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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.

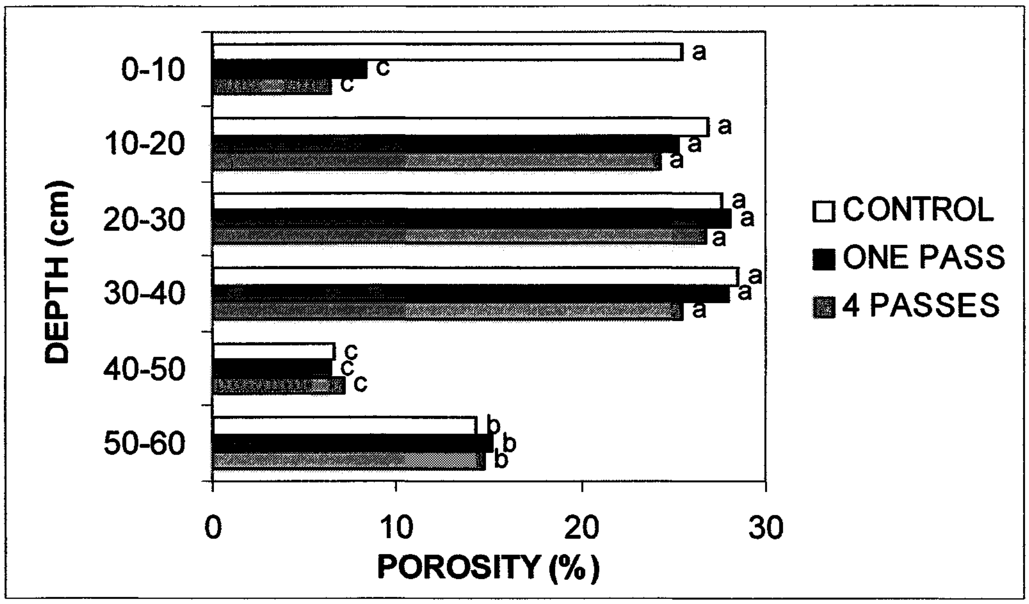

Fig. 1 – Effects of soil compaction, caused by one and four passes of tractors, on soil porosity expressed as a percentage of area occupied by pores larger than 50 μm per thin section. Mean of six replications. Values followed by the same letter are not significantly different at the 0.05 level employing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

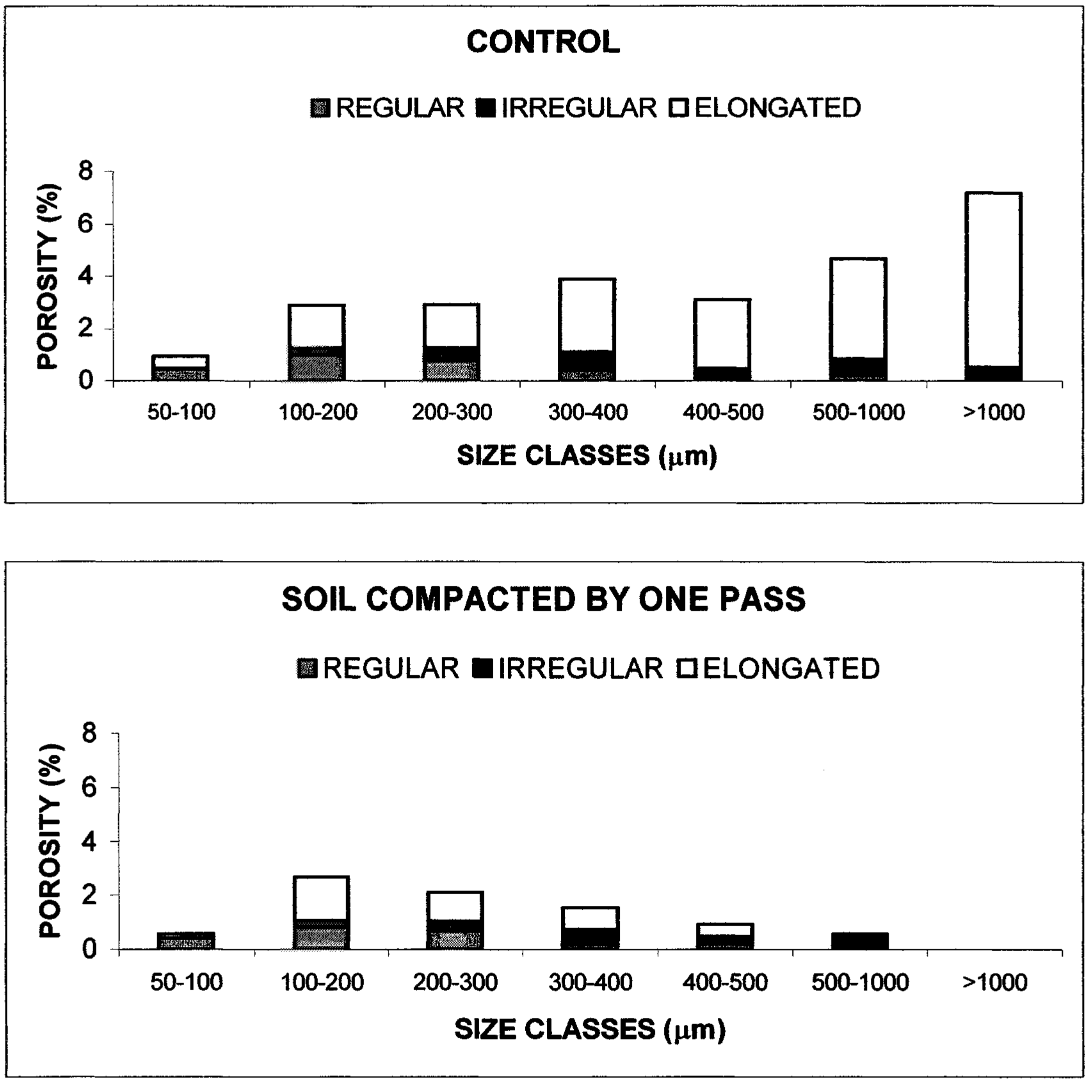

Fig. 2- Pore shape and size distribution, according to the equivalent pore diameter for regular and irregular pores, or the width for elongated pores, in the surface layer (0-10 cm).

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).

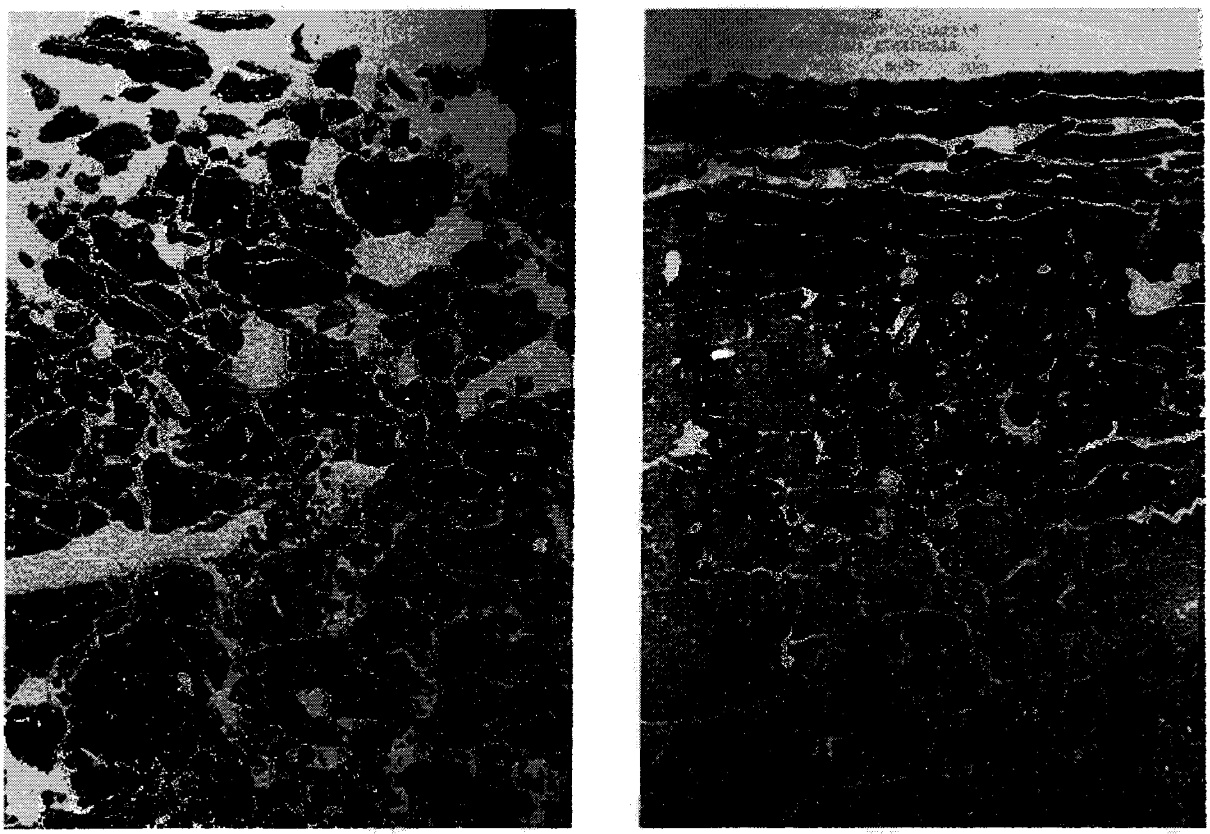

Fig. 3 – Macrophotographs of vertically oriented thin sections from the surface layer (0-5 cm) of the uncompacted (left) and compacted areas (right) of a loam soil. Plain polarized light. Pores appear white. The change of the subangular blocky structure of the uncompacted areas into a massive platy structure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

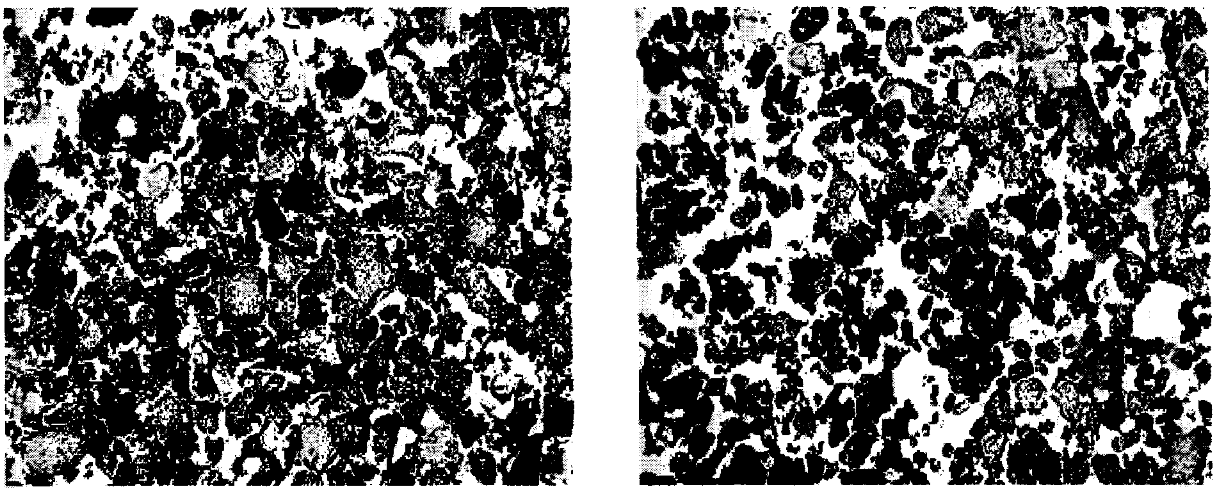

Fig. 4 - Microphotographs of vertically oriented thin sections from the surface layer (0-5 cm) of the compacted (left) and uncompacted areas (right) of a sandy forestry soil. Plain polarized light. Pores appear white, quartz grains grey and organic materials black. The reduction of porosity in compacted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

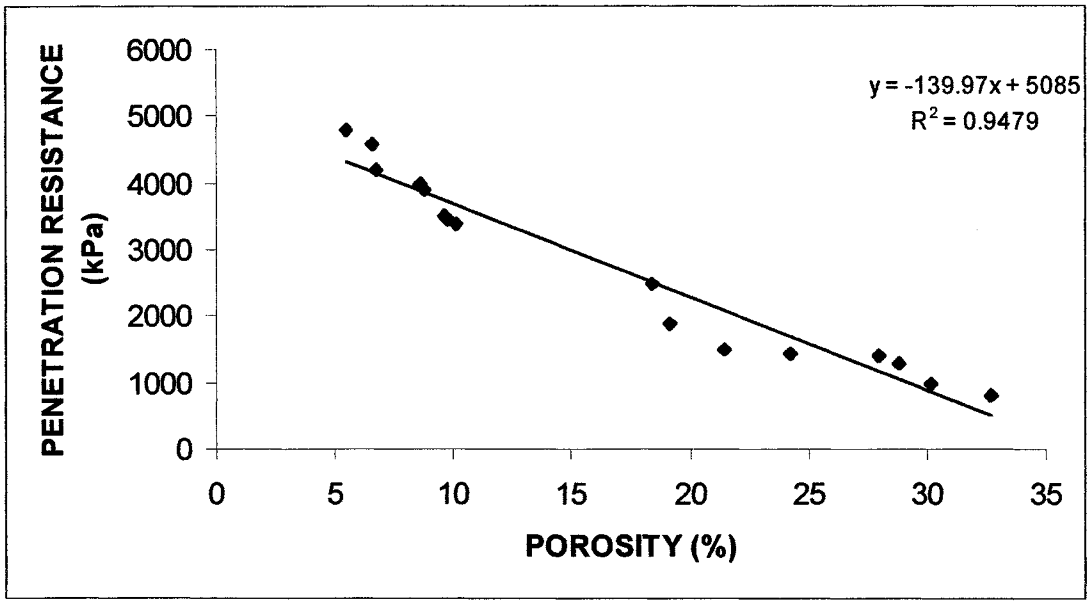

Fig. 5 – Correlation between soil porosity and penetration resistance in the surface layer (0-10 cm) of the compacted and uncompacted areas.

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.

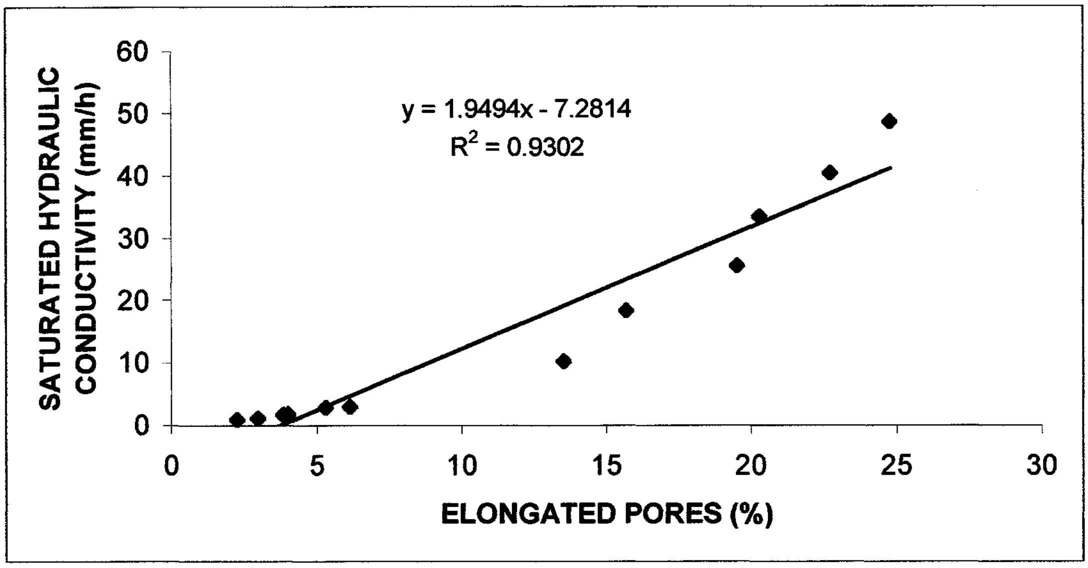

Fig. 6 - Correlation between soil porosity formed by elongated pores and saturated hydraulic conductivity in the surface layer (0-10 cm) of the compacted and uncompacted areas.

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.

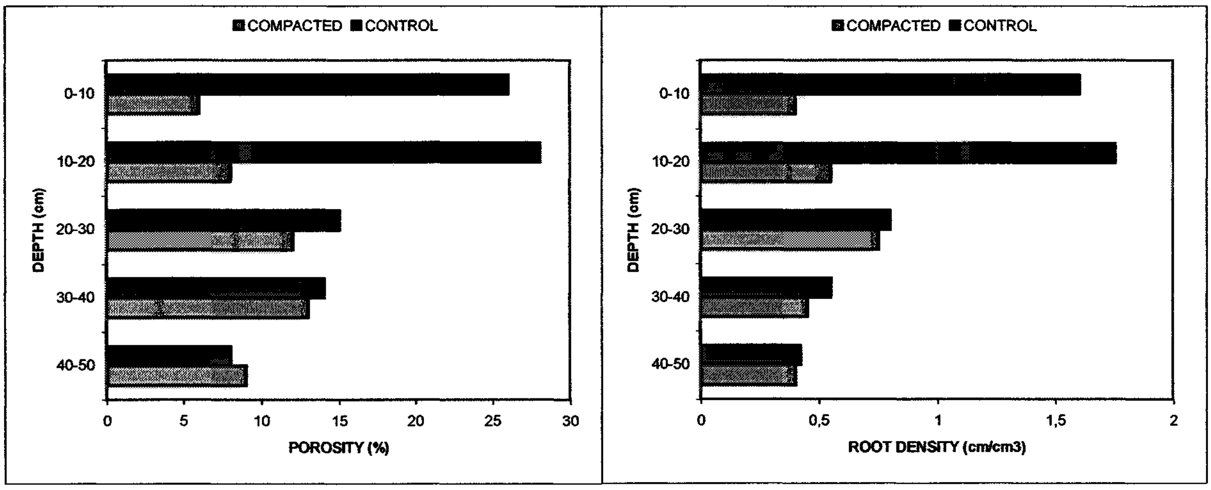

Fig. 7 - Effects of soil compaction, caused by wheel traffic of machines in a peach orchard, on soil porosity expressed as a percentage of area occupied by pores larger than 50 μm per thin section (on the left) and on root density expressed as root length/cm³ (right).

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.

References

Bazzoffi, P., Chisci, G., 1986. Effetto del passaggio dei macchinari agricoli di differenti pratiche agronomiche su alcune caratteristiche fisiche di un suolo limoso-argilloso del Mugello (Toscana). Annali Istituto Sperimentale per lo Studio e la Difesa del Suolo, 17, 41-56.

Bazzoffi, P., Pellegrini, S., Rocchini, A., Morandi, M., Grasselli, O., 1998. The effect of urban refuse compost and different tractor tyres on soil physical properties, soil erosion and maize yield. Soil Tillage Res. (in press).

Bouma, J., Jongerius, A., Boersma, O.H., Jager, A., Schoonderbeek D., 1977. The function of different types of macropores during saturated flow through four swelling soil horizons. Soil Sci. Soc. Am. J. 41, 945-950.

Bullock, P., Newman, A.C.D., Thomasson, A.J., 1985. Porosity aspects of the regeneration of soil structure after compaction. Soil Tillage Res. 5, 325-341.

Dexter, A.R., 1988. Advances in characterization of soil structure. Soil Tillage Res. 11, 199-238.

Fiès, J.C., 1992. Analysis of soil texturalporosity relative to skeleton particle size, using mercury porosimetry. Soil Sci. Soc. Am. J. 56, 1062-1067.

Greenland, D.J., 1977. Soil damage by intensive arable cultivation: temporary or permanent? Philosophical Transactions of the Royal Society of London, 281, 193-208.

Klute, A., Dirksen, C., 1986. Hydraulic conductivity and diffusivity: laboratory methods. In: A. Klute (Editor), Methods of Soil Analysis, Part 1. Second Edn. Am. Soc. Agron. Publ., Madison, pp. 687-734.

Marsili, A., Servadio, P., Pagliai, M., Vignozzi, N., 1998. Variazioni di alcune proprietà fisico-meccaniche del terreno agrario sottoposto al passaggio di trattrici cingolate di elevata potenza. Rivista di Ingegneria Agraria (in press).

McBratney, A.B., Moran, C.J., Stewart, J.B., Cattle, S.R., Koppi, A.J., 1992. Modifications to a method of rapid assessment of soil macropore structure by image analysis. Geoderma, 53, 255-274.

Mermut, A.R., Grevers, M.C.J., de Jong, E., 1992. Evaluation of pores under different managemet systems by image analysis of clay soils in Saskatchewan, Canada. Geoderma, 53, 357-372.

Moran, C.J., McBratney, A.B., 1992. Acquisition and analysis of three-component digital images of soil pore structure. I. Method. J. Soil Sci. 43, 541- 550.

Murphy, C.P., 1986. Thin section preparation of soils and sediments. A B Academic Publishers, Herts, U.K., pp. 149.

Pagliai, M., 1987. Micromorphometric and micromorphological investigations on the effect of compaction by pressures and deformations resulting from tillage and wheel traffic. In: G. Monnier, M.J. Goss (Editors), Soil compaction and regeneration. Proceedings of the Workshop on Soil Compaction: Consequences and Structural Regeneration Processes. Avignon, 17-18 September 1985. Published for the Commission of the European Communities by A.A. Balkema, Rotterdam, pp. 31-38.

Pagliai, M., 1988. Soil porosity aspects. International Agrophysics, 4, 215-232.

Pagliai, M., Bazzoffi, P., Panini, T., 1993. Compattamento e degradazione strutturale del suolo in seguito al passaggio di mezzi meccanici. Cellulosa e Carta, 4, 11-19.

Pagliai, M., Febo, P., La Marca, M., Lucamante, G., 1992. Effetti del compattamento provocato da differenti tipi di pneumatici su porosità e struttura del terreno. Rivista di Ingegneria Agraria, 3, 168- 176.

Pagliai, M., La Marca, M., Lucamante, G., 1983. Micromorphometric and micromorphological investigations of a clay loam soil in viticulture under zero and conventional tillage. J. Soil Sci. 34, 391-403.
Pagliai, M., La Marca, M., Lucamante, G., Genovese, L., 1984. Effects of zero and conventional tillage on the length and irregularity of elongated pores in a clay loam soil under viticulture. Soil Tillage Res. 4, 433-444.
Pagliai, M., Pezzarossa, B., La Marca, M., Lucamante, G., 1988. Variazioni della porosità del terreno in seguito al compattamento provocato dal passggio di trattori. Rivista di Ingegneria Agraria, 2, 120-126.
Pagliai, M., Piovanelli, C., D'Egidio, G., 1995. L'incidenza del compattamento nei processi di degradazione del suolo. Atti del Convegno SISS, Il Ruolo della Pedologia nella Pianificazione e Gestione del Territorio (a cura di Angelo Aru e Daniele Tomasi), Cagliari 6-10 Giugno 1995, pp. 187-194.
Pagliai, M., Rousseva, S., Vignozzi, N., Piovanelli, C., Pellegrini, S., Miclaus, N., 1998. Tillage Impact on Soil Quality. I. Soil Porosity and Related Physical Properties. Italian Journal of Agronomy (in press).
Pezzarossa, B., Pagliai, M., 1990. Investigation of root density in a peach orchard in relation to soil porosity by use of image analysis. Agricoltura Mediterranea, 120, 226-231.
Ringrose-Voase, A.J., Bullock, P., 1984. The automatic recognition and measurement of soil pore types by image analysis and computer programs. J. Soil Sci. 35, 673-684.
Russell, E.W., 1978. Arable agriculture and soil deterioration. In: Transactions of the 11th International Congress of Soil Science, 19-27 June 1978 at University of Alberta, Edmonton. Canadian Society of Soil Science, Alberta, Vol. 3, 216-227.
Tippkötter, R., 1983. Morphology, spatial arrangement and origin of macropores in some hapludalfs, West Germany. Geoderma, 29, 355-371.

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Changes of some physical properties of a clay soil following passage of rubber- and metal-tracked tractors

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Abstract

The aim of this research was to evaluate the change in physical properties of an arable clay soil following passage of rubber- and metal-tracked tractors in view of increased use of tracked tractors for ploughing on clay soil in centre-south and insular Italy. Field tests were carried out on arable soil cropped to lucerne (*Medicago sativa* L.) to compare two types of tracked tractors, one with rubber tracks (CAT Challenger Ch35) and one with metal tracks (FIAT FA 150) in order to establish the compacting effects resulting from one and four passes of the tractors on the same track. The following parameters were studied: soil penetration resistance, bulk density and its increment ratio, pressure distribution on soil along the length of the tracks, soil macroporosity and hydraulic conductivity. Multiple passes made by the two tractors induced very similar effects in the surface soil in regards to soil penetration resistance and dry bulk density. Mean values of penetration resistance (0 to 0.20 m depth), were 2425 kPa for rubber tracked tractor and 2415 kPa for metal-tracked tractor; dry bulk density values were 1.52 and 1.48 Mg m^{-3}, respectively. The decrease in macroporosity, in particular that of elongated pores in the soil surface layer (0–0.10 m depth) was greater in treatments involving the rubber-tracked tractor (from 10.6% to 4.0%) than for the metal-tracked tractor (from 10.6% to 7.3%). Following traffic of the two tractors hydraulic conductivity decreased and the lowest values were found after one and four passes of the rubber-tracked tractor (1.5 and 0.08 mm h^{-1}, respectively). A highly significant correlation between hydraulic conductivity and elongated pores and a significant correlation with total macroporosity were found. Significant exponential relationships between macroporosity and penetration resistance for one and four passes of both tractors were found in the surface soil. A significant difference was found between tractors and for correlations of penetration resistance values above control values. However, in the soil surface with respect to the higher degree of porosity, treatments involving the metal-tracked tractor showed better soil structure quality.

Keywords: Tracked tractors; Soil compaction; Soil porosity; Soil penetration resistance; Soil structure

1. Introduction

Compaction is one of the fundamental parameters for evaluating the environmental impact of agricultural machinery traffic on soil. In highly mechanised

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systems of crop production, agricultural and forest crops can be influenced adversely by excessive soil compactness. This term indicates the extent to which compaction processes have influenced the packing of the constituent parts of the soil fabric, and it can be measured or assessed by a wide range of soil properties, such as bulk density, porosity, pore size distribution, etc. (Soane and Van Ouwerkerk, 1994a, b, 1995).

For a tracked vehicle, the nature of the pressure distribution under a track is one of the most important performance parameters. The nature of the deformation of the soil layer beneath the tracks is dependent on the pressure distribution over the supporting length of the track (Sofiyan and Maximenko, 1965; Rowland, 1972; Brusentsev, 1967). Track-type tractors have the potential for causing less soil compaction because the tracks usually have a greater surface area than wheels for tractors with equivalent power ratings (Brown et al., 1992). Tracked tractors are still used in many farming areas where large drawbar loads are required. The large ground contact area of the track results in high tractive efficiencies, high dynamic traction ratios, low ground pressures, and good stability on steep slopes. However, travel speeds and maneuverability are limited by the heavy metal track design. Additionally, travel on public roads is restricted in most areas due to road surface damage from penetration by the track grousers. The use of metal-tracked tractors in agriculture has declined since the introduction of large four-wheel drive tractors which are characterised by moderate drawbar pulls, high speeds and good maneuverability which increases their productivity over metal-tracked tractors. High speeds and pneumatic tyres also allow travel on public roads.

Tractors equipped with an innovative rubber belt track design have been introduced to the agricultural market with the objective of combining the high tractive efficiencies, high dynamic traction ratios and low soil compaction attributes of tracked tractors with the high travel speed and maneuverability of four-wheel drive tractors (Esch et al., 1990). Tracked tractors are still used widely on Italian clay and steeply sloped soil particularly in centre-south and insular areas, because the system of metal-tracked tractors is specialised and at the peak of technical evolution (Bekker, 1956, 1969) while rubber-tracked tractors could also be utilized in such areas profitably.

The intensification of soil tilling has engendered soil degradation, and hence in the past 20 years both tilling and crop rotations have been reconsidered significantly. Alongside minimal tillage, meadow rotations, including lucerne, have been used for more years (4 or 5) with the aim of regenerating soil structure. Obviously, meadow management requires numerous tractor passes for mowing and this can cause soil compaction.

The objective of this study was to investigate soil compaction of clay soil cropped to alfalfa for 5 years, previously subjected to tracked tractors passes, one equipped with innovative rubber tracks and one equipped with metal tracks in comparison. Parameters measured included soil penetration resistance, bulk density and its increment ratio, pressure distribution on soil along the length of the tracks, soil porosity and hydraulic conductivity.

2. Materials and methods

2.1. Soil and treatments

The field tests were carried out using two large tractors fitted with different types of tracks, one with rubber tracks (CAT Challenger 35) and the other with metal tracks (FIAT FA 150). The main technical characteristics of these tractors and their tracks are given in Table 1. In March 1997, on a plain terrain 30 km north of Rome, compaction tests were carried out on a well drained clay soil, classified as Vertic Cambisol according to the Food and Agriculture Organization (FAO, 1988). The soil was cropped to lucerne for 5 years previously, making one and four passes on the same track left by the tractor for a total of four treatments, in a randomised block of eight plots, each 420 m^2. Measurements were also made on a control area with no traffic adjacent to every plot (Table 2). Forward speed was 0.44 m s^{-1} for both tractors.

The initial soil conditions are given in Table 3. Soil moisture content was measured at a depth from 0.05 to 0.10 m by taking samples of soil immediately outside the track left by the tractors and in the control areas using a corer sampling ring. These samples were weighed and dried until they reached a constant weight. Soil compaction was quantified by measuring

Table 1
Main technical characteristics of the two tractors and their tracks

Tractor	CAT Ch35	FIAT FA150
Measured mass (kg)	10240	13000
PTO Power (kW)	131	114
Track tread (m)	1.81	1.73
Overall width (m)	2.63[a]	2.28
Overall length (m)	5.55	3.85
Cabin height max (m)	3.05	3.15
Height above soil of implement hitch (m)	0.498	0.40
Type of track	2 reinforced rubber tracks	2 metal tracks
Total track length (m)	9.99 external	7.32 internal
Track thickness (m)	0.028	0.011
Lugs per track (number)	36	40
Distance between centres of lugs (m)	0.23	0.175
Lug height (m)	0.07	0.048
Lug width (m)	0.08	0.017
Radius of steering area (m)	2.60	3.00
Supporting wheels (number)	3[b]	6[b]
Diameter of driving wheel (m)	1.46	0.72
Diameter of support wheels (m)	0.36	0.27
Diameter of track wheel (m)	0.81	0.70
Ground contact length (m)	2.30	2.29
Track width (m)	0.46	0.55
Total area of support of the two tracks on soft terrain (m^2)	2.11	2.52
Average ground contact pressure (kPa)	48	50
Track pre-tension load (kN)	59	–

[a]Version used for the tests.
[b]Drive wheels not included.

Table 2
Treatments

Treatments	Type of track	Number of passes on same track
Ch35–1	Rubber	1
Ch35–4	Rubber	4
FA150–1	Metal	1
FA150–4	Metal	4
Control	–	No passes

cone penetration resistance, dry bulk density, and pressure along the length of the tracks and soil structure was determined by measuring porosity and hydraulic conductivity.

2.2. Penetration resistance and dry bulk density

Soil penetration resistance was measured in the tracks left by each tractor after one and four passes and on the control areas, which had no traffic, using a hand penetrograph with a 60° cone and base area of 100 mm^2 driven into the soil at a constant rate. For each plot, including the control areas, 20 penetrometer readings were taken at depths of 0–0.10, 0.10–0.20, 0.20–0.30 and 0.30–0.40 m.

Dry bulk density was measured by taking samples of soil below the tracks left by each tractor, after one and four passes and from the control areas using a corer with a 100 cm^3 volume sample ring (i.d. 5 cm, length 5.1 cm and wall thickness of 0.15 cm) from the 0.05 to 0.10 m depth. These samples were weighed and dried until they reached a constant weight. In addition, the increment ratio of density (Γ_n) was used as a compaction criterion (Fujii, 1992) and is defined as:

$$\Gamma_n = (\gamma_n - \gamma_0)/\gamma_0 = (\gamma_n/\gamma_0) - 1 \quad (1)$$

where γ_0 is the initial density (control) and γ_n is the density after the nth (one and four) tractor's passes.

Table 3
Soil conditions

FAO classification	Vertic Cambisol
Soil organic carbon (Walkley and Black, 1934) (0–0.50 m depth), g 100 g^{-1}	1.9
Particle size distribution, g 100 g^{-1}	
Sand (2000–50 μm)	12
Silt (50–2 μm)	32
Clay (<2 μm)	56
Plastic limit, g 100 g^{-1}	26.5
Liquid limit, g 100 g^{-1}	52.5
Plastic index, g 100 g^{-1}	26.0
Moisture content, g 100 g^{-1} (from a depth of 0.05 to 0.10 m)	
Group Ch35	21
Group FA150	21
Control	22

2.3. Soil pressure distribution

Soil pressure distribution along the length of the track was measured with the tractors moving in forward and reverse on soil which had not been used for the previous tests, using a pneumatic sensor (torus shape, torus radius R=8.3 cm, ring section radius r=3.0 cm, torus volume=1474 cm^3, torus pre-inflation pressure=5 kPa) installed in the soil from 0.10 to 0.16 m depth (median 0.13 m depth) perpendicular to the tractor's path with its pressure gauges placed outside the tractor path area on the soil surface. During the passes, the tractor's path was such that the centre line of the track passed over the centre of the sensor and the gauge was immediately read. In order to allow this reading, the tractor's speed (0.1 m s^{-1}) was slower than that of the previous passes (0.44 m s^{-1}). The soil pressure distribution was also measured with the tractor moving in reverse, as there can be excessive soil compactness at the end of the field where the tractors turn and reverse. In particular, the Ch35 tractor equipped with differential steering can operate with two tracks rotating in opposite directions when the transmission shift lever is in neutral.

2.4. Porosity and saturated hydraulic conductivity measurements

The macropore system was characterised by image analysis performed on thin sections from undisturbed soil samples. For this purpose, six undisturbed samples were collected in the surface layer (0–0.10 m) and in the 0.10–0.20 m layer of control plots and in the areas compacted by one and four passes of each tractor.

Samples were 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 were analysed by means of image analysis techniques (Pagliai et al., 1984) using PC-IMAGE software produced by Foster Findlay Associates (London). Total porosity and pore distribution were measured according to their shape and size. These photographs covered 4.5 cm×5.5 cm of the thin section, avoiding the edges where disruption can occur. In this experiment the instrument was 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 were 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 were also examined using a Zeiss "R POL" microscope at 25× magnification to observe soil structure.

To measure saturated hydraulic conductivity, six undisturbed cores (5.68 cm diameter and 9.5 cm high) were collected from the 0–0.10 m layer of each plot in areas adjacent to those sampled for thin section preparation. The samples were slowly saturated and saturated hydraulic conductivity was measured using the falling-head technique (Klute and Dirksen, 1986).

3. Results and discussion

3.1. Penetration resistance and dry bulk density

Mean values of soil penetration resistance (kPa) at various depths (0–0.10, 0.10–0.20, 0.20–0.30 and 0.30–0.40 m), standard deviations from the mean (kPa), coefficients of variation and dry bulk densities

Table 4
Mean values of soil layers of penetration resistance, standard deviations, coefficient of variation and soil dry bulk density

Treatments	Depth (m)	Mean resistance (kPa)	Standard deviation(kPa)	CV (%)	Dry bulk density (Mg m^{-3})
Ch35–1	0–0.10	1900 a, a	235	12.0	1.47 a, a
	0.10–0.20	2000 a, a	100	5.0	
	0.20–0.30	2050 a, a	195	9.5	
	0.30–0.40	2100 a, a	166	7.9	
Ch35–4	0–0.10	2400 b, a	149	6.2	1.48 ab, a
	0.10–0.20	2450 b, a	224	9.1	
	0.20–0.30	2300 a, a	513	22.3	
	0.30–0.40	2200 a, a	680	30.9	
FA150–1	0–0.10	2100 a, a	117	5.6	1.49 a, a
	0.10–0.20	2400 a, b	143	6.0	
	0.20–0.30	2000 a, a	143	7.2	
	0.30–0.40	2080 a, a	85	4.1	
FA150–4	0–0.10	2280 a, a	402	17.6	1.52 ab, a
	0.10–0.20	2550 a, a	500	19.6	
	0.20–0.30	2450 ab, a	470	19.2	
	0.30–0.40	2550 b, b	257	10.1	
Control	0–0.10	1650 c	274	16.7	1.46 a
	0.10–0.20	1800 c	123	6.9	
	0.20–0.30	1820 a	274	15.0	
	0.30–0.40	1940 a	56	2.9	

(Mg m^{-3}) for the various plots are shown in Table 4 subdivided by tractor type (Ch35 and FA150) and number of passes of the same track (1 and 4) in addition to those for the control plots. Table 5 shows the mean of the same values for a depth of 0–0.40 m, as well as the increment ratio of density (Γ_n) after one and four passes on the same track left by the tractors. The statistically significant difference between the two means was determined by means of the student's test. In the tables and figures, mean values for penetration resistance, dry bulk density and further below in porosity are flanked on the same line by letters. Each two means which share a letter do not differ significantly (Gomez and Gomez, 1976). Letters before the comma refer to the comparison for the same tractor at the same depth of sample for the various number of passes and to the control plot. Letters after the comma refer to the comparison between the two tractors for the same number of passes. Small letters indicate a level of significance of ≤ 0.02 while capital letters indicate a level of significance of ≤ 0.01. Results shown in Tables 4 and 5 indicate that for both tractors soil penetration resistance and dry bulk density increased with the number of passes on the same track and this finding agrees with that of other studies (Marsili and Servadio, 1992, 1996).

Table 5
Mean values from 0 to 0.40 depth of penetration resistance, standard deviations, coefficient of variation, soil dry bulk density and its increment ratio (Γ_n)

Treatments	Depth (m)	Mean resistance (kPa)	Standard deviation (kPa)	CV (%)	Dry bulk density (Mg m^{-3})	Γ_n
Ch35–1	0–0.40	2012 A, A	85	4.2	1.47 a, a	0.68
Ch35–4	0–0.40	2337 B, A	111	4.7	1.48 ab, a	1.37
FA150–1	0–0.40	2145 A, B	175	8.2	1.49 a, a	2.05
FA150–4	0–0.40	2457 B, B	127	5.2	1.52 ab, a	4.11
Control	0–0.40	1802 C	119	6.6	1.46 a	–

Lower case letter 0.02 level of probability, capital letter 0.01 level of probability.

Examining the values of penetration resistance for different soil layers (Table 4) it appears that differences between the Ch35–4 passes and Ch35–1 pass are statistically significant only in the upper layers (0–0.10 and 0.10–0.20 m depth), while differences between FA150-4 passes and FA150-1 pass are statistically significant only in the deepest layer (0.30–0.40 m depth). Compared with the control plot, in the first two layers (0–0.10 and 0.10–0.20 m) all the differences are statistically significant, while in the lower layers (0.20–0.30 and 0.30–0.40 m) only the difference with the FA150–4 passes is statistically significant.

A comparison of the mean penetration resistance for one pass of the two tractors shows that in the layers there is a statistically significant difference between the FA150–1 pass and Ch35–1 pass in favour of the Ch35–1 pass only in the second layer (0.10–0.20 m depth). This proves that soil strength in the lower layers (from 0.20 to 0.30 and from 0.30 to 0.40 depth in this case) for these types of tractors in the same field conditions should be considered as not being significantly influenced.

A comparison of the treatments for four passes reveals that there is a statistically significant difference between the FA150–4 passes and Ch35–4 passes in favour of the Ch35–4 passes, but only in the deepest layer (0.30–0.40 m). This suggests that multiple passes made by the two tractors cause very similar effects on the soil.

An analysis of results for mean soil penetration resistance in the 0 to 0.40 m depth (Table 5) shows that for both tractors differences between one and four passes are significant. All the differences between the treatments and the control are significant in favour of the latter. A comparison of the mean values for penetration resistance from 0 to 0.40 m for the two tractors shows that the difference for the treatments both for one pass and for four passes are statistically significant in favour of the treatment Ch35–1 pass and Ch35–4 passes.

The values of dry bulk density between 0.05 and 0.10 m depth increased with the increase in the number of passes on the track. The differences between treatments Ch35–4 passes and the control, and between FA150–4 passes and the control were statistically significant (Table 5). The increment ratio of density (Γ_n) with reference to control was significant only for treatment Ch35–4 passes, while for the FA150 tests with reference to the control all treatments were significant.

3.2. Soil pressure distribution

Soil pressure distribution results, measured on the length of the track at 0.13 m depth, for the Ch35 tractor and the FA150 tractor are shown in Figs. 1 and 2, respectively. The distribution of soil pressure along the track for the tractor Ch35 moving forward (Fig. 1), is rather linear beneath all the track support wheels and this finding agrees with the results of the penetrometer tests. Peaks pressure (P_{max}) beneath the track at supporting wheels at 0.13 m depth are not very marked due to higher load of track pre-tension (59 kN). The average value of all Pmax values was 30 kPa (Rowland, 1972). Displacement of the center of pressure towards the front of the tractor, as well as the decrease of the track belt tension between the third supporting wheel and the drive wheel during reverse movement due to reversal of the drive wheel rotation direction, gives rise to a more irregular soil pressure diagram. Values of pressure under the track decrease between the second supporting wheel and the drive wheel (Fig. 1). Space average value of all P_{max} values was 26 kPa.

Soil pressure distribution along the track, measured for the FA150 tractor (Fig. 2) moving forward, is generally linear towards the front of the tractor. Pressure increases between the fourth and the sixth support wheel. During reverse movement the center of pressure moved toward the front of the tractor, and pressure values increased under the front of the tractor, while under the rear, the decrease of pressure was less evident compared with the rubber track tractor (Ch35). Peak pressures (Pmax) beneath the track at supporting wheels, (0.13 m depth), in forward and reverse are not very marked due to the low ratio of roller pitch to track link pitch equal to 1.54 (Sofiyan and Maximenko, 1965). Average value of all P_{max} values was 25 kPa in forward and 27 kPa in reverse (Rowland, 1972).

3.3. Macroporosity

Total macroporosity, expressed as a percentage of area occupied by pores larger than 50 μm per thin

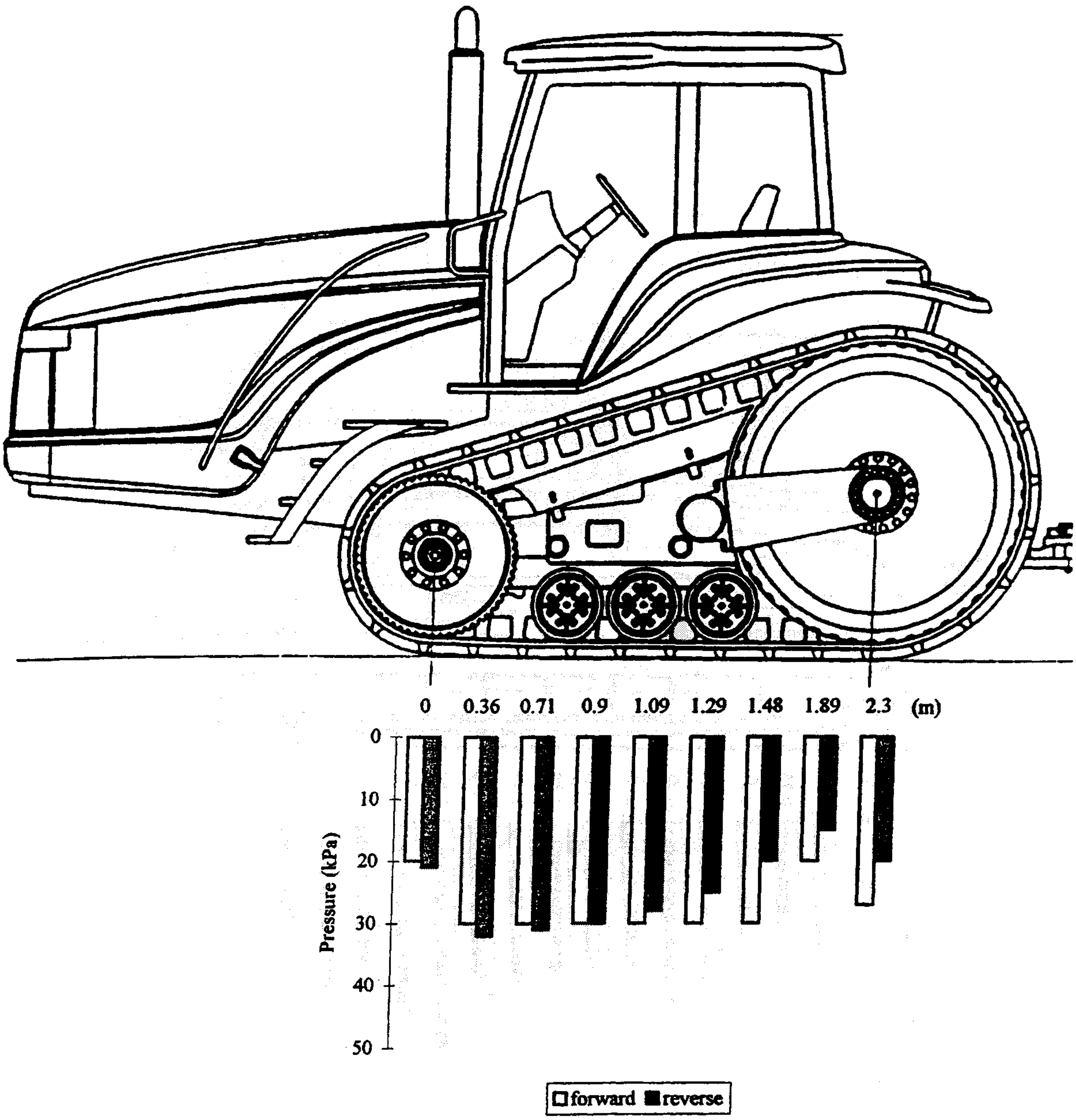

Fig. 1. Soil pressure distribution, recorded along the length of the track at 0.13 m depth for the Ch35 tractor moving forward and reverse.

section, in the control and compacted areas is showed in Fig. 3. Macroporosity decreased in the surface layer (0–0.10 m) after a single pass and such a decrease was more pronounced after four passes. The compacting effect of traffic by tracked tractors seemed to be limited to the surface layer. In fact, the macroporosity in the 0.10–0.20 m layer did not show significant differences between uncompacted areas and those compacted by one and four passes of the two tractors. Results also revealed that the decrease of macroporosity in the surface layer (0–0.10 m) following traffic by tracked tractors was different after the passes of the two tractors. The Ch35 tractor caused a significant reduction of macroporosity after only one pass, in comparison to the control area. Such a porosity reduction increased significantly after four passes. The FA150 caused a significant reduction of macroporosity only after four passes and such a value was higher,

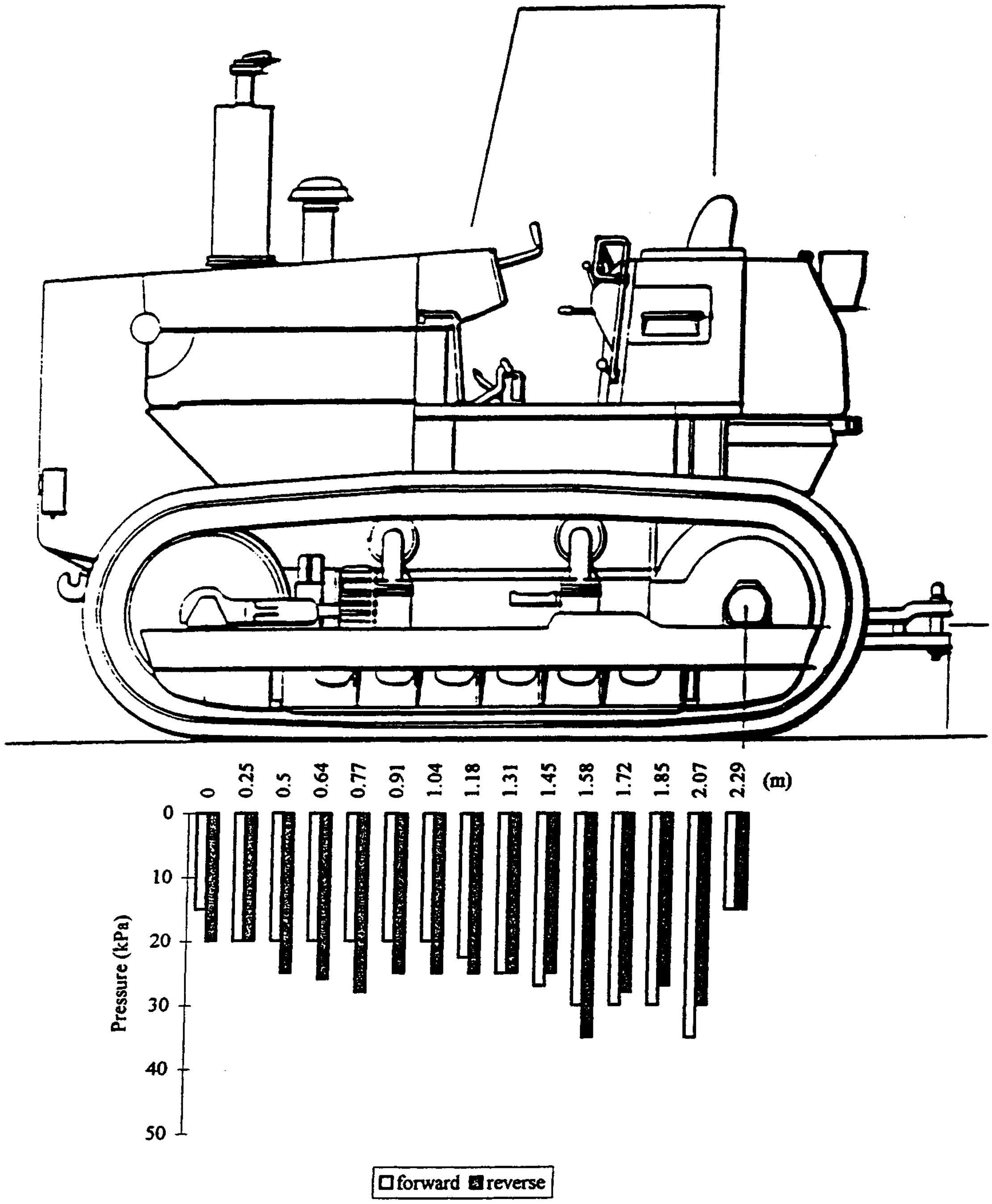

Fig. 2. Soil pressure distribution, recorded along the length of the track at 0.13 m depth for the FA150 tractor moving forward and reverse.

although not significantly, than that measured in plots under one pass of the Ch35 tractor. The decrease of macroporosity after a single pass of the FA150 tractor was not significant in comparison to control areas.

According to the micromorphometric method, a soil is considered dense or compact when the total macroporosity is less than 10%, moderately porous when the macroporosity 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 intensity of compaction is likely to be rather

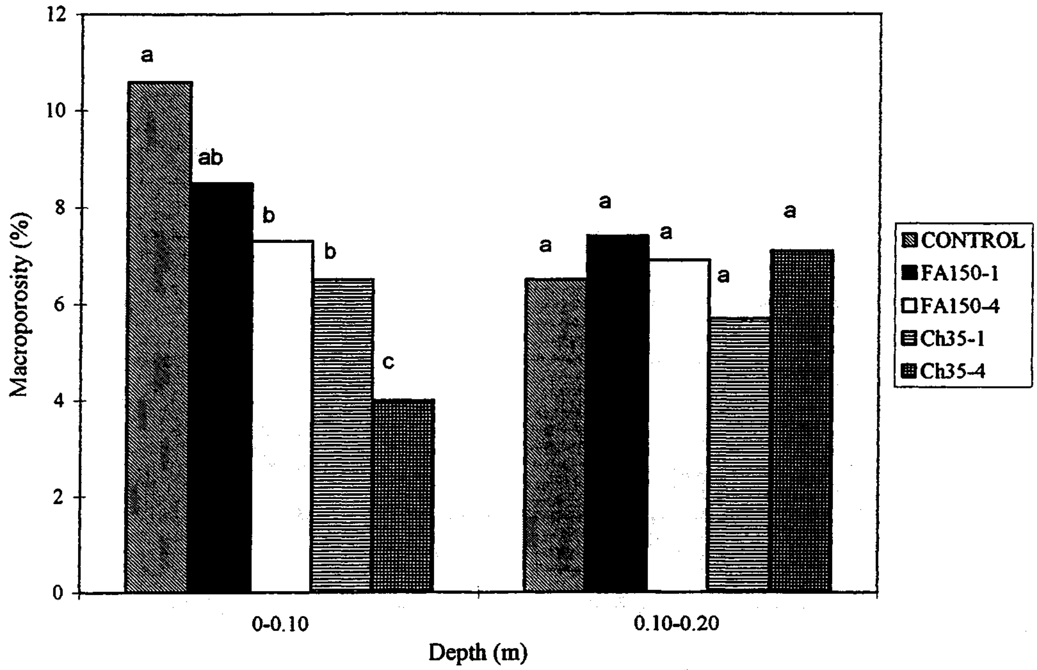

Fig. 3. Effects of soil compaction, caused by one (Ch35–1; FA150–1) and four passes (Ch35–4; FA150–4) of the two tractors (Ch35 and FA150), on soil macroporosity expressed as a percentage of area occupied by pores larger than 50 μm per thin section. Average of six replicates. Within each depth, values followed by same lower case letter are not significantly different at 0.05 level.

serious because the total compacted macroporosity was below 10%.

3.4. Pore shape and size distribution

Soil compaction following traffic of the two tracked tractors not only reduced total macroporosity but also modified the pore system in soil, i.e., modified the shape and size distribution of pores. Pore shape and size distribution in the 0–0.10 m layer of the areas compacted by the passes of the two tractors showed large differences compared with uncompacted areas (Fig. 4). The reduction in macroporosity following compaction from one and four passes of the tractors was due to the decrease in the proportion of elongated pores. Such pores are the most important, because many of these pores directly affect plant growth by promoting root penetration and storage and transmission of water and gases. For example, according to Russel (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 50 to 500 μm are the transmission pores (elongated and continuous pores) which 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 (Greenland, 1977; Pagliai et al., 1983).

The reduction of macroporosity following compaction from one and four passes of the tractors was also due to the decrease in the proportion of irregular pores larger than 500 μm, important for soil aeration. Many of these pores were practically closed or transformed into thin elongated pores oriented parallel to the soil surface without continuity in the vertical direction.

3.5. Soil structure

Variations in macroporosity, pore shape and size distribution following compaction by traffic of tracked tractors 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 along the 0–0.20 m layer (Fig. 5(a)), while in compacted areas the structure was strongly massive in the

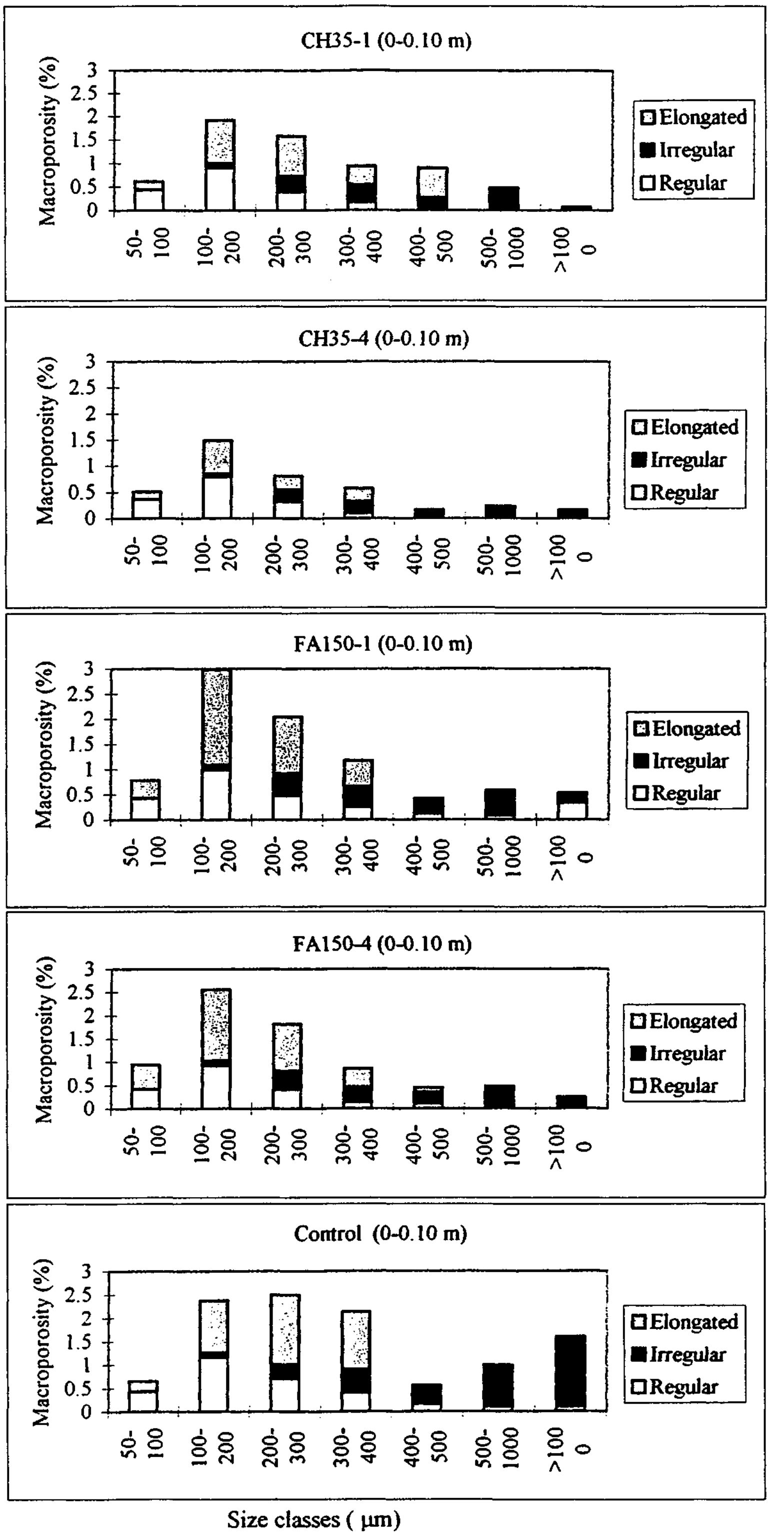

Fig. 4. Macropore size distribution, according to the equivalent pore diameter for regular and irregular pores, or the width for elongated pores, in the surface soil layer (0–0.10 m).

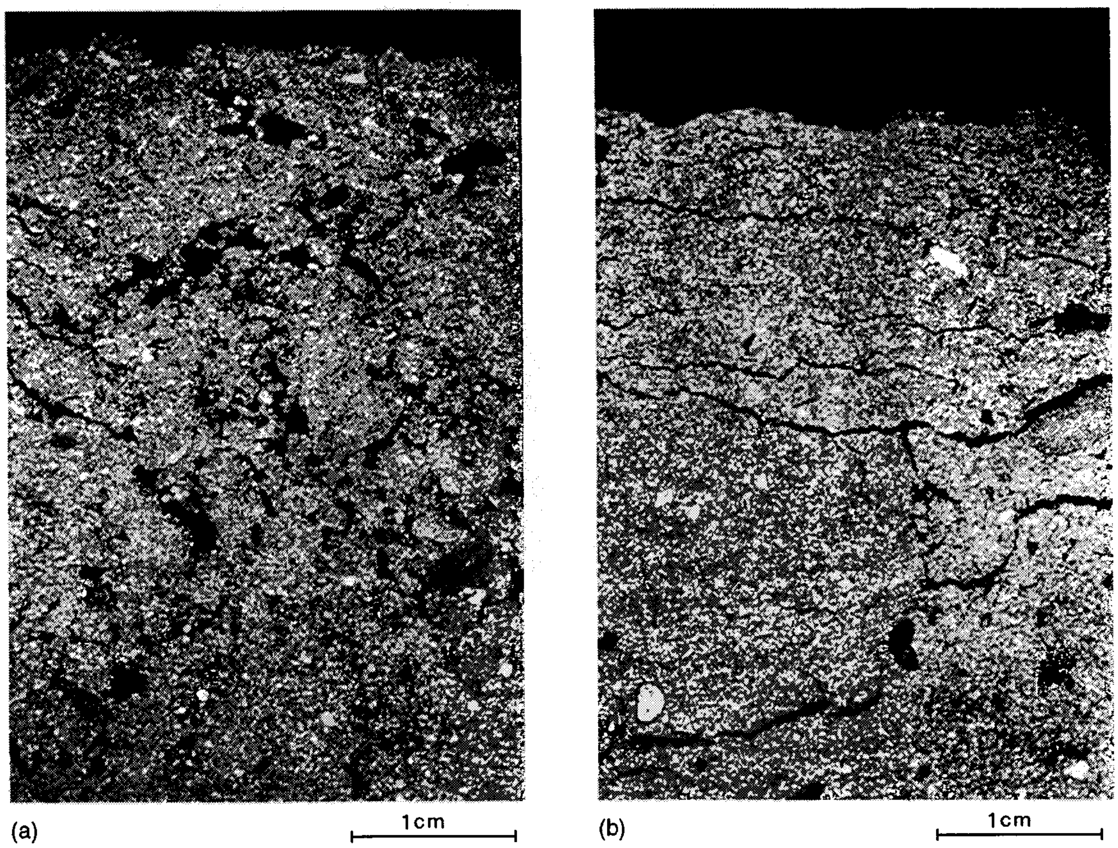

Fig. 5. Macrophotographs of vertically oriented thin sections from the surface layer (0–0.06 m) of the uncompacted (a) and compacted areas (b). Crossed Nicols; i.e. the pictures are taken under polarized light and pores appear black. The change of the subangular blocky structure of the uncompacted areas into a massive platy structure of the compacted areas is very evident.

0–0.10 m layer, and in the surface layer (0–0.05 m) the thin elongated pores were oriented parallel to the soil surface, thus originating a platy structure typical of compacted soils (Fig. 5(b)). Therefore, the few elongated pores were not vertically continuous and practically useless for water infiltration, thus increasing the probability of water stagnation or surface runoff and, as a consequence, the risk of soil erosion depending on the soil slope.

As was the case for total macroporosity, in the 0.10–0.20 m layer, pore shape and size distribution did not show significant differences between the uncompacted areas and those compacted by one or four passes of the two tractors, thus confirming that the compacting effect of tracked tractors was limited to the surface layer in this soil. The decrease of soil macroporosity in the 0.10–0.20 m layer, in comparison to the surface layer of uncompacted areas, was mainly due to the reduction in the proportion of irregular pores larger than 500 μm, probably because of a decrease of biological activity with respect to the surface layer. Many of these pores were, in fact, biopores formed by soil fauna activity.

3.6. Correlation between soil macroporosity and saturated hydraulic conductivity

Saturated hydraulic conductivity in the 0–0.10m layer was relatively low in the uncompacted control areas (Fig. 6). Thus, this soil has inherently low permeability, which is in agreement with the low value of macroporosity, particularly elongated pores. Following traffic of the two tractors, hydraulic conductivity decreased and the lowest values were found after the pass of the Ch35 tractor. With four passes of this tractor, hydraulic conductivity was drastically reduced. This is in agreement with the low presence of elongated pores which, as already said, were dis-

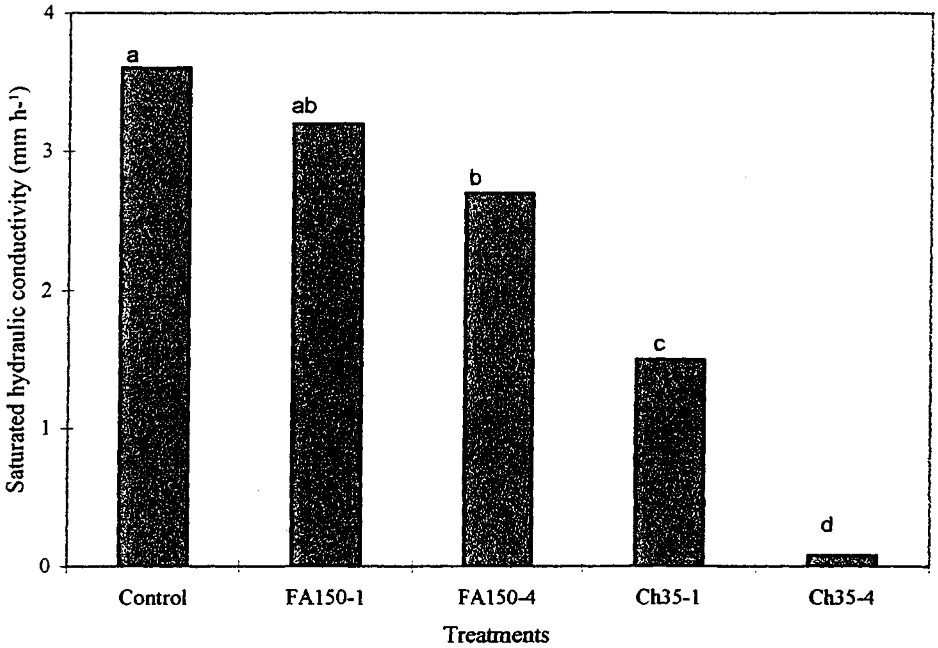

Fig. 6. Effects of soil compaction, caused by one (Ch35–1; FA150–1) and four passes (Ch35–4; FA150–4) of the two tractors (Ch35 and FA150), on saturated hydraulic conductivity in the surface soil layer (0–0.10 m). Average of six replicates. Values followed by same lower case letter are not significantly different at 0.05 level.

tributed parallel to the soil surface without continuity in the vertical direction.

A highly significant correlation between hydraulic conductivity and elongated pores and a significant correlation with total macroporosity were found (Fig. 7). This confirmed that hydraulic conductivity is directly correlated with elongated continuous pores and these results stressed that compaction is one of the most serious aspects of soil and environmental degradation, since the strong reduction of water infiltration may increase risks of soil erosion and run-off of agricultural chemicals.

3.7. Relation between total macroporosity and soil penetration resistance

Previous studies (Pagliai et al., 1992) on the effects of compaction caused by different types of tyres on total macroporosity and soil structure would appear to have demonstrated a good correlation in the compacted surface layer (0–0.10 m) between macroporosity and soil penetration resistance. Fig. 8 shows the relations between penetration resistance and total macroporosity at 0–0.10 m depth for single and multiple passes of tractors equipped with rubber and metal tracks.

The values are interpreted by a exponential type regression, namely:

$$P = ae^{bR} \qquad (2)$$

where P is total macroporosity expressed in %, R is penetration resistance in MPa, a and b are coefficients, which in this case amount to 31 and −0.63, respectively, for single and multiple passes with the metal-tracked tractor and 89.6 and −1.31, respectively, for single and multiple passes with the rubber track tractor.

A highly significant exponential relationship (Fig. 8) between macroporosity and penetration resistance for one and four passes with a metal-tracked tractor (FA150-1 pass and FA150-4 passes) and a significant exponential relationship between macroporosity and penetration resistance for one and four passes with a rubber tracked tractor (Ch35-1 pass and Ch35-4 passes) were found. A significant difference between the FA150 and Ch35 correlations in favour of FA150 was found for penetration resistance values higher of the control value. These results indicate that

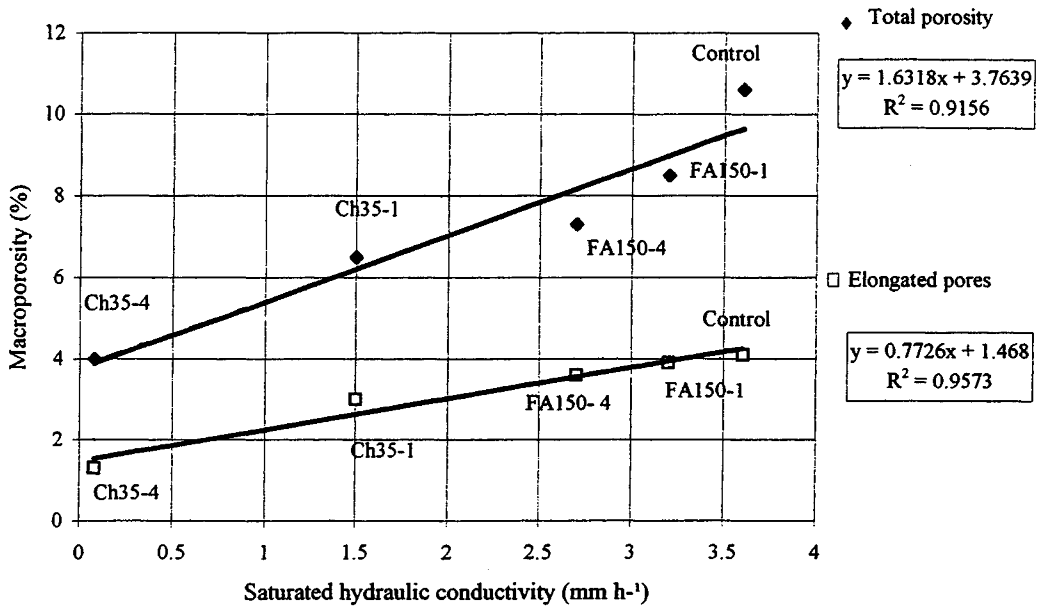

Fig. 7. Correlation between hydraulic conductivity and elongated pores and total porosity in the surface layer (0–0.10 m).

in these test conditions the rigid tracks reduced soil compaction in the surface layer, and resulted in a higher degree of macroporosity.

4. Conclusions

Tests conducted on two high-powered tractors with two different types of tracks allowed us to evaluate the degree of soil compaction by analysing variation in some physical properties. Comparing the results of one pass of the two tractors, statistically significant differences in soil penetration resistance were recorded only in layers close to the surface (0.10–0.20 m depth), while the results for four passes showed significant differences only in the deepest layer (0.30–0.40 m). Moreover, all the differences between treatments and the control were significant in the surface

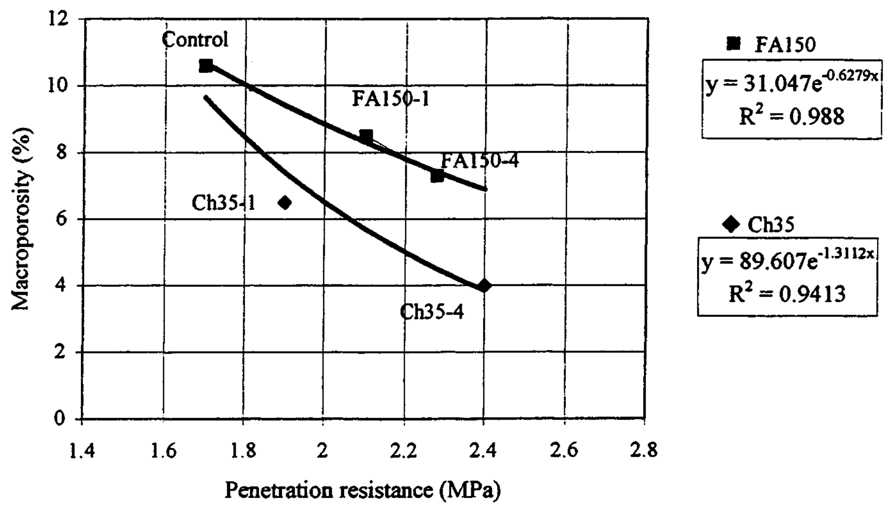

Fig. 8. Relations between soil penetration resistance and macroporosity single and multiple passes of tractors equipped with metal and rubber tracks in the soil layer (0–0.10 m depth).

layer. This leads one to suggest that multiple passes made by the two tractors induced very similar effects in the soil. A similar trend was found for dry bulk density and its increment ratio.

Soil pressure distribution along the length of the track was generally linear for the rubber-tracked tractor and similar to that obtained for the metal-tracked tractor. This result was obtained with a heavy pre-tension load on the rubber tracks. As a result of the bigger size of the traction lugs of the rubber track with reference to the metal track, the decrease in porosity, in particular of elongated pores in the soil surface layer (0–0.10 m), was greater in treatments involving the rubber-tracked tractor than for the metal-tracked tractor. Further study is therefore needed to perfect the shape and size of lugs.

Hydraulic conductivity of the surface layer was relatively low at the test site as the soil is only slightly permeable, and was inversely proportional to macroporosity, or, more precisely, to elongated pores. The highest conductivity value was recorded for the control treatment, while the lowest value was recorded for the treatment where the rubber-tracked tractor made four passes. A highly significant correlation between hydraulic conductivity and elongated pores and a significant correlation with total macroporosity were found. The surface layer of the soil also showed a highly significant exponential relationship between macroporosity and penetration resistance. However, with respect to the higher degree of macroporosity, treatments involving the metal-tracked tractor showed better soil structure quality.

References

Bekker, M.G., 1956. Theory of Land Locomotion, University of Michigan Press, Ann Arbor, MI.

Bekker, M.G., 1969. Introduction to Terrain-Vehicle Systems, University of Michigan Press, Ann Arbor, MI.

Bouma, J., Jongerius, A., Boersma, O.H., Jager, A., Schoonderbeek, D., 1977. The function of different types of macropores during saturated flow through four swelling soil horizons. Soil Sci. Soc. Am. J. 41, 945–950.

Brown, H.J., Cruse, R.M., Erbach, D.C., Melvin, S.W., 1992. Tractive device effects on soil physical properties. Soil Tillage Res. 22, 41–53.

Brusentsev, A.I., 1967. The tractive performance of tractors with bulldozers. Terramechanics 4(4), 9–16.

Esch, J.H., Bashford, L.L., Von Bargen, K., Ekstrom, R.E., 1990. Tractive performance comparisons between rubber belt track and four-wheel-drive tractor. Trans. ASAE 33, 1109–1115.

Fujii, H., 1992. Problems between soil and construction machinery with special reference to field compaction. Terramechanics 29, 35–55.

Food, Agriculture Organization, 1988. FAO/Unesco Soil Map of the World, revised legend. World Resources Report 60. FAO, Rome, 138 pp.

Gomez, K.A., Gomez, A.A., 1976. Statistical Procedures for Agricultural Research. The International Rice Research Institute, Los Baños, Philippines, pp. 97–119.

Greenland, D.J., 1977. Soil damage by intensive arable cultivations: temporary or permanent? Phil. Trans. Roy. Soc. London 281, 193–208.

Klute, A., Dirksen, C., 1986. Hydraulic conductivity and diffusivity: laboratory methods. In: A. Klute (Ed.), Methods of Soil Analysis, Part 1. 2nd ed. Am. Soc. Agron. Publ., Madison, pp. 687–734.

Marsili, A., Servadio, P., 1992. Prove sul compattamento del terreno agrario con due diversi tipi di pneumatici a confronto. (Tests on agricultural soil compaction with two different types of tyres in comparison). Rivista di Ingegneria Agraria 4, 193–199.

Marsili, A., Servadio, P., 1996. Compaction effects of rubber or metal-tracked tractor passes on agricultural soils. Soil Tillage Res. 37, 37–45.

Murphy, C.P., 1986. Thin Section Preparation of Soils and Sediments, 1st ed. AB Academic Publishers, Herts, UK.

Pagliai, M., .1988. Soil porosity aspects. Int. Agrophysics 4, 215–232.

Pagliai, M., La Marca, M., Lucamante, G., 1983. Micromorphometric and micromorphological investigations of a clay loam soil in viticulture under zero and conventional tillage. Soil Sci. 34, 391–403.

Pagliai, M., La Marca, M., Lucamante, G., Genovese, L., 1984. Effects of zero and conventional tillage on the length and irregularity of elongated pores in a clay loam soil under viticulture. Soil Tillage Res. 4, 433–444.

Pagliai, M., Febo, P., La Marca, M., Lucamonte, G., 1992. Effetti del compattamento provocato da differenti tipi di pneumatici su porosità e struttura del terreno. (Compaction effects caused from different types of tyres on macroporosity and soil structure). Rivista di Ingegneria Agraria 3, 168–176.

Rowland, D., 1972. Tracked Vehicle Ground Pressure and its Effect on Soft Ground Performance. Proceedings of the Fourth International Conference on Terrain-Vehicle Systems, Stockholm, Sweden, pp. 353–384.

Russel, E.W., 1978. Arable Agriculture and Soil Deterioration. Trans. 11th International Congress of Soil Science, 19–27 June 1978, University of Alberta, Edmonton. Canadian Society of Soil Science, Alberta, Vol. 3, pp. 216–227.

Soane, B.D., Van Ouwerkerk, C. (Eds.), 1994a. Soil Compaction in Crop Production. Developments in Agricultual Engineering 11. Elsevier, Amsterdam, pp. 662.

Soane, B.D., Van Ouwerkerk, C., 1994b. Soil compaction problems in word agriculture. In: Soane, B.D., Van Ouwerkerk, C. (Eds.), Soil Compaction in Crop Production. Developments

in Agricultual Engineering 11. Elsevier, Amsterdam, pp. 1–26.
Soane, B.D., Van Ouwerkerk, C., 1995. Implications of soil compaction in crop production for quality of the environment. Soil Tillage Res. 35, 5–22.
Sofiyan, A.P., Maximenko, Ye.I., 1965. The distribution of pressure under a tracklaying vehicle. Terramechanics 2(3), 11–16.
Tippkötter, R., 1983. Morphology, spatial arrangement and origin of macropores in some hapludalfs. West Germany. Geoderma 29, 355–371.
Walkley, A., Black, I.A., 1934. An examination of Degijareff method for determining soil organic matter and proposed modification of the chromic acid titration method. Soil Sci. 63, 251–264.

Ital. J. Agron., 2, 1, 11-20

Tillage Impact on Soil Quality. I. Soil Porosity and Related Physical Properties

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ABSTRACT

BACKGROUND. Intensive cultivation of some agricultural soils can lead to a deterioration in soil structure and other soil physical properties and, consequently, to environmental degradation. To evaluate the suitability of a loam soil (Eutric Cambisol), representative of the hilly environment of Central Italy, to alternative tillage systems, an experiment was carried out where different types of soil tillage for maize cultivation were investigated.

METHODS. Micro and macroporosity, pore shape and size distribution, bulk density, aggregate stability, saturated hydraulic conductivity and water content were analysed. Soil structure conditions were evaluated by characterizing porosity using a combination of mercury intrusion porosimetry, image analysis and micromorphological observations.

RESULTS. In the surface layer (0-10 cm) the macroporosity did not show much difference between the different tillage systems, while in the subsurface layers the differences were more pronounced. In the soil tilled by ripper subsoiling the macroporosity was generally higher and homogeneously distributed through the profile while the other tillage systems showed a significant reduction of porosity at the lower cultivation depth. Also the microporosity within the aggregates, measured by mercury intrusion porosimetry, increased in the soil tilled by ripper subsoiling and the higher macroporosity in this soil was due to a larger number of elongated transmission pores. The resulting soil structure was more open and more homogeneous, thus allowing better water storage and movement, as confirmed by the higher water content and hydraulic conductivity in the soil tilled by ripper subsoiling. Aggregates were less stable in deep and shallow ploughed soils and this resulted in a more pronounced tendency to form surface crust compared with soils under minimum tillage and ripper subsoiling.

CONCLUSIONS. This results seemed to indicate that it is possible to adopt alternative tillage systems to prevent soil physical degradation.

Key-words: soil tillage systems, soil structure, soil pore system, soil thin sections, image analysis

INTRODUCTION

The need to reduce the environmental impact of agricultural activities and to control soil structure degradation is one of the main aims of land management. It has led farmers to consider the possibility of adopting "more simplified" cultivation practices as an alternative to conventional tillage. The abandoning of traditional farming rotations and adoption of intensive monocultures, without application of farmyard manure to the soil, has decreased the organic matter content in Italian soils with evident deterioration of soil structure. In fact, the main consequence of long-term intensive cultivation is the degradation of soil structure which can reduce the effect of chemical fertilizers. As soil erosion increases, solid soil particles and nutrients can be transported with the consequent risk surface water pollution. Moreover, the resulting soil porosity conditions are often unfavourable to crop growth (Pagliai et al., 1983; 1984; 1995). 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, desertification and compaction, 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).

The aim of this research was to determine the effects of different types of tillage practices on soil structural characteristics through the quantification of differences in soil physical properties of a common soil type in the irrigated hilly environment of Central Italy, where maize is the most widespread and economically significant crop.

MATERIALS AND METHODS

Soil and treatments

A field experiment was established in 1994 at the Fagna Agricultural Experimental Centre (Scarperia - Firenze) of the Research Institute for Soil Study and Conservation (Firenze, Italy) on a loam soil classified as Typic Udifluvent according to United States Department of Agriculture (USDA, 1985). Three replications of each of four management practices were tested in 50 m 10 m plots. The tillage treatments were: 1) conventional deep tillage (mouldboard ploughing to a depth of 40 cm) (DP); 2) shallow tillage (mouldboard ploughing to a depth of 20 cm) (SP); 3) minimum tillage (harrowing with a disc harrow to a depth of 10 cm) (MT) and 4) ripper subsoiling to a depth of 50 cm (RS).

The soil had been cultivated with maize since 1970 adopting the same traditional management practices and, since 1980, the fertilization has been mineral alone without any addition of farmyard manure or other organic materials.

Porosity measurements

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, six undisturbed samples were collected in the surface layer (0-10 cm) and in the 10-20 cm layer of each plot in June 1994, November 1994, June 1995 and November 1995. In November 1995 samples were also collected in the 20-30 and 40-50 cm layers and additional samples were collected in the surface layer (0-10 cm) of areas compacted by harvesting machinery. Samples were dried by acetone water replacement (Miedema et al., 1974; Murphy, 1986), impregnated with a polyester resin and made into 6×7 cm vertically oriented thin sections (Murphy, 1986).

Photographs of the sections (Pagliai et al., 1984) were analysed by means of image analysis techniques using a PC-IMAGE software (Foster Findlay Associates, London, UK). Total porosity and pore distribution were measured according to the shape and size of the pores. These photographs covered 4.5×5.5 cm^2 of the thin section, avoiding the edges where disruption could have occurred. In this experiment, the instrument was 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 round) pores (shape factor from 1 to 2), irregular pores (shape factor from 2 to 5) and elongated pores (shape factor >5). These classes correspond approximately to those used by Bouma et al. (1977). Pores of each shape group were 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 were also examined using both a Zeiss "R POL" microscope at 25x magnification to observe micro-structures and crust formation and a macroepidiascope at 2x magnification to observe macro-structure.

For mercury intrusion porosimetry, six undisturbed samples were collected from the 0-10 cm layer of each plot in the areas adjacent to those sampled for thin section preparation. Aggregates with a volume up to 4 cm^3 were 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 were determined within the range 0.007-50 µm.

Aggregate stability

A modification of the wet-sieving method of Malquori and Cecconi (1962) was used to determine the water stability of soil aggregates. Air-dried soil aggregates (1-2 mm), collected in the surface layer (0-10 cm) of all plots in November 1995, were placed in 0.25 mm mesh sieves and moistened by capillary rise from a layer of wet sand, then immersed in deionized water and shaken with an alternate rotating movement (60 times per minute) at room temperature. The water stability index (WSI) was calculated as 100(1-A/B), where A and B are the oven-dry weights of aggregates passing through the sieve after 5 and 60 min, respectively. Each determination was made at least in triplicate.

Saturated hydraulic conductivity, bulk density and soil water content

Six undisturbed cores (5.68 cm diameter and 9.5 cm deep) were collected from the 0-10 cm layer of each plot in areas adjacent to those sampled for thin section preparation in November 1995. The samples were slowly saturated and the saturated hydraulic conductivity was measured using the falling-head technique (Klute and Dirksen, 1986). Following these measurements, samples were oven dried at 105 °C and the bulk density was determined.

The gravimetric soil water content in the 0-10 cm layer was measured in November 1995.

Statistical analysis

All data were analysed by analysis of variance (ANOVA) using CoStat (Cohort Software, 1990). The means were compared employing Duncan's multiple range test.

RESULTS AND DISCUSSION

Porosity

In the surface layer (0-10 cm) total macroporosity (pores larger than 50 µm) did not show significant differences between treatments in the June samplings (Figure 1), while in the November sampling the porosity generally decreased with respect to the June sampling. In November the porosity in the DP and SP soils was significantly lower than in the soils under MT and RS. For a better interpretation of these results it can be stressed that according to the micromorphometric method, a soil is considered dense (compact) when the total macroporosity is < 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). Overall porosity values were lower in the 10-20 cm layer and the differences between

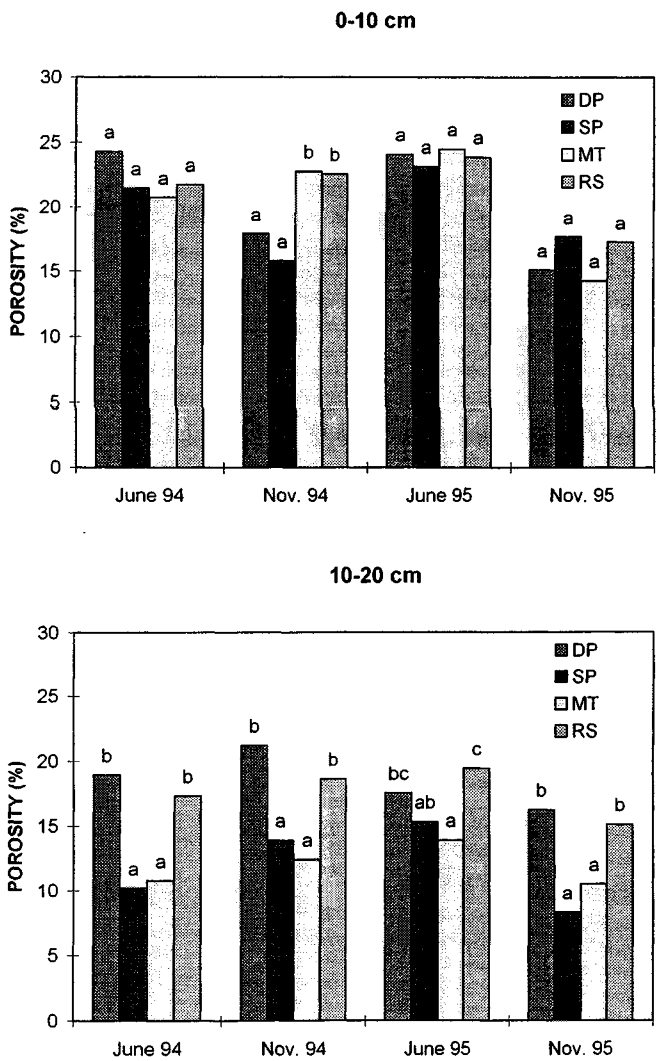

Figure 1. Effects of different tillage systems on soil macroporosity in thin sections, from 0-10 and 10-20 cm layer, expressed as a percentage of total area occupied by pores > 50 µm (DP, deep ploughing; SP, shallow ploughing; MT, minimum tillage; RS, ripper subsoiling). Total porosity values, within each sampling time, differ significantly when followed by different letters at $P \leq 0.05$.

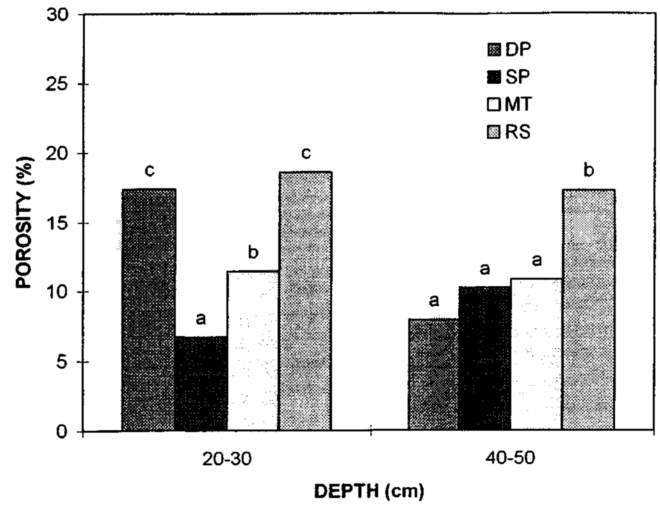

Figure 2. Effects of different tillage systems on soil macroporosity in thin sections, from 20-30 and 40-50 cm layer at the sampling of November 95, expressed as a percentage of total area occupied by pores > 50 μm (DP, deep ploughing; SP, shallow ploughing; MT, minimum tillage; RS, ripper subsoiling). Total porosity values, within each sampling time, differ significantly when followed by different letters at P ≤ 0.05.

tillage systems were more pronounced (Figure 1). At all sampling times, in the MT and SP soils the porosity was significantly lower than in soils tilled by DP and RS, indicating a compact soil structure. Figure 2 shows the trend of macroporosity in the sublayers. The 20-30 cm layer of the SP treatment showed a significantly lower value of macroporosity indicating, in this case, a compact soil structure such as a ploughpan or ploughsole. In the MT soil the porosity remained significantly lower than in DP and RS soils. In the 40-50 cm layer only the RS treatment showed a significantly higher macroporosity value, indicating that with this tillage system the porosity was homogeneously distributed throughout the cultivated profile. In this layer, the DP soil showed the lower value of macroporosity and a strong reduction with respect to the upper layers due to the formation of a ploughpan at the lower cultivation limit. However, the macroporosity was lower in this layer and, consequently, the soil was rather compact in MT and SP plots also.

For a thorough characterization of soil macropores, the main aspects to be considered are not only pore shape but also pore size distribution, especially of elongated continuous pores, because many of these pores directly affect plant growth by easing root penetration, 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 function as a water reservoir for plants and micro-organisms. Transmission pores (elongated and continuous pores), ranging from 50 to 500 μm, are important both in soil-water-plant relationships and in maintaining good soil structure conditions. Damage to soil structure can be recognized by a decrease in the proportion of transmission pores.

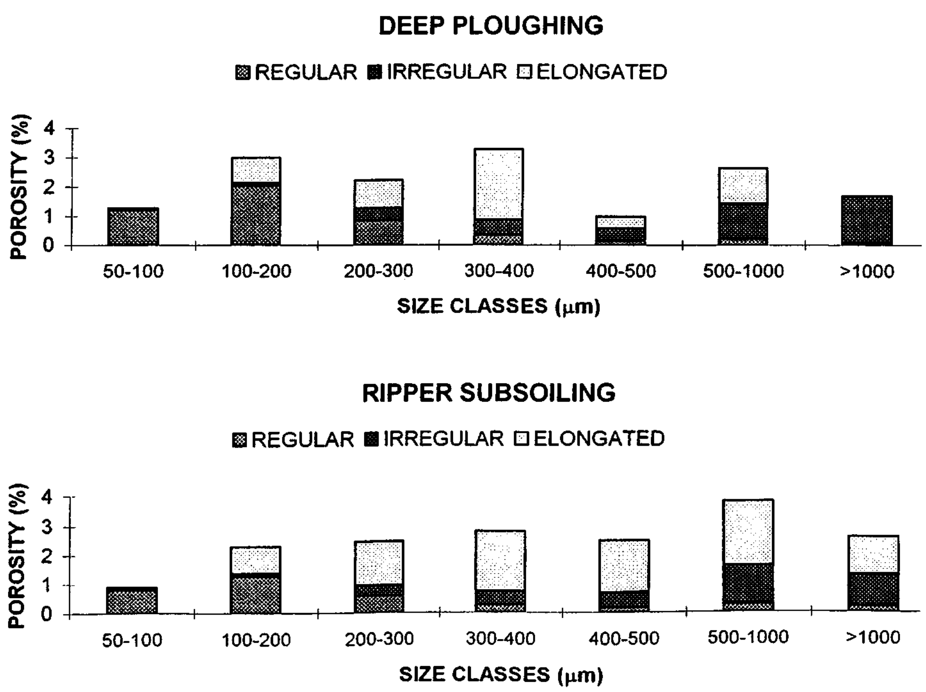

Figure 3. Pore size distribution, expressed as equivalent pore diameter, for regular and irregular pores and width for elongated pores in the surface layer (0-10 cm) in November 1995.

In the surface layer (0-10 cm), even though the total macroporosity generally did not show significant differences between tillage systems, the pore shape and size distribution showed some differences, particularly between RS and the other tillage systems that showed the same trend of deep ploughing shown in Figure 3. The main differences were represented by the higher proportion of elongated pores in the range of transmission pores (50-500 μm) as well as in pores > 500 μm. Figure 4 clearly shows that the decrease of macroporosity in the 10-20 cm layer of SP and MT soils could be ascribed to the reduction of the proportion of elongated pores, especially those in the larger size classes. Regular and irregular pores did not show evident differences. This means that, in this type of soil, the different tillage systems only modify the elongated pores which, as already said, are important in determining the soil structure conditions. Generally, many of the regular and irregular pores are "biopores" formed by soil biological activity (soil fauna) and this shows that in such a soil and for the period considered, the different tillage systems did not influence this activity. As in the case of macroporosity (Figure 2) the pore shape and size distribution was rather homogeneous throughout the soil profile

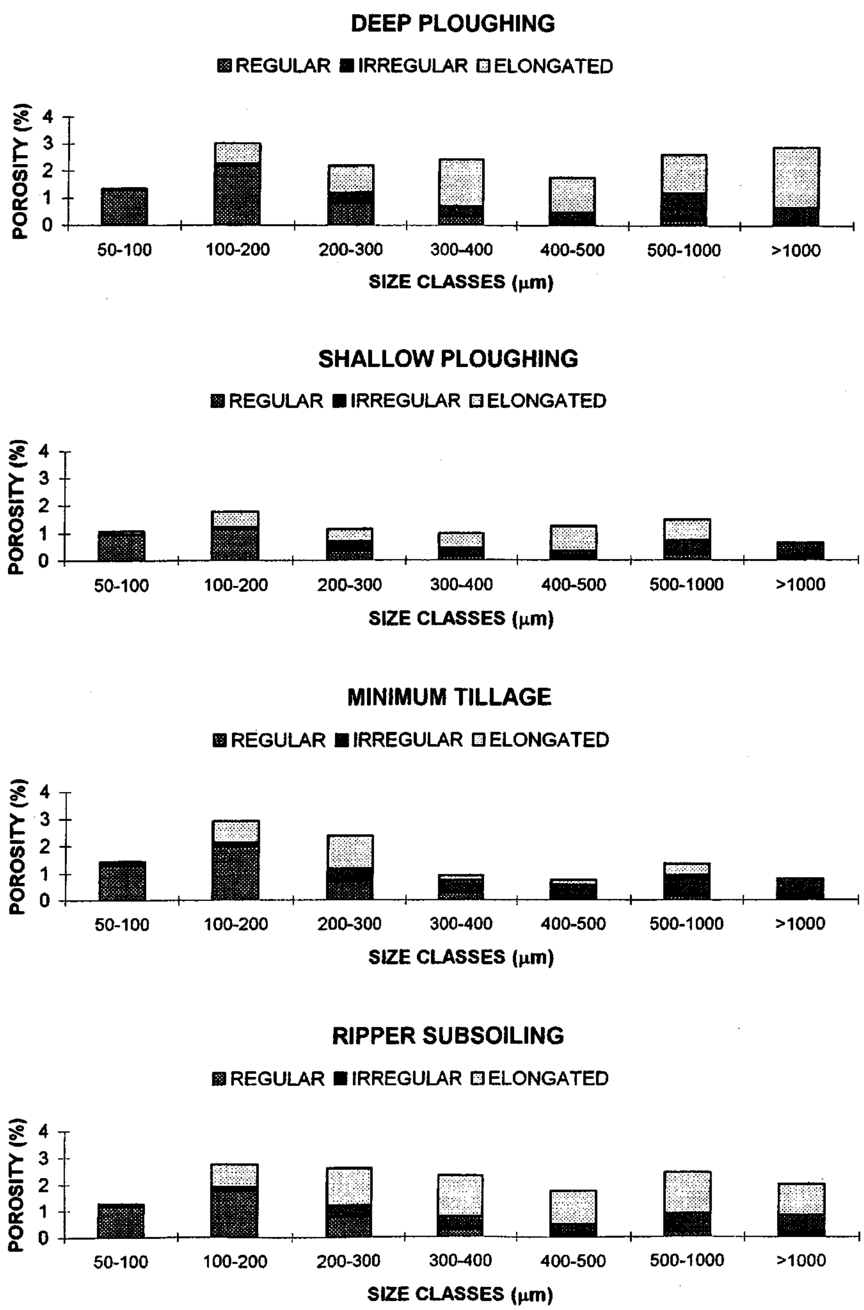

Figure 4. Pore size distribution, expressed as equivalent pore diameter, for regular and irregular pores and width for elongated pores in the 10-20 cm layer in November 1995.

tilled by RS, while the decrease of porosity in the sublayers (20-30 and 40-50 cm) of the soil under the other tillage systems also indicated a reduction of elongated pores.

Figure 5 shows the decrease of macroporosity in the compacted areas of soil tilled by DP after the passage of machinery for harvesting. In these areas, however, the porosity did not show significant differences between tillage systems and it was confirmed that the compaction caused a four-fold decrease in soil porosity between the wheel tracks and a six-fold decrease under the wheel tracks compared to the adjacent uncompacted soil (Pagliai et al., 1988). This decrease was due to a reduction of all larger pores but mainly the elongated pores which can negatively effect water infiltration.

Total pore volume measured by the mercury intrusion porosimetry inside the aggregates of the 0-10 cm layer sampled in November 1995 was greater in the MT and RS treatments than in conventional tillage treatments (Figure 6). This trend was similar for the other sampling times and, therefore, not reported in the figure. This decrease in conventional ploughed soil was mainly due to the reduction of volume of storage pores (0.5-50 μm). The use of mercury intrusion porosimetry to determine the pore volume within the aggregates can be very useful in assessing the suitability of soil for reduced tillage, since it allows the amount of water available to plants to be determined (Pagliai, 1988). The increase of this type of pores in soils following MT and RS treatments is important for the improvement of the available water storage capacity. Pores smaller than 0.5 μm, called "residual pores" according to the Greenland classification (1977), showed a relatively low proportion and no significant differences were detected between the types of tillage. Residual pores retain water at low potentials which is unavailable to roots or for drainage and they generally become dominant in dense soils (Ajmone Marsan et al., 1994).

These results confirmed that the RS treatment was the most efficacious in improving the quality of the pore system. In fact, the increase of storage pores was associated to an increase of transmission pores as observed in Figure 3.

Aggregate stability

The effects of tillage systems on the stability of aggregates in water by wet sieving in the surface layer (0-10 cm) is reported in Table 1. The relatively low values of the WSI show that the soil aggregates were not very stable under the destructive force of water action. However, MT and RS significantly increased the WSI compared with the conventional tillage treatments. The aggregate stability is an important parameter for the evaluation of the impact of tillage systems because it is strictly related to soil degradation aspects. Soils with poor stability are more susceptible to crusting and erosion. Therefore, alternative tillage systems, like MT and RS,

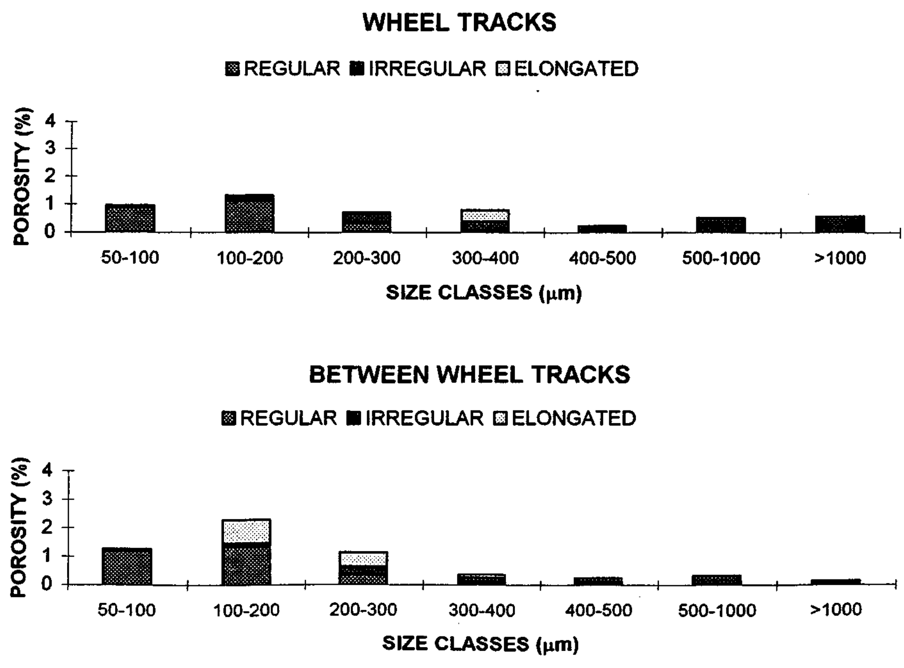

Figure 5. Pore size distribution, expressed as equivalent pore diameter, for regular and irregular pores and width for elongated pores in the surface layer of the areas compacted by wheel tracks in the plots tilled by DP at the sampling of November 1995.

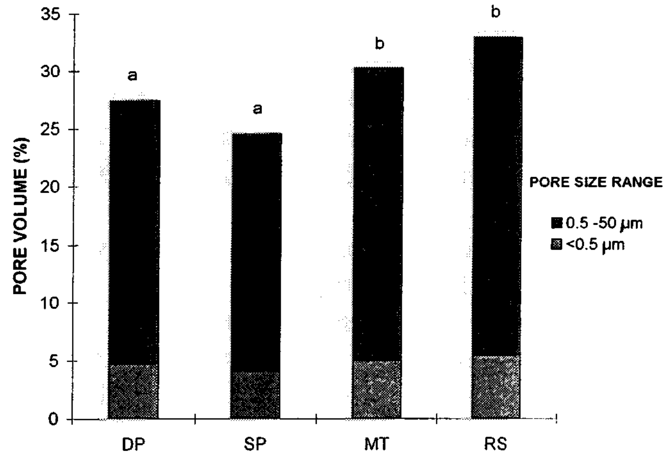

Figure 6. Microporosity inside the aggregates from the 0-10 cm layer measured by mercury intrusion at the sampling of November 1995. (DP, deep ploughing; SP, shallow ploughing; MT, minimum tillage; RS, ripper subsoiling). Total porosity values differ significantly when followed by different letters at P ≤ 0.05.

seem to be more efficacious in preventing soil structure degradation than conventional tillage.

Saturated hydraulic conductivity, soil water content and bulk density

The values of saturated hydraulic conductivity of the 0-10 cm layer (Table 1) show that the soil was moderately permeable. In the soil tilled by RS, where the proportion of elongated continuous pores was higher, the hydraulic conductivity was significantly higher. The MT soil also showed a higher hydraulic conductivity compared to the conventionally tilled soil.

The soil water content, measured at the time of harvesting, was significantly higher in soil tilled by MT and RS than in DP and SP soil. These data are in agreement with the high number of storage pores (0.5-50 µm) in the MT and RS tillage systems.

The bulk density showed that the lowest value was found in RS soil. This is in agreement with the better quality of the pore system in soil under this treatment. The other treatments did not show significant differences.

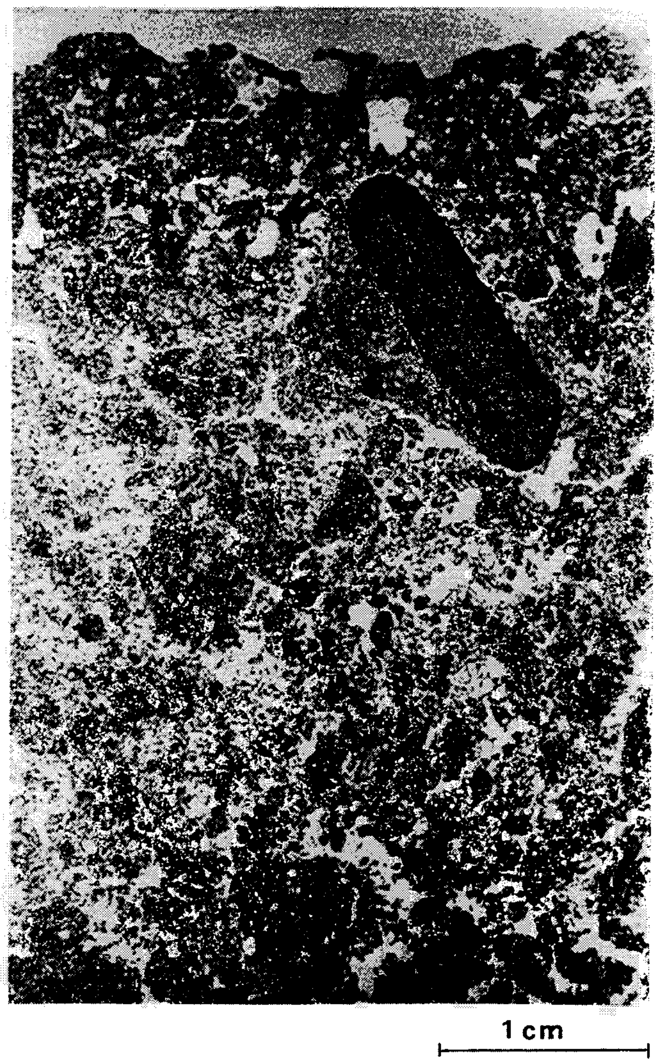

Figure 7. Macrophotograph of vertically oriented thin section from samples of the 0-6 cm layer of soil tilled by ripper subsoiling. A subangular blocky structure can be noticed. Plain light (pores appear white).

Soil structure

The differences in pore shape and size distribution through the Ap horizon between the different tillage systems reflect the type of soil structure. Micromorphological examination of thin sections revealed that, under the RS treat-

Table 1. Effects of tillage systems on soil aggregate stability, saturated hydraulic conductivity, gravimetric soil water content and bulk density in the surface layer (0-10 cm) in November 1995. Values in each row differ significantly between treatments (P ≤ 0.05) when followed by different letters.

Soil Property	Deep Ploughing	Shallow Ploughing	Minimum Tillage	Ripper Subsoiling
Water Stability Index	10.4 a	11.3 a	14.7 b	15.3 b
Saturated Hydraulic Conductivity (mm h^{-1})	20.1 b	10.2 a	33.4 c	42.8 d
Gravimetric Water Content (%)	22.4 a	21.6 a	24.1 b	25.2 b
Bulk Density (Mg m^{-3})	1.4 ab	1.5 b	1.6 b	1.3 a

ment, a subangular blocky structure (Figure 7) was present homogeneously down through the profile while in the MT soil this structure was present in the surface (0-10 cm) layer. Below this layer the soil structure was more compact. In DP soil the structure was more complex: at the soil surface a compact platy crust was present. Below this thin layer, different types of soil structure could be present, such as a vughy structure (Figure 8) in which numerous pores break up the continuity of fine materials (Bullock et al., 1985) or a subangular blocky structure. This latter type of soil structure was distributed homogeneously to a depth of about 40 cm. In the 40-50 cm layer the structure became rather compact (massive) and a ploughpan at the lower limit of cultivation appeared well developed. This compact layer strongly reduced the continuity of elongated pores. In the SP treatment the soil structure in the surface layer was similar to the DP soil, while it appeared more compact in the 10-20 cm layer and the ploughpan was well developed in the 20-30 cm layer.

The surface crusts, observed in the conventionally tilled soils, are formed by raindrop impact, which causes the mechanical destruction of soil aggregates and this indicates that ploughing forms surface soil aggregates which are less rain stable than after MT and RS, as confirmed by the lower values of the WSI. The presence of such surface crusts in DP and SP soils may also explain the lower values of saturated hydraulic conductivity in these soils compared to MT and RS soils.

In the surface layer of the areas compacted by

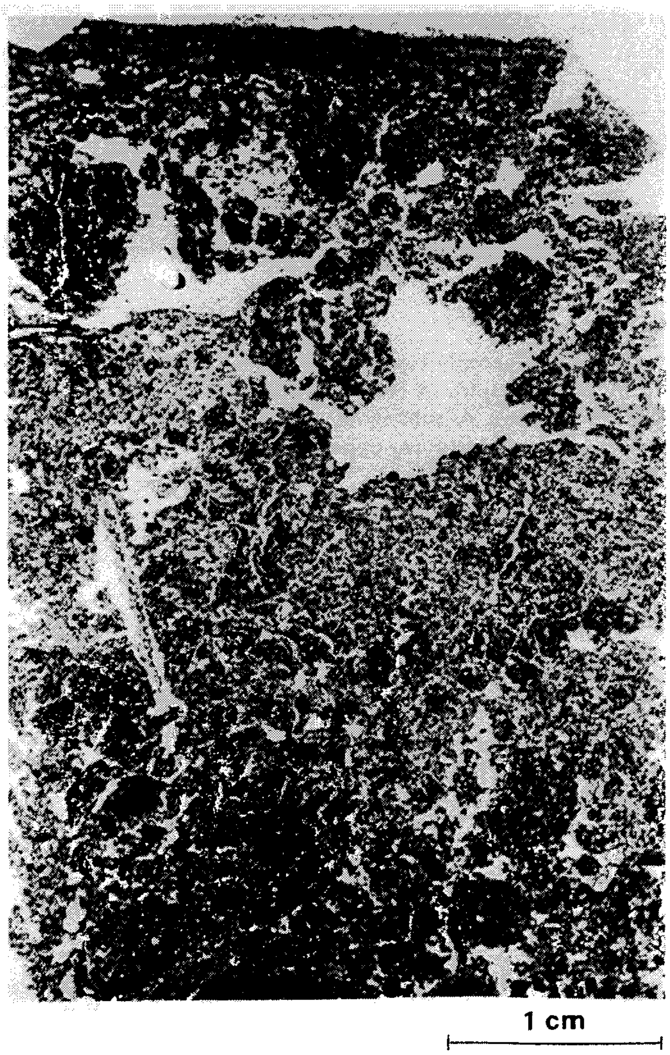

Figure 8. Macrophotograph of vertically oriented thin section from samples of the 0-6 cm layer of deep ploughed soil. A surface crust and the vughy structure below can be noticed. Plain light.

Figure 9. Macrophotograph of vertically oriented thin section from samples of the 0-6 cm layer of areas compacted by wheel tracks. A compacted platy structure is visible. Plain light.

wheel tracks a very dense platy structure was observed. The few thin elongated pores were oriented parallel to the soil surface and not interconnected in a vertical direction (Figure 9). This leads, as a consequence, to a strong reduction of water infiltration and, therefore, to a possible increase of surface runoff.

CONCLUSIONS

The results found in this experiment and for this type of soil, characterized by low capacity of soil structure, and particularly microstructure, regeneration, indicate that the better quality of the pore system, with a higher proportion of elongated transmission pores was observed in soil tilled by the RS treatment. Such a pore system produced a more open and homogeneous structure that facilitated water movement, as shown by the higher hydraulic conductivity. The increase of storage pores in RS soil was also important because it leads to an increase of available water for plants. Soil aggregates from soil tilled by RS were more resistant to the destructive effect of water action than those of ploughed soils. Lower aggregate stability in ploughed soils leads to a pronounced formation of surface crusts or the formation of a ploughpan at the lower cultivation limit.

MT showed the same results as RS only in the surface layer (0-10 cm). The decrease in porosity below this layer may reduce water drainage only in the case of heavy rains concentrated in a short period. In this case the excess water may contribute to soil structure degradation with damage to crop development, otherwise MT could be a good alternative to conventional ploughing (DP and SP).

The results of this study confirmed that both DP and SP induced the more relevant modification of soil physical properties resulting in damage to soil structure. The negative aspects associated with these management systems are the formation of surface crusts and ploughpan at the lower cultivation limit. The formation of the ploughpan and the decrease of porosity in the subsurface layers of shallow ploughed soil, besides a reduction in water movement may also hamper root growth.

The combination of mercury intrusion porosimetry-image analysis-micromorphological observations is very useful for assessing soil suitability for alternative tillage systems such as RS and MT and can also help to explain differences in water movement and aggregate stability between different tillage systems.

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REFERENCES

Ajmone Marsan F., Pagliai M., Pini R., 1994. Identification and properties of fragipan soils in the Piemonte Region (Italy). Soil Sci. Soc. Am. J., 58, 891-900.

Bouma J., Jongerius A., Boersma O.H., Jager A., Schoonderbeek D., 1977. The function of different types of macropores during saturated flow through four swelling soil horizons. Soil Sci. Soc. Am. J., 41, 945-950.

Bullock P., Fedoroff N., Jongerius A., Stoops G., Tursina T., 1985. Handbook for soil thin section description. Waine Res. Pub., Wolverhampton, U.K.

Cohort Software, 1990. CoStat Statistical Software. Berkeley, California, USA.

Fiès J.C., 1992. Analysis of soil textural porosity relative to skeleton particle size, using mercury porosimetry. Soil Sci. Soc. Am. J., 56, 1062-1067.

Greenland D.J., 1977. Soil damage by intensive arable cultivation: temporary or permanent? Phil. Trans. Royal Soc., London, 281, 193-208.

Klute A., Dirksen C., 1986. Hydraulic conductivity and diffusivity: laboratory methods. In: A. Klute (ed.): Methods of Soil Analysis, Part 1. Second Ed. A.S.A. Publ., Madison, Wisconsin, USA. pp. 687-734.

Malquori A., Cecconi S., 1962. Determinazione seriale dell'indice di struttura del terreno. Agrochimica, 6, 199-205.

McBratney A.B., Moran C.J., Stewart J.B., Cattle S.R., Koppi A.J., 1992. Modifications to a method of rapid assessment of soil macropore structure by image analysis. Geoderma, 53, 255-274.

Mermut A.R., Grevers M.C.J., de Jong E., 1992. Evaluation of pores under different management systems by image analysis of clay soils in Saskatchewan, Canada. Geoderma, 53, 357-372.

Miedema R., Pape T., Van de Wall G.J., 1974. A method to impregnate wet soil samples, producing high quality thin sections. Neth. J. Agr. Sci., 22, 37-39.

Moran C.J., McBratney A.B., 1992. Acquisition and analysis of three-component digital images of soil pore structure. II. Application to seed beds in a fallow management trial. J. Soil. Sci., 43, 551-566.

Murphy C.P., 1986. Thin section preparation of soils and sediments. A B Academic Publishers, Herts, U.K. pp. 149.

Pagliai M., 1988. Soil porosity aspects. Int. Agrophys. 4, 215-232.

Pagliai M., La Marca M., Lucamante G., 1983. Micromorphometric and micromorphological investigations of a clay loam soil in viticulture under zero and conventional tillage. J. Soil Sci., 34, 391-403.

Pagliai M., La Marca M., Lucamante G., Genovese L., 1984. Effects of zero and conventional tillage on the length and irregularity of elongated pores in a clay loam soil under viticulture. Soil Till. Res., 4, 433-444.

Pagliai M., Pezzarossa B., La Marca M., Lucamante G., 1988. Variazioni della porosità del terreno in seguito al compattamento provocato dal passaggio di trattori. Riv. di Ing. Agr., 2, 120-126.

Pagliai M., Raglione M., Panini T., Maletta M., La Marca M., 1995. The soil structure after ten years of conventional and minimum tillage of two Italian soils. Soil Till. Res., 34, 209-223.

Ringrose-Voase A.J., Bullock P., 1984. The automatic recognition and measurement of soil pore types by image analysis and computer programs. J. Soil Sci., 35, 673-684.

Russell E.W., 1978. Arable agriculture and soil deterioration. Trans. 11th Int. Congr. Soil Sci. Edmonton, 19-27 June 1978. Can. Soc. Soil Sci., Alberta, Vol. 3, 216-227.

Tippkötter R., 1983. Morphology, spatial arrangement and origin of macropores in some hapludalfs, West Germany. Geoderma, 29, 355-371.

USDA, 1985. Key to soil taxonomy. Management Support Service. Tech. Monogr. No. 6, USDA, Cornell University, Ithaca, NY.

IMPATTO DELLE LAVORAZIONI SULLA QUALITÀ DEL SUOLO. I. POROSITÀ E PROPRIETÀ FISICHE CORRELATE

RIASSUNTO

SCOPO. Le continue lavorazioni intensive in molti suoli possono causare una degradazione della struttura e di altre proprietà fisiche del suolo con conseguenti danni per l'ambiente. Al fine di verificare la possibilità di introdurre sistemi di lavorazione alternativi a quelli tradizionali per la coltura del mais in un terreno a tessitura franca (Eutric Cambisol), rappresentativo dell'ambiente collinare dell'Italia Centrale, è stato condotto un esperimento tendente a valutare l'effetto di differenti sistemi di lavorazioni su alcune proprietà fisiche del suolo.

METODO. Sono state valutate la micro e macroporosità, la morfologia e distribuzione dimensionale dei pori, la massa volumica apparente, la stabilità degli aggregati, la conducibilità idraulica in suolo saturo e il contenuto gravimetrico d'acqua. Le condizioni strutturali sono state valutate attraverso la caratterizzazione della porosità mediante porosimetria a mercurio, analisi di immagine su sezioni sottili di terreno e osservazioni micromorfologiche.

RISULTATI. Nello strato superficiale (0-10 cm) la macroporosità non mostrava variazioni significative fra i diversi sistemi di lavorazione, mentre negli strati subsuperficiali tali differenze erano più pronunciate. Nel terreno rippato la macroporosità era generalmente più alta e distribuita uniformemente lungo il profilo coltivato, mentre gli altri sistemi di lavorazione mostravano una riduzione di porosità al limite inferiore di coltivazione. Anche la microporosità all'interno degli aggregati, misurata con il porosimetro a mercurio, aumentava nel terreno rippato e la più alta macroporosità in questo terreno era dovuta alla più alta proporzione dei pori allungati di trasmissione. La risultante struttura del terreno appariva più aperta e più omogenea permettendo così una maggiore riserva idrica e migliori movimenti dell'acqua, come confermato dalla più alta conducibilità idraulica proprio nel terreno interessato da rippatura. La stabilità degli aggregati era inferiore nel terreno interessato da aratura sia profonda sia superficiale, ove appariva più pronunciata la tendenza alla formazione di croste superficiali rispetto al terreno interessato dalla lavorazione minima e dalla rippatura.

CONCLUSIONI. Questi risultati hanno evidenziato la possibilità di adottate sistemi di lavorazione alternativi alle tradizionali arature al fine di prevenire o attenuare la degradazione fisica del suolo.

Parole chiave: lavorazioni del terreno, struttura del suolo, sistema dei pori, sezioni sottili, analisi di immagine.

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Tillage Impact on Soil Quality. II. Biological Properties in Surface Soil

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ABSTRACT

BACKGROUND. The purpose of our experiments was to determine the response of microbial populations to four different tillage systems (minimum tillage MT, shallow tillage SP, ripper subsoiling RS and conventional deep tillage DP), applied to continuous maize on loamy soil classified as Typic Udifluvent soil.
METHODS. The respiratory activity was determined by incubating the soil at 25 °C with soda lime pellets. Soil microbial biomass C (SMBC) was estimated using the FI method. Organic C (OC) was determined with a Mettler automatic titrator. The mineralization index (respiratory activity C/organic C ratio) and the metabolic quotient qCO_2 (respiratory activity C / biomass C ratio) were calculated from the obtained data. Phosphatase activity was determined by incubating the soil with p-nitrophenylphosphate.
RESULTS. The results of this study refer to the analyses of soil samples taken at depths of 0-15 cm, two years after the start of the experiments. In the minimum tillage system, the respiratory activity, metabolic quotient, mineralization index and phosphatase activity were higher than those of the other tillage systems, while a higher biomass value was found in the ripper subsoiling system. The higher concentration of crop residues in the surface layer and less alteration to the soil structure, inherent in minimum tillage, caused an increase in microbial metabolic activities.
CONCLUSIONS. After two years of using alternative tillage systems, minimum tillage was revealed as particularly favourable towards the development of microbial metabolic activities at depths of 0-15 cm, although it did not influence the conservation of organic matter and microbial biomass C more than the other tillage systems.

Key-words: soil tillage systems; respirometry; biomass; qCO_2; C-organic; phosphatase activity.

INTRODUCTION

Intensive agricultural production and continued use of land resources cause the decline of the agro-ecosystems through erosion and the loss of soil microbial biodiversity, and this leads to a loss of productivity.
Whalley et al. (1995) found that microorganism populations change under different management systems and that these changes are affected by differences in rooting patterns, with such effects on agriculture and the environment as different yields, erosion, NO_x emission.
Angers et al., (1993) indicated that different tillage systems modify the distribution of crop residues with depth. There is general agreement that, in the absence of tillage, organic matter tends to concentrate in the upper few centimeters of the soil. Since conventional tillage mixes the soil, the distribution is more uniform throughout the ploughed layers than in a no-till soil (Kern and Johnson, 1993; Campbell et al., 1996).
Although the microbial biomass comprises only a small portion (from 1.0 to over 4.0%) of the total soil organic C (Jenkinson and Ladd, 1981; Anderson and Domsch, 1989), it is very important as a repository of nutrients for plants (Schnürer et al., 1985).
Carter (1986) and Powlson et al. (1987), suggested that microbial biomass-C could be used as an indicator of the early changes in soil organic matter (SOM) brought about through management practices such as tillage and straw incorporation.
Changes in soil management cause the microbial biomass to increase or decrease much faster than the total amount of SOM and therefore it can be affirmed that the biomass is a much more

sensitive indicator of changing soil conditions than total SOM content, and so the biomass can serve as an early warning of such changes long before they are detected in other ways (Brookes, 1995).

Respiratory activity is usually the most widely used parameter to determine the microbiological activity of the soil. Since the breakdown of organic material is common to all heterotrophs, this parameter is often used for the complete evaluation of the microbial activity of the soil (Franzluebbers et al. 1995).

The mineralization index of C can be obtained from the ratio between emitted CO_2 and the total quantity of organic C in the soil. This will indicate how quickly the SOM in the soil is destroyed by microorganisms. An evaluation of increases and decreases in organic substances in a particular soil sample and over a given period is also required (Dommergues, 1960; Florenzano,1983).

The microbial metabolic quotient, qCO_2, represents the CO_2-C produced per unit biomass-C and time (Anderson and Domsch,1985 and 1990). Since the microbial respiration in the field is subject to extreme environmental and seasonal variations, this index is only considered an indicator of a very precise environmental stress (Brookes, 1995). When the microbial biomass is stressed, the metabolic quotient rises, i.e. an increase in the quantity of C is oxygenated per unit of biomass in order to repair and maintain the biochemical machine of the cell active (Wardle and Ghani, 1995).

The value of the qCO_2 may be used to quantify the effects caused by environmental differences. Nevertheless, the qCO_2, by its holistic nature, cannot show specific changes within the microbial population under different management regimes (Ceccherini et al., 1996).

Microorganisms are the major source of soil enzymes. Phosphatase is a general name used to describe a broad group of enzymes that catalyze the hydrolysis of both esters and anhydrides of phosphoric acid (Deng and Tabatabai, 1997). Soil phosphatase can occur exocellularly as well as within the living cell.

Part of this activity is independent of the causes that regulate the intracellular metabolic activity of microrganisms. Nevertheless the effect can be very important in understanding the life of the ecosystem because it has an essential role in the mineralization of P, causing the release of phosphates from organic esters (Nannipieri et al., 1995).

We used conventional methods to assess the effects of the different tillage systems (minimum tillage, shallow tillage, ripper subsoiling and deep tillage) on soil microflora under continous maize cultivation. The experimental plots had been deep ploughed and planted with maize for the previous twenty-seven years. The responses of surface microbial populations to different tillage systems were studied at the process level in terms of microbial biomass, soil respiration, soil organic carbon and phosphatase activity at the end of the second year after introduction of the alternative tillage systems. The mineralization index and qCO_2 were inferred from the other paramenters.

MATERIALS AND METHODS

Soil and treatments

The study was conducted at the Fagna Agricultural Experimental Centre (Scarperia-Firenze) of the Research Institute for Soil Study and Conservation (Firenze, Italy) on a loam soil (Table 1), classified as Typic Udifluvent (USDA, 1985). The climate is temperate with dry summers and autumns. The experiment, which began in 1994, consisted of three replications of each of four tillage treatments. Each plot was 10 m × 50 m. The following tillage systems were used: minimum tillage, harrowing with a disk harrow to a depth of 10 cm (MT); shallow tillage, mouldboard ploughing to a depth of 20 cm (SP); ripper subsoiling 50 cm deep (RS); conventional deep tillage, mouldboard ploughing to a depth of 40 cm (DP).

It is important to mention the background of

Table 1. Physical and chemical characteristics of the soil.

Gravel	5	%
Sand (mm 2 ÷ 0.05)	45	%
Silt (mm 0.05 ÷ 0.002)	38	%
Clay (< 0.002 mm)	17	%
pH	7.8	
Total $CaCO_3$	6	%
Organic Matter	1.8	%
Total K_2O	1.5	%
Exchangeable K_2O	100	ppm
Total P_2O_5	1.3	%
Ass. P_2O_5	65	ppm
Total N	0.12	%

this particular soil. Since 1970, the land has been cultivated with maize crops adopting the same traditional management practices. Since 1980, there has been only mineral fertilization with no addition of farmyard manure or other organic materials.

Three soil samples were collected from each plot at depths of 0-15 cm. The soil was sieved at 2 mm and kept at 5 °C; the experiments were carried out over a period of one week. This article reports the results of the second year after the introduction of the alternative tillage systems.

Soil respiration, biomass-C and metabolic quotient qCO_2

The respiratory activity was determined after harvest before the soil was prepared for the next crop, by Edwards' method (Edwards, 1982) which was modified as follows: the soil samples were divided into 3 subsamples of 100 g, adjusted to 50% of water holding capacity (WHC), incubated at 25 °C in 1 l flasks, in the presence of soda lime pellets. The soda lime was substituted twice in 10 days. The evolved CO2, as CO2-C, was measured by the gravimetric method and expressed as mg CO2 kg-1 dry soil 24 h-1.

Microbial Biomass C (MBC) was estimated with the fumigation-incubation (FI) method using the following equation (Jenkinson and Powlson, 1976):

$$BC = \frac{Fc}{kc}$$

where *Fc* is CO_2-C (evolved from fumigated soil during the 0-10 days incubation period) minus CO_2-C (evolved from non-fumigated soil during the same incubation period) and *kc* is 0.45 (Anderson and Domsch, 1978; Jenkinson, 1988; Wu et al., 1996; Martens, 1995). The biomass was expressed in mg C kg^{-1} of dry soil.

The qCO_2 was inferred from the ratio between CO_2-C and biomass-C as reported by Anderson and Domsch (1985 and 1986).

Organic carbon and mineralization index

The Organic C content (OC) was evaluated by oxidation with the method described by Yeomans and Bremner (1988), using a Mettler automatic titrator.

The mineralization index was calculated from the ratio between respiratory CO_2-C and total organic carbon content (Dommergues,1960).

Phosphatase activity

Phosphatase activities in the soil were assayed by spectrophotometer using the Tabatabai and Bremner method (Tabatabai and Bremner, 1969) which involves the determination of p-nitrophenolphosphate released by incubation at 37 °C for 1 h of 1 g of soil with universal buffer. The method makes it possible to study the activity of phosphomonoesterases (acid and alkaline phosphatases), phosphodiesterase, and phosphotriesterase in soils.

Statistical analysis

The results were statistically tested by one way completely randomised analysis of variance (ANOVA) and the means were compared employing Duncan's multiple range test. The results of the statistical analysis are summarized in tables 2 and 3.

RESULTS AND DISCUSSION

Soil respiration, microbial biomass and qCO_2

Respirometry values at depths of 0-15 cm were significantly ($P < 0.001$) higher in plots under MT compared with the other tillage treatments (Table 3). This might be due to the reduced disturbance of the soil in this tillage system, in comparison with others used in the experiment, in particular, the deep ploughing method.

Table 2. One way ANOVA randomised complete blocks among the different tillage systems.

Variable	Mean square	F	Significance level
Respirometry	291.15	42.34	0.0002 ***
Biomass-C	7273.06	6.24	0.0282 *
qCO_2	0.70	19.90	0.0016 **
C-organic	0.0031	2.48	0.1581 ns
Mineralization index	0.0013	15.3	0.0032 **
Phosphatase	13128.22	129.16	0.0000 ***

Significantly greater amounts of CO_2-C were released from zero tillage and reduced tillage soils than from conventionally tilled soil (Costantini et al., 1996).

For the microbial biomass-C content at depths of 0-15 cm, there were significant differences between tillage systems, with a higher content of biomass C under RS compared with the other tillage treatments (Table 3).

This might be due to the reduced disturbance of the surface soil in this tillage system, in comparison with others that were used in the experiment, in particular, the DP.

More abundant microbial biomass was observed in the superficial layers of MT corrisponding to greater accumulation of SOM in the upper part of the Ap horizon (Blevis et al., 1977; Doran, 1980; Sakamoto and Oba, 1991; Alvarez et al., 1995b).

In our experiments, even though the biomass C was lower in the MT plots than in RS plots, the respiratory activity was the highest. This indicates that the soil biomass, in the surface layer, has a more active metabolism under minimum tillage as also shown by the metabolic quotient (Table 3).

Organic C and carbon mineralization

The values of organic content at depths of 0-15 cm were not significantly different among the four tillage treatments (Tables 2 and 3). The experimental plots have been cultivated with continuous maize with conventional ploughing for 27 years. In the last 15 years no organic matter has been added (except maize residues). Consequently it is reasonable to expect no tillage effects on SOM contents after two years of treatment.

Angers et al. (1995), under maize production for 11 years, found that maize-derived C was evenly distributed with depth in the mouldboard plough treatment and accumulated at the surface in the shallow, reduced-tillage treatments, but had no detectable effect on SOM turnover and on the fate of maize residues when the whole Ap horizon (0-24 cm) was considered.

The mineralization index was also significantly higher in the MT plots (Table 3) and this should be related to the abundance of crop roots, rhizosphere products and more optimal air-filled porosity.

So it is possible to presume, in agreement with Ehlers (1975) and Pagliai et al. (1996), that the reduced alteration of the soil structure, due to the reduced energy input inherent to the MT, has preserved a larger number of stable biopores and assured a better circulation of the aqueous and gaseous phases, a higher availability of nutrients and an increase in microbial metabolic activity.

According to Salinas-Garcia et al. (1997) C mineralization was highest in no-tillage and minimum tillage; at the same time, the soil where mouldboard ploughing was used, the mineralization of C is much lower. Similar results were found by Alvarez et al. (1995a) after 12 years of experiments at the soil surface and decreased rapidly with depth under no-tillage and chisel tillage.

Phosphatase activity

The activities of phosphatases were significantly different for all the tillage systems. The Duncan's test showed that the highest activity resulted as being in the MT plots with the lowest determined under DP; moreover, the activity in SP plots was higher than in RS plots (Table 3).

Differences in microbial dynamics due to management practices may also be reflected by differences in the enzyme activities of soils. A study by Dick (1984) indicated that the activities of acid and alkaline phosphatase, in the 0-7.5 cm profile, were significantly greater in soils from no-tillage plots than those from conven-

Table 3. Microbial activity and phosphatase activity under different tillage systems and relative mean Duncan's test, $P \leq 0.05$. MT: Minimum Tillage; RS: Ripper Subsoiling; SP: Shallow Ploughing; DP: Deep Ploughing.

Tillage System	Respirometry (mg CO_2·kg soil^{-1}·24h^{-1})	Microbial Biomass (MBC) (mg C·kg soil^{-1})	qCO_2 (mg C-CO_2· mg MBC^{-1}·100^{-1})	Organic C (OC) (%)	Mineralization index (mg C-CO_2· OC^{-1}·100^{-1})	Phosphatase activity (µg PNF·g soil^{-1}·h^{-1})
MT	73.70 a	579.31 b	3.47 a	1.160 a	0.17 a	495.16 a
RS	59.06 b	659.50 a	2.45 b	1.170 a	0.14 b	395.50 c
SP	51.47 c	541.56 b	2.60 b	1.107 a	0.13 b	446.33 b
DP	54.50 bc	598.40 ab	2.50 b	1.113 a	0.13 b	348.83 d

tional tillage plots. According to Deng and Tabatabai (1997) the activities of acid phosphatase, alkaline phosphatase and phosphodiesterase were significantly greater in no-tillage and chisel ploughing than those in mouldboard ploughing.

CONCLUSIONS

A comparison between different cultivation systems of maize in a single-crop system requires an analysis of the results based on periods of equal length. Superficially, the results of our studies may seem limited. However, if we take into consideration that these results refer only to the end of the second year of experiments and remember that these soils had been worked for many years using conventional tillage methods, we realize that they are quite interesting because they show that even after a short period, the microflora of the soil is significantly altered.

After two years of adopting alternative tillage systems, MT was revealed as being particularly suitable for the development of microbial metabolic activities in the soil at depths of 0-15 cm, even though it did not influence the conservation of organic matter and microbial biomass C any more than the other tillage systems.

Tillage systems do significantly modify the respiration and the mineralization index. The higher respiratory activity in the MT plots may be a consequence of a greater metabolic activity of the biomass; in other words, of a differential C use efficiency. This fact was also supported by the other metabolic parameters considered, indicating that the degradation of organic substrates in the surface layer is higher under the MT system than under the other treatments. The greater microbial activity observed at the surface layer may be due to the higher concentration of crop residues, more confined to depths of 0-10 cm and not distributed in the soil profile as occurs in DP plots.

The metabolic quotient was also higher in the MT plots; this leads us to think that tillage management should also be considered among the factors of disturbance that determine an elevation of qCO_2, like rewetting of dry soil, herbicide application, acidification and substrate addition (Wardle and Ghani, 1995).

The increase in the phosphatase activity in the plots with reduced tillage, attributed to improved conditions that are created by the microflora, clearly indicates the likelihood of reducing the chemical and energy inputs without altering the fertility of the soil.

In conclusion, the MT regime in this particular soil, seems to be a good alternative to conventional ploughing, in accordance with the sustainable agricultural policy, as it supports a higher microbial soil metabolic activity.

REFERENCES

Alvarez R., Diaz R.A., Barbero N., Santanatoglia O.J., Blotta L., 1995a. Soil organic carbon, microbial biomass and CO_2-C production from three tillage systems. Soil Tillage Res., 33, 17-28.

Alvarez R., Santanatoglia O.J., García R., 1995b. Soil respiration and carbon inputs from crops in a wheat-soybean rotation under different tillage systems. Soil Use Manag., 11, 45-50.

Anderson J.P.E., Domsch K.H., 1978. Mineralization of bacteria and fungi in chloroform-fumigated soils. Soil Biol. Biochem., 10, 207-213.

Anderson T.-H., Domsch K.H., 1985. Determination of eco-physiological maintenance requirements of soil microorganisms in a dormant state. Biol. Fertil. Soils, 1, 81-89.

Anderson T.-H., Domsch K.H., 1986. Carbon assimilation and microbial activity in soil. Z. Pflanzenernaehr. Bodenk., 149, 457-468.

Anderson T.-H., Domsch K.H., 1989. Rations of microbial biomass carbon to total organic carbon in arable soils. Soil Biol. Biochem., 21, 471- 479.

Anderson T.-H., Domsch K.H., 1990. Application of eco-physiological quotients (qCO_2 and qD) on microbial biomasses from soil of different cropping histories. Soil Biol. Biochem., 22, 251-255.

Angers D.A., N'Dayegamiye A., Côté D., 1993. Tillage-induced differences in organic matter of particle-size fractions and microbial biomass. Soil Sci. Soc. Am. J., 57, 512-516.

Angers D.A., Voroney R.P., Côté D., 1995. Dynamics of soil organic matter and corn residues affected by tillage practices. Soil Sci. Soc. Am. J., 59, 1311-1315.

Blevis R.L., Thomas G.W., Cornelius P.L., 1977. Influence of no-tillage and nitrogen fertilization on certain soil properties after five years of continuous corn. Agron. J., 69, 383-386.

Brookes P.C., 1995. Le proprietà microbiologiche come potenziali indicatori del monitoraggio dell'inquinamento del suolo. Bollettino S.I.S.S., 6, 89-122.

Campbell C.A., McConkey B.G., Zentner R.P., Selles F., Curtin D., 1996. Tillage and crop rotation effects on soil organic C and N in a coarse-textured Typic Haploboroll in southwestern Saskatchewan. Soil Tillage Res., 37, 3-14.

Carter M.R., 1986. Microbial biomass as an index for tillage-induced changes in soil biological properties. Soil Tillage Res., 7, 29-40.

Ceccherini M.T., Castaldini M., Azzini A., Piovanelli C., Bazzicalupo M., Miclaus N., 1996. Effects of swine manure fertilization on the biodiversity of the soil microbial community. Atti Società Italiana di Ecologia, 17, 235-238.

Costantini A., Cosentino D., Segat A., 1996. Influence of tillage systems on biological properties of a Typic Argiudoll soil under continuous maize in central Argentina. Soil Tillage Res., 38, 265-271.

Deng S.P., Tabatabai M.A., 1997. Effect of tillage and residue management on enzyme activities in soils: III. Phosphatases and arylsulfatase. Biol. Fertil. Soils, 24, 141-146.

Dick W.A., 1984. Influence of long-term tillage and crop rotation combinations on soil enzyme activities. Soil Sci. Soc. Am. J., 48, 569-574.

Dommergues Y., 1960. La notion de coefficent de mineralisation du carbone dans le sols. L'Agronomie Tropical, XV, 1, 54-60.

Doran J.W., 1980. Soil microbial and biochemical changes associated with reduced tillage. Soil Sci. Soc. Am. J., 44, 765-771.

Edwards N.T., 1982. The use of soda-lime for measuring respiration rates in terrestrial systems. Pedobiologia, 23, 321-330.

Ehlers W., 1975. Observations on earthworms channels and infiltration on tilled and untilled loess soil. Soil Sci., 119, 242-249.

Florenzano G., 1983. Fondamenti di microbiologia del terreno. REDA, Roma.

Franzluebbers A.J., Zuberer D.A., Hons F.M., 1995. Comparison of microbiological methods for evaluating quality and fertility of soil. Biol. Fertil. Soils, 19, 135-140.

Jenkinson D.S., 1988. The determination of microbial biomass carbon and nitrogen in soil. In: Wilson J. R. (ed.): Advances in Nitrogen Cycling in Agricultural Ecosystems, 368-386. CAB International, Wallingford.

Jenkinson D.S., Ladd J.N., 1981. Microbial biomass in soil: measurement and turnover. In: Paul E.A., Ladd J.N. (eds.): Soil Biochemistry, Vol. 5, 415-471. Marcel Dekker, New York.

Jenkinson D.S., Powlson D.S., 1976. The effects of biocidal treatment on metabolism in soil. V. A method for measuring soil biomass. Soil Biol. Biochem., 8, 209-213.

Kern J.J., Johnson M.G., 1993. Conservation tillage impacts on national and atmospheric carbon levels. Soil Sci. Soc. Am. J., 57, 200-210.

Martens R., 1995. Current methods for measuring microbial biomass C in soil: Potentials and limitations. Biol. Fertil. Soils, 19, 87-99.

Nannipieri P., Landi L., Badalucco L., 1995. La capacità metabolica e la qualità del suolo. Riv. di Agron., 29, 3 Suppl., 312-316.

Pagliai M., Barbafieri M., Benetti A., 1996. Riflessi dei sistemi colturali sulle caratteristiche fisiche del terreno. In: Bonari E., Pagliai M. (eds.): Sistemi colturali alternativi in maiscoltura, 89-107. S.T.A.R.-CNR, Pisa.

Powlson D.S., Brookes P.C., Christensen B.T., 1987. Measurement of microbial biomass provides an early indication of changes in total soil organic matter due to the straw incorporation. Soil Biol. Biochem., 19, 159-164.

Sakamoto K., Oba Y., 1991. Relationship between the amount of organic material applied and soil biomass content. Soil Sci. Plant Nutr., 37, 387-397.

Salinas-Garcia J.R., Hons F.M., Matocha J.E., 1997. Soil carbon and nitrogen dynamics as affected by long-term tillage and nitrogen fertilization. Biol. Fertil. Soils, 25, 182-188.

Schnürer J., Clarholm M., Rosswall T., 1985. Microbial biomass and activity in an agricultural soil with different organic matter contents. Soil Biol. Biochem., 17, 611-618.

Tabatabai M.A., Bremner J.M., 1969. Use of p-nitrophenylphosphate for assay of soil phosphatase activity. Soil Biol. Biochem., 1, 301-307.

USDA (United States Department of Agriculture), 1985. Keys to Soil Taxonomy. Management support service. Tech. Monogr. No. 6, USDA, Cornell University, Ithaca, NY.

Wardle D.A., Ghani, A., 1995. A critique of the microbial metabolic quotient ($q\mathrm{CO}_2$) as a bioindicator of disturbance and ecosystem development. Soil Biol. Biochem., 12, 1601-1610.

Whalley W.R., Dumitru E., Dexter A.R., 1995. Biological effects of soil compaction. Soil Tillage Res., 35, 53-68.

Wu J., Brookes P.C., Jenkinson D.S., 1996. Evidence for the use of a control in the fumigation-incubation method for measuring microbial biomass carbon in soil. Soil Biol. Biochem. 28, 4/5, 511-518.

Yeomans J.C., Bremner J.M., 1988. Organic carbon, modified Mebius procedure. Commun. Soil Sci. Plant Anal., 19, 1467-1476.

IMPATTO DELLE LAVORAZIONI SULLA QUALITA' DEL SUOLO. II. PROPRIETA' BIOLOGICHE NELLO STRATO SUPERFICIALE DEL SUOLO.

SOMMARIO

SCOPO. Scopo del nostro lavoro è studiare la risposta delle popolazioni microbiche a quattro differenti lavorazioni del terreno (lavorazione minima MT, aratura superficiale SP, rippatura profonda RS e aratura convenzionale DP), in una monocoltura di mais attuata su un suolo di medio impasto classificato come Typic Udifluvent.

METODI. L'attività respiratoria è stata determinata incubando i terreni a 25 °C in presenza di calce sodata in granuli. La biomassa del suolo (SMBC) è stata stimata usando il metodo della fumigazione con cloroformio e successiva incubazione. Per la determinazione del C organico (OC) ci si è avvalsi di un titolatore automatico Mettler. Da questi dati è stato calcolato l'indice di mineralizzazione (rapporto percentuale fra C della respirazione e C organico) e il quoziente metabolico qCO_2 (rapporto percentuale fra C della respirazione e C della biomassa). L'attività fosfatasica è stata determinata per incubazione del terreno in presenza di p-nitrofenilfosfato.

RISULTATI. I risultati del presente lavoro si riferiscono ad analisi effettuate due anni dopo l'inizio della prova su campioni di terreno prelevati alla profondità di 0-15 cm. Nella lavorazione minima l'attività respiratoria, il quoziente metabolico, l'indice di mineralizzazione e l'attività fosfatasica sono più alti che nelle parcelle con gli altri tipi di lavorazione, mentre il più alto valore della biomassa si rileva nelle parcelle lavorate con rippatura profonda. Evidentemente la maggior concentrazione di residui vegetali nello strato superficiale e la ridotta alterazione della struttura del suolo, nel caso della lavorazione minima, determinano migliori condizioni per l'espletarsi delle attività metaboliche dei microrganismi.

CONCLUSIONI. Dopo due anni dall'introduzione di sistemi di lavorazione del terreno alternativi all'aratura convenzionale, la lavorazione minima si rivela particolarmente favorevole per l'incremento delle attività metaboliche dei microrganismi nello strato 0-15 cm di profondità del terreno, anche se non influenza più delle altre lavorazioni il contenuto di sostanza organica e la biomassa.

Parole chiave: lavorazioni del terreno; respirazione; biomassa; qCO_2; C-organico; attività fosfatasica.