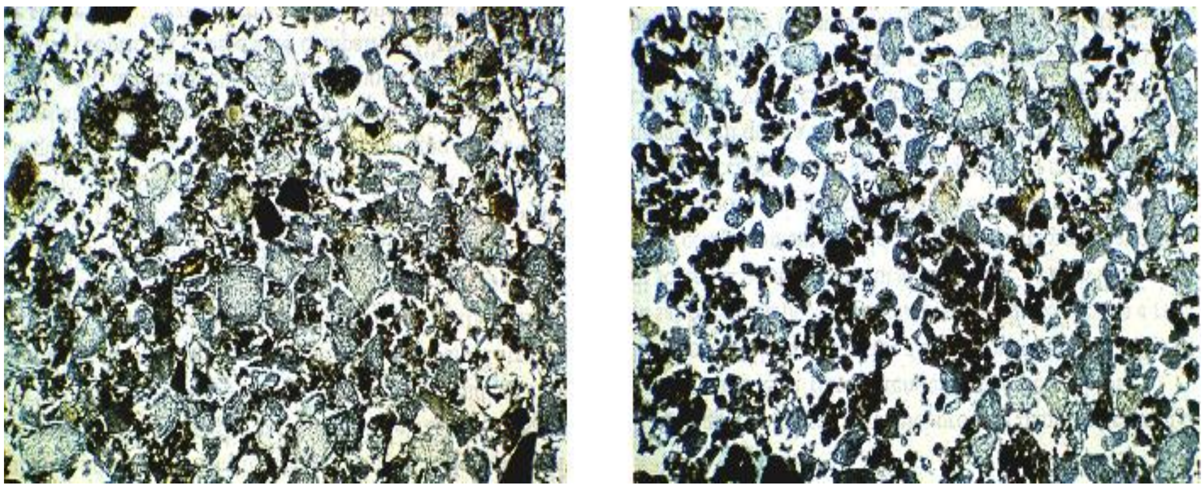


Fig. 4 - Microphotographs of vertically oriented thin sections from the surface layer (0-5 cm) of the compacted (left) and uncompacted areas (right) of a sandy forestry soil. Plain polarized light. Pores appear white, quartz grains grey and organic materials black. The reduction of porosity in compacted areas (left) which may cause difficulty for root growth is evident. Frame length 3 mm.

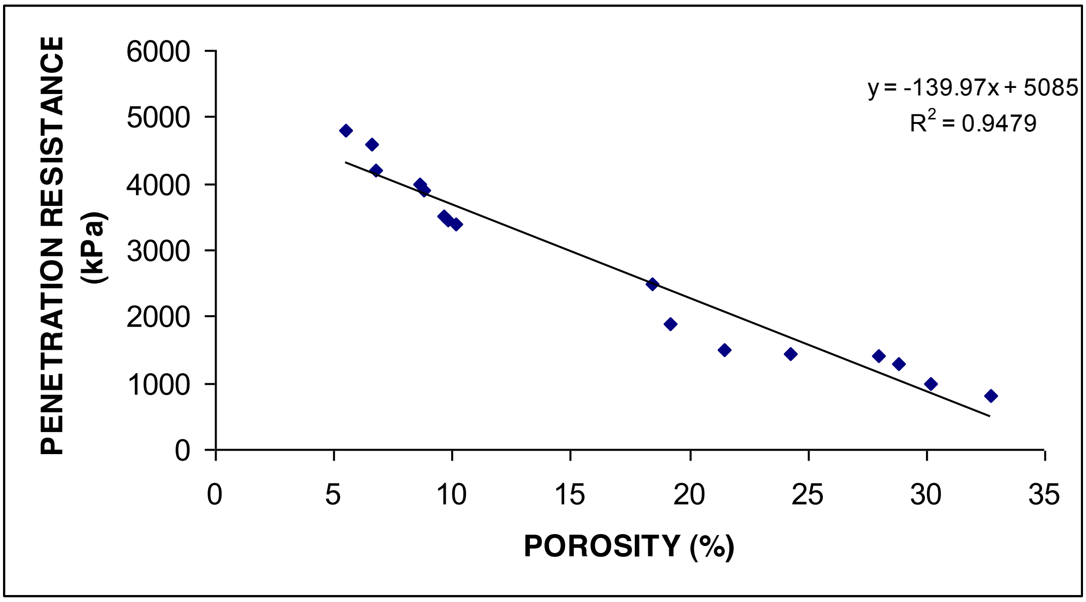


Fig. 5 – Correlation between soil porosity and penetration resistance in the surface layer (0-10 cm) of the compacted and uncompacted areas.

Another experiment on a clay loam soil with a slope of 15%, in which the effect of compost addition and compaction by normal and low-pressure tractor tyres on the physical properties and erosion of soil was investigated, Bazzoffi et al. (1998) showed that the compost addition reduced the penetration resistance in compacted soil after the wheel traffic. Some difference were also foud between conventional and low-pressure tyres. These latter seemed to have a lower compacting effect concerning the penetration resistance but they increased surface runoff and erosion. In fact, compaction due to low pressure tyres, although lower than with normal tyres, involves a larger surface of soil because of the wider tread. Consequently, the wheel-pass tracks are larger when low-pressure tyres are used and the number of isolated aggregates on the soil surface decreases. The passage of tyres also determines the destruction of surface aggregates, with the production of smaller compound particles (Dexter, 1988). When using large low-pressure tyres, a wider track is formed up and down the slope compared with normal tyres; consquently there is a more widespread destruction of larger aggregates of the seed-bed. This action may explain the higher quantity of fine fraction in the sediment when large low-pressure tyres were used. Wider tracks may also be responsible for the increase runoff volumes observed during the experiment; in fact, compression reduces the superficial roughness and laminar flow may involve a wider zone.

Correlation between soil porosity and saturated hydraulic conductivity

Fig. 6 shows a highly significant correlation between hydraulic conductivity and elongated pores in a loam soil compacted by wheel traffic and uncompacted (Pagliai et al. 1995; 1998). This confirmed that hydraulic conductivity is directly correlated with elongated continuous pores and these results stressed that the compaction is one of the most significant aspect not only of soil degradation but also of environmental degradation, since the reduction of water infiltration may increase the risk of soil erosion.

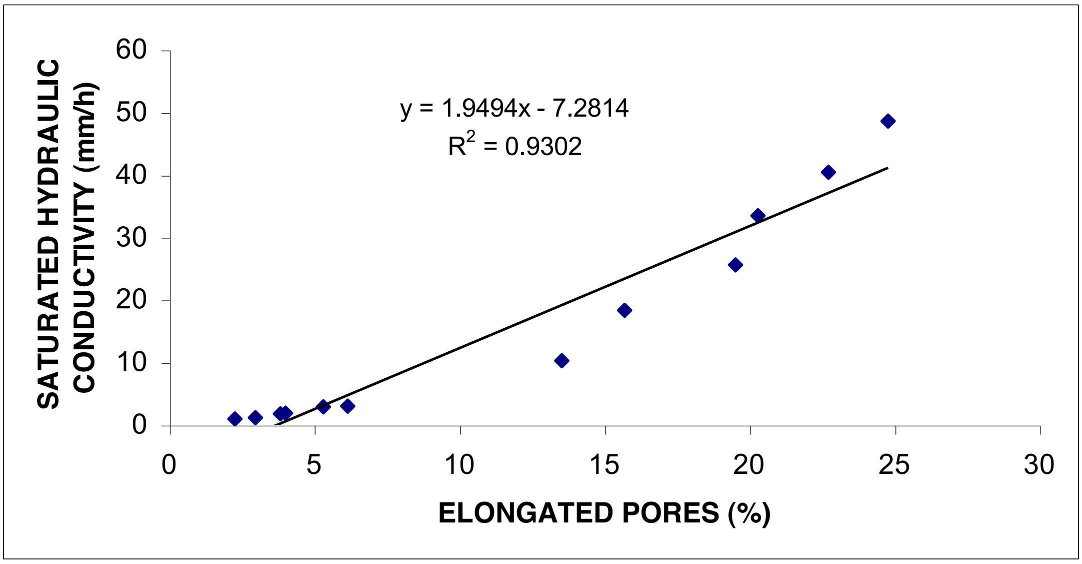


Fig. 6 - Correlation between soil porosity formed by elongated pores and saturated hydraulic conductivity in the surface layer (0-10 cm) of the compacted and uncompacted areas.

Correlation between soil porosity and root growth

The soil structure modifications, the decrease of soil porosity, the increase of penetration resistance following compaction may hamper root growth besides reducing water infiltration. This aspect was studied in a sandy loam grassed soil cultivated to peach orchard (Pezzarossa and Pagliai, 1990). The porosity and root density were measured until 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. 7.

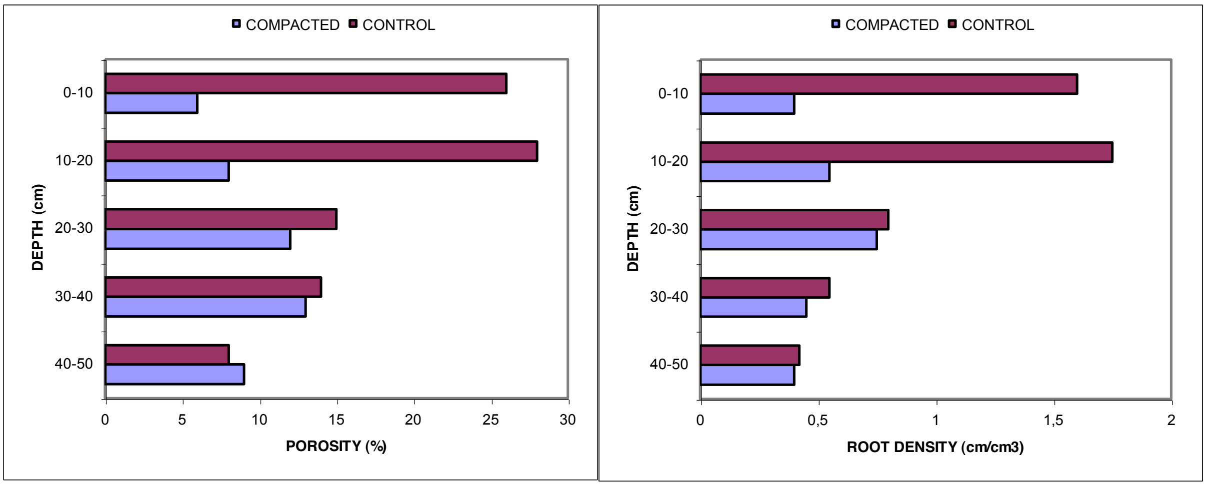


Fig. 7 - Effects of soil compaction, caused by wheel traffic of machines in a peach orchard, on soil porosity expressed as a percentage of area occupied by pores larger than 50 µm per thin section (on the left) and on root density expressed as root length/cm^3 (right).

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 lessened, the root density increased showing approximately the same value as in uncompacted soil. It should be stressed that the peach orchard field was permanently grassed and irrigated, so the continuous wheel traffic on the same track caused a more pronounced compacting effect than in the previous mentioned loam soil cultivated to maize.

Soil structure regeneration

Soil structure regeneration is a characteristic strongly related to the soil type and depends on the alternation of wetting and drying cycles. This aspect was studied in a clay loam soil by Pagliai (1987) where, besides the sampling at the compaction time, sampling at 4, 8 and 12 months after wheel traffic were planned; in the meantime the soil remained undisturbed. Just after the compaction the porosity showed a strong reduction involvimg all morphological type of pores, over all the size of elongated pores was drastically reduced. After 4 months the situation was practically the same and after 8 months from the compaction the porosity increased, even though it remained significantly lower than in uncompacted areas. Only after 12 months the porosity did not show significant differences between uncompacted and compacted soil due to the effect of wetting and drying cycles and the biological activity which allowed the soil to regenerate its structure. Other experiments showed that in some clay soils the soil structure regeneration after compaction may take several years (Bullock et al., 1985). In the sandy loam soil previously mentioned (Pagliai et al., 1988; 1992) the soil structure was good but strictly dependent on the number of wetting and drying cycles.

Conclusions

Experimental results showed that the soil compaction due to wheel traffic and the subsoil compaction (plough pan or plough sole) caused a reduction of soil porosity to values inadequate for water movement and root growth, because such a reduction involved not only elongated pores larger than 500 μm but also those ranging from 50 to 500 μm i.e, the transmission pores. The reduction of soil porosity is always associated with an increase in penetration resistance and with a decrease in hydraulic conductivity.

The damages cause by soil compaction after wheel traffic appear just after one pass and they may increase after multiple passes on the same track. The more the compacting effect is pronounced, the longer is the time necessary for soil structure regeneration. Deep investigations are still necessary into the type of tyres and pressure inflation and probably it would be necessary to reconsider, where possible, besides the size and weight of agricultural machinery, the use of tractors with metal tracks to prevent or decrease soil compaction damage.

In Italy subsoil compaction is strongly under evaluated, especially the compact layer at the lower limit of cultivation (plough sole) largely widespread in the alluvial soils in the plains generally cultivated by monoculture.

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