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Soil structure and the effect of management practices

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Abstract

To evaluate the impact of management practices on the soil environment, it is necessary to quantify the modifications to the soil structure. Soil structure conditions were evaluated by characterizing porosity using a combination of mercury intrusion porosimetry, image analysis and micromorphological observations. Saturated hydraulic conductivity and aggregate stability were also analysed.

In soils tilled by alternative tillage systems, like ripper subsoiling, the macroporosity was generally higher and homogeneously distributed through the profile while the conventional tillage systems, like the mouldboard ploughing, showed a significant reduction of porosity both in the surface layer (0–100 mm) and at the lower cultivation depth (400–500 mm). The higher macroporosity in soils under alternative tillage systems was due to a larger number of elongated transmission pores. Also, the microporosity within the aggregates, measured by mercury intrusion porosimetry, increased in the soil tilled by ripper subsoiling and disc harrow (minimum tillage). The resulting soil structure was more open and more homogeneous, thus allowing better water movement, as confirmed by the higher hydraulic conductivity in the soil tilled by ripper subsoiling. Aggregates were less stable in ploughed soils and this resulted in a more pronounced tendency to form surface crust compared with soils under minimum tillage and ripper subsoiling.

The application of compost and manure improved the soil porosity and the soil aggregation. A better aggregation indicated that the addition of organic materials plays an important role in preventing soil crust formation.

These results confirm that it is possible to adopt alternative tillage systems to prevent soil physical degradation and that the application of organic materials is essential to improve the soil structure quality.

Keywords: Soil structure; Soil tillage; Soil compaction; Soil crusting; Soil thin sections; Image analysis

1. Introduction

Soil degradation is a major environmental problem worldwide, and there is strong evidence that the soil degradation processes present an immediate threat to both biomass and economic yields, as well as a long-term hazard to future crop yields. Therefore, it is absolutely necessary that such soil degradation processes must be put under control. 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

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farmers to consider the possibility of adopting lower impact cultivation practices as an alternative to conventional farming (Cannell and Hawes, 1994). This is to overcome the negative effect that abandoning traditional farming rotations and adopting intensive monocultures, without application of farmyard manure to the soil, have had on diminished soil organic matter content and consequently soil structural stability (Lal et al., 1994). 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 of surface water pollution. Moreover, the resulting soil porosity conditions are often unfavourable to crop growth (Pagliai et al., 1995).

To evaluate the impact of management practices on the soil environment it is necessary to quantify the modifications to the soil structure (Danielson and Sutherland, 1986). Soil structure is one of the most important properties affecting crop production because it determines the depth that roots can penetrate, the amount of water that can be stored in the soil and the movement of air, water and soil fauna (Hermavan and Cameron, 1993; Langmaack, 1999). Soil quality is strictly related to soil structure and much of the environmental damage in intensive arable lands such as erosion, desertification and susceptibility to compaction, originate from soil structure degradation. Moreover, soil functions strongly depend on the quality of soil structure, with optimum structure defined as soil having the widest range of possible uses (Dexter, 2002). 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. Pore space measurements quantify soil structure because the size, shape and continuity of pores affect many important processes in soils (Ringrose-Voase and Bullock, 1984).

A detailed insight into the complexity of the pore system in soil can be obtained by using mercury intrusion porosimetry to quantify pores less than 50 μm (equivalent pore diameter) inside the soil aggregates (Fiès, 1992), and image analysis on thin sections prepared from undisturbed soil samples to quantify pores larger than 50 μm, i.e. macropores, which determine the type of soil structure. Technological and theoretical advances in sample preparation and image analysis have improved the methods for direct quantification of soil pores (Moran and McBratney, 1992). By three-dimensional analysis of the soil pore system it is now possible to gain quantitative information about important parameters, such as pore connectivity and tortuosity, affecting in particular the preferential flow of soil water (funnel and fingered flow). This can be obtained by stereology (Ringrose-Voase, 1996) and serial sectioning (Vogel, 1997); however, both these methodologies are time consuming. More advanced, non-destructive image analysis techniques are the X-ray computed tomography (Zeng et al., 1996) and the Synchrotron (Di Carlo et al., 1997), both permitting a detailed insight of the spatial pores arrangement and the study of the associated water movement. All these methods allow the quantification of the effects of different management systems on soil porosity and structure and in turn, the identification of the best practices for sustainable crop production.

Results of field experiments frequently recommend the adoption of reduced tillage practices to prevent soil structural degradation and soil losses by erosion, thereby reducing consequent environmental impacts (Unger et al., 1991; Gomez et al., 1999). Soil structure degradation following intensive agricultural activities, soil compaction, loss of structural stability and the formation of surface crusts give rise to the loss of continuity of elongated transmission pores, which reduces water transport, resulting in increased runoff and soil erosion. Until now, pore structure has not been adequately quantified and sufficiently considered in models for soil erosion prediction, land management optimisation and environmental impact.

The aim of this study was to evaluate and summarize the effects of different types of management practices, namely tillage and manure application, on soil structural characteristics. We quantified soil porosity by mercury intrusion porosimetry and image analysis on soil thin sections and some related physical properties, like hydraulic conductivity and aggregate stability on soils, representative of the hilly environment of central Italy and of the plains of northern Italy, under different types of tillage and manure application, cultivated by maize and sorghum.

2. Materials and methods

2.1. Soils and treatments

2.1.1. Soil tillage

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). It is on a loam soil classified as Typic Haplustept (USDA-NRCS, 1999) or Lamellic Calcaric Cambisol (FAO-IUSS-ISRIC, 1998). Some major characteristics of the soil are reported in Table 1. Three replicates of each of four management practices were tested in 50 m × 10 m plots. The tillage treatments considered were: (1) harrowing with a disc harrow to a depth of 100 mm (minimum tillage, MT); (2) mouldboard ploughing to a depth of 400 mm (conventional deep tillage, CP); and (3) ripper subsoiling to a depth of 500 mm (RS).

The soil had been cropped with maize since 1970 adopting the same traditional management practices. Since 1980, the fertilisation was mineral alone without any addition of farmyard manure or other organic materials.

2.1.2. Applications of manures

This field experiment was located in the alluvial plain of the Taro river, near Parma (Emilia-Romagna, northern Italy). The soil is classified as Udifluventic Ustochrepts (USDA-NRCS, 1999) or as Haplic Calcisol (FAO-IUSS-ISRIC, 1998). The main characteristics of the soil are shown in Table 1. The field was planted with grain sorghum (*Sorghum bicolor* (L.) Moench), and four replications of each of four treatments were tested in 55 m × 5.5 m plots arranged in a randomised block design as follows: (1) compost addition at 40 Mg ha^{-1} rate (high rate); (2) compost addition at 10 Mg ha^{-1} rate (low rate); (3) livestock manure at 10 Mg ha^{-1} rate; and (4) control.

Table 1
Main physical and chemical characteristics of the two soils

Main soils characteristics	Cambisol	Calcisol
Sand (g kg^{-1})	400	148
Silt (g kg^{-1})	422	587
Clay (g kg^{-1})	178	265
CEC (me/100 g)	14.6	20.5
pH (1:2.5) H_2O	8.1	8.0
Organic matter (%)	1.4	2.1
$CaCO_3$ (%)	5.2	15.0
Total N (Kjieldahl) (g kg^{-1})	1.1	1.25
C/N	7.4	9.6

Mean values for 0–350 and 0–200 mm layer for the Cambisol and the Calcisol, respectively.

Compost and manure were applied in September 2001 when the experiment was established. The field was then ploughed to 300 mm depth in October 2001, and harrowed for seedbed preparation in the middle of March 2002; sowing was carried out at the beginning of May 2002. Samples were taken, in one block only, six weeks after sowing and at the end of the summer season, during which the more intense rainstorms occur. Rainfall depth in this time span was 412 mm.

2.2. Soil 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 image analysis, six replicate undisturbed samples were collected at 100-mm increments between 0 and 600 mm in each plot under different tillage systems at the ripening time of the maize. In the soil under manure application, six replicate undisturbed samples were taken in the surface layer (0–100 mm) two months after seedbed preparation and at the end of the grain sorghum-growing season.

Samples were dried by acetone replacement of water (Murphy, 1986), impregnated with a polyester resin and made into 60 mm × 70 mm, vertically oriented thin sections of 30 μm thickness (Murphy, 1986). IMAGE PRO-PLUS software produced by Media Cybernetics (Silver Spring, MD, USA) calculated pore structure features from digital images of the thin sections, using the approach described by Pagliai et al. (1984). The analysed image covered 45 mm × 55 mm of the thin section, avoiding the edges where disruption can occur. Total porosity and pore distribution were measured according to pore shape and size, the instrument being set to measure pores larger than 50 μm. Pore shape was expressed by a shape factor [perimeter^2/(4π × area)] so that pores could be divided into regular (more or less rounded) (shape factor 1–2), irregular (shape factor 2–5) and elongated (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 their equivalent pore diameter (regular and irregular pores), or their width (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, i.e. to gain a qualitative assessment of the structure.

For mercury intrusion porosimetry, in each plot under different tillage systems, six undisturbed samples were collected from the surface soil layer (0–100 mm) 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 are determined within the range 0.007–50 μm.

2.3. Saturated hydraulic conductivity

To measure saturated hydraulic conductivity, six undisturbed cores (57 mm diameter and 95 mm high) were collected at 100-mm increments between 0 and 600 mm in each plot under different tillage systems, in areas adjacent to those sampled for thin section preparation. The samples were slowly saturated and the saturated hydraulic conductivity was measured using the falling-head technique (Klute and Dirksen, 1986).

2.4. Aggregate stability

To determine the water stability of soil aggregates a wet-sieving method was used (Pagliai et al., 1997). Air-dried soil aggregates (1–2 mm), collected in the surface layer (0–100 mm) of the plots under different tillage systems, were placed on a 0.25 mm mesh sieve and moistened by capillary rise from a layer of wet sand. They were then immersed in de-ionised water and shaken with an alternate vertical movement (30 times per minute) at room temperature. The water stability index (WSI) was calculated as $(B - C)/((A \times k) - C) \times 100$, where A is the mass of air-dried soil aggregates, B is the oven-dry mass of aggregates remained in the sieve, C is the mass of sand fraction and k is the correction factor for soil moisture content (k = mass of oven-dry aggregates divided by the mass of air-dry aggregates). Each determination was made at least in triplicate.

3. Results and discussion

3.1. Soil tillage

In comparison with continuous conventional ploughing, alternative tillage systems, like minimum tillage, ripper subsoiling, etc., improve the soil pore system, increasing the storage pores (0.5–50 μm) and the amount of the elongated transmission pores (50–500 μm). The volume of storage pores (0.5–50 μm) measured by mercury intrusion porosimetry inside the aggregates was greater in ripper subsoiling and minimum tillage treatment than in conventional ploughing treatment (Fig. 1). The higher microporosity in ripper and minimum tillage soils could be related to an increase of water content in soil and consequently, to an increase of available water for plants (Pagliai et al., 1995, 1998a).

Fig. 2 shows the total porosity occupied by pores larger than 50 μm, expressed as percentage of total area of thin section. In the surface layer (0–100 mm) of conventionally tilled soil the macroporosity (pores >50 μm) was significantly lower than in soils under minimum tillage or ripper subsoiling. The ripped soil showed the highest macroporosity, which was homogeneously distributed along the cultivated profile. It is important to stress that the lowest value of total macroporosity was found in the 400–500 mm layer of conventionally tilled soils.

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 (pores larger than 50 μm) 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).

For a thorough characterisation 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 affect plant growth directly by easing root penetration, and increasing the storage and transmis-

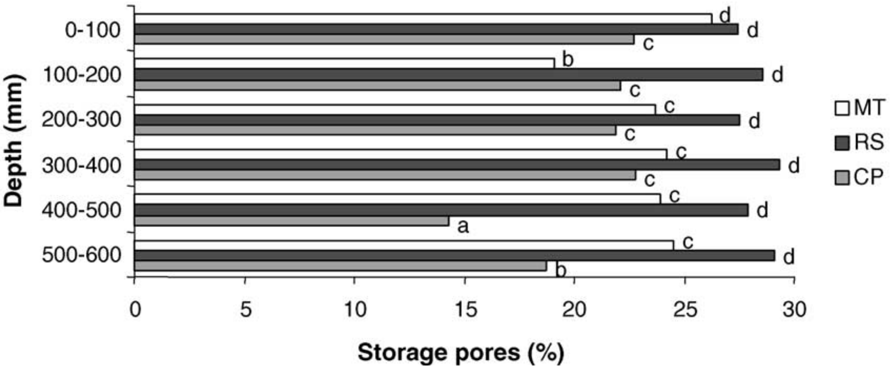

Fig. 1. Effects of tillage systems on storage pores inside the aggregates measured by mercury intrusion porosimetry along the soil profile (MT, minimum tillage; RS, ripper subsoiling; CP, conventional deep ploughing). Values differ significantly when followed by different letters at $P \leq 0.05$ employing the Duncan's multiple range test.

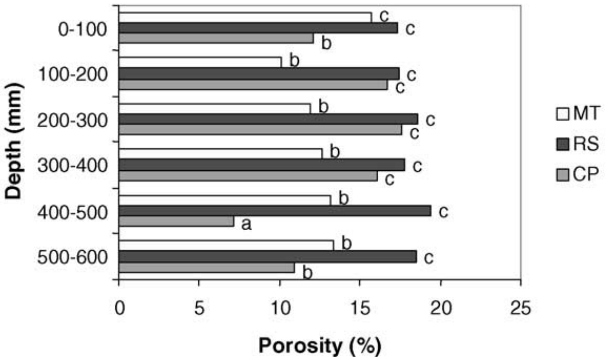

Fig. 2. Effects of tillage systems on total macroporosity distribution along soil profile expressed as a percentage of total area occupied by pores larger than 50 μm per thin section (MT, minimum tillage; RS, ripper subsoiling; CP, conventional deep ploughing). Macropore values differ significantly when followed by different letters at $P \leq 0.05$ employing the Duncan's multiple range test.

sion of water and gases. Moreover, Russell (1978) and Tippkötter (1983) noted that 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 microorganisms. 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 recognised by a decrease in the proportion of transmission pores.

Mean values of elongated transmission pores, expressed as the percentage of total area of the thin section occupied by these pores, are reported in Fig. 3. Results showed that in the surface layer (0–100 mm)

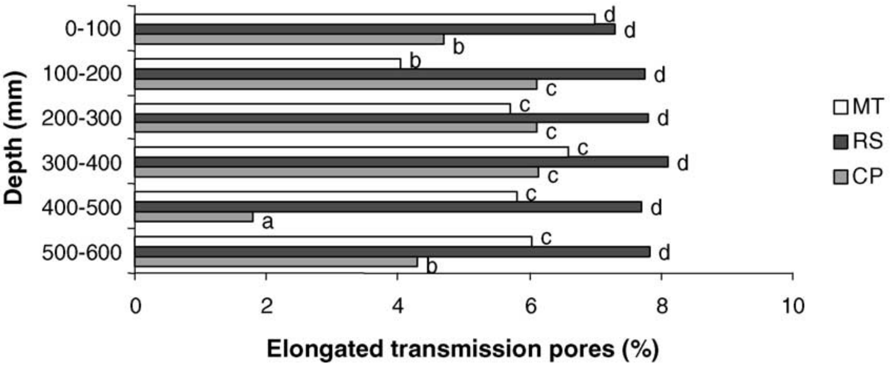

Fig. 3. Effects of tillage systems on elongated transmission pore distribution along soil profile expressed as a percentage of total area occupied by pores ranging from 50–500 μm per thin section (MT, minimum tillage; RS, ripper subsoiling; CP, conventional deep ploughing). Elongated transmission pore values differ significantly when followed by different letters at $P \leq 0.05$ employing the Duncan's multiple range test.

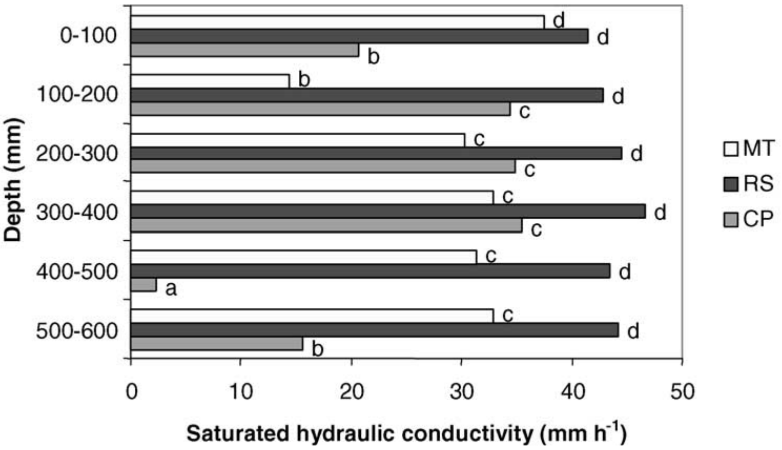

Fig. 4. Effects of tillage systems on saturated hydraulic conductivity distribution along soil profile (MT, minimum tillage; RS, ripper subsoiling; CP, conventional deep ploughing). Hydraulic conductivity values differ significantly when followed by different letters at $P \leq 0.05$ employing the Duncan's multiple range test.

the elongated transmission pores in the conventionally ploughed soils were significantly lower than in the soils under minimum tillage and ripper subsoiling, as was the case for total macroporosity. The micromorphological observations revealed a more developed surface crust in conventionally tilled soils that may cause the decrease of soil porosity. In the 100–200 mm layer in the minimally tilled soils, the elongated transmission pores were significantly lower than in soil under the other tillage systems, indicating a more compact soil structure. In the 400–500 mm layer of soil ploughed to a depth of 400 mm (conventional ploughing), the elongated transmission pores strongly decreased, thus indicating that the structure became rather compact (massive) and a ploughpan at the lower limit of cultivation was well developed. These data also indicated that in this type of soil the differences in total macroporosity can be ascribed to the differences of elongated transmission pores, while the regular and irregular pores did not show significant changes following different types of tillage.

The values of saturated hydraulic conductivity along the cultivated profile are reported in Fig. 4 and showed the same trend of the elongated transmission pores (Fig. 3), as confirmed by significant ($P \leq 0.05$) correlation coefficients of 0.98, 0.93 and 0.96 for conventional ploughing, ripper subsoiling and minimum tillage, respectively (Pagliai et al., 1998b). The resulting soil structure of alternative tillage systems is more open and more homogeneous, thus allowing greater water movement, as confirmed by the higher values of hydraulic conductivity measured in soils under minimum tillage and ripper subsoiling (Pagliai et al., 2000).

The continuous conventional tillage, moreover, caused a decrease of soil organic matter content that was associated to a decrease of aggregate stability (Fig. 5), consequently leading to the formation of surface crusts (Fig. 6).

Surface crusts are a dangerous aspect of soil degradation; they are formed mainly by raindrop impact, which causes the mechanical destruction of soil aggregates, so reducing seedling emergence, soil–atmosphere gas exchange, water infiltration and in-

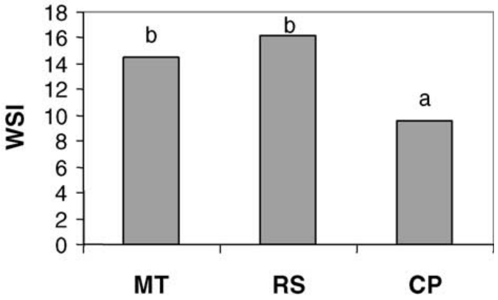

Fig. 5. Effects of tillage systems on aggregate stability in the surface layer (0–100 mm) (MT, minimum tillage; RS, ripper subsoiling; CP, conventional deep ploughing). Values differ significantly ($P \leq 0.05$) when followed by different letters employing the Duncan's multiple range test.

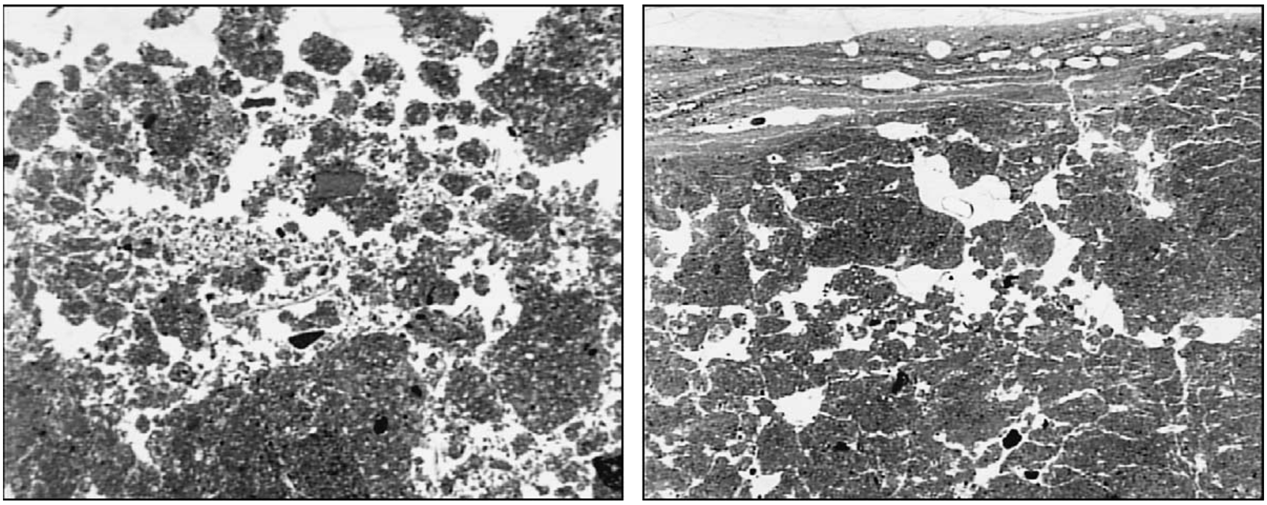

Fig. 6. Macrophotographs of vertically oriented thin sections prepared from undisturbed samples from the surface layer (0–100 mm) of soil tilled by continuous deep ploughing (left) and the same soil after raindrop impact (right). Surface crust formation is very evident. Frame length 35 mm × 28 mm.

creasing surface runoff (Sumner and Stewart, 1992). The particles dispersed by water form a compact layer of horizontally oriented plate-like particles at the soil surface during drying. This compact layer contains few large pores that provide continuous, vertical transmission pathways that conduct water. Surface crusts are much more developed in intensively cultivated soils with low organic matter content where the surface aggregates are less stable under rainfall (Bajracharya and Lal, 1999).

The reduction of porosity revealed in the 400–500 mm layer of the soil tilled by mouldboard ploughing (Figs. 1–3) must be regarded as another hazardous aspect of soil degradation. This compaction of the soil is caused by the shearing by tillage implements, producing a compact layer (ploughpan) formed at the lower limit of cultivation in continually ploughed soils (Fig. 7). This layer is characterised by the strong decrease of elongated transmission pores and consequently hydraulic conductivity, as shown by the relationship in Fig. 8 (Pagliai et al., 2000). The significance of subsoil compaction is underestimated, even though such a ploughpan is largely widespread in the alluvial soils of plains cultivated by monoculture. Subsoil compaction increases the frequent flooding of such areas when heavy rains are concentrated in a short time (rainstorm), because the presence of the ploughpan strongly reduces drainage. Alternative tillage practices, like ripper subsoiling, are able to avoid the formation of this compact layer. Compaction by implements receives far less attention than the more obvious impacts of wheel traffic.

Recent studies (Marsili et al., 1998; Servadio et al., 2001; Pagliai et al., 2003) have shown that the decrease of soil porosity in the compacted areas, following the passage of agricultural machineries, was strongly correlated with an increase of soil penetration resistance and a decrease in hydraulic conductivity. The formation of a platy structure seems to be a common feature in soil following compaction by traffic.

Intensive continuous cultivation is not the only cause of soil structure degradation; other management practices like irrigation are also important, especially in the longer term. Specific researches in the Po Valley (north Italy) have shown that after 10 years of impounding irrigation in clay, clay loam and sandy loam soils, the structural conditions appeared greatly changed: massive structure, modification of the pore shape and pore size distribution increased migration of clay particles from the ploughed horizon Ap to the B horizon. This confirmed the results previously obtained by Mathieu (1982) in tropical regions. These experiments conducted in a peach orchard near Verona (Italy) also showed that soil porosity of the surface layer decreased during the irrigation season and that the decrease was significantly greater when irrigation was by impounding rather than under sprinkler-

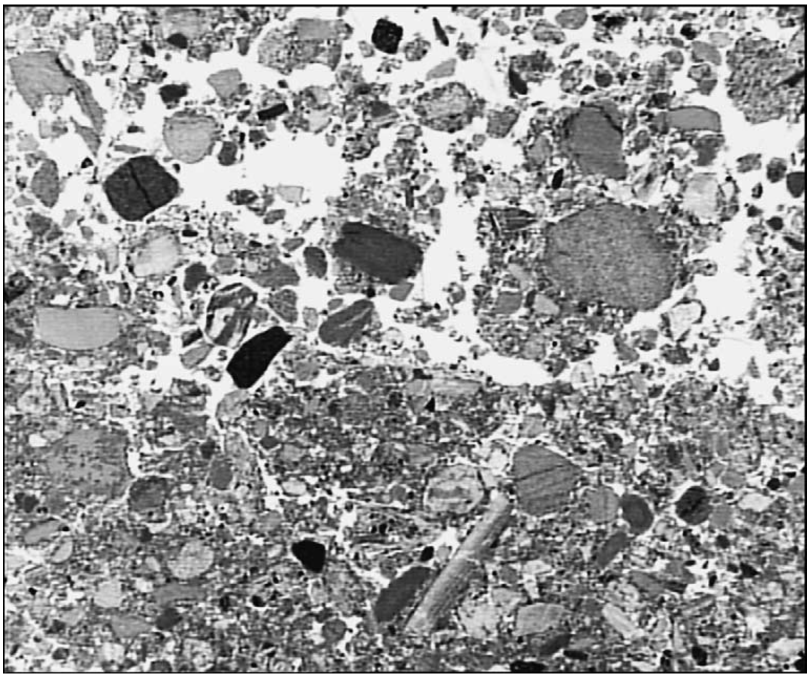

Fig. 7. Macrophotograph of a vertically oriented thin section prepared from the 400–500 mm layer of soil tilled by continuous deep ploughing. The lower limit of cultivation (ploughpan) is visible. Frame length 35 mm × 28 mm.

irrigation, due to a reduction in elongated pores (Fig. 9). The latter was associated with a lower water content in the surface soil and reduced root density (Pezzarossa et al., 1991). The larger amount of water applied with this system caused progressive soil compaction, resulting in decreased porosity and structural degradation. This caused decreased water infiltration and under these conditions, 30% of applied water was lost by run-off. It is clearly intuitive that runoff along the inter-row transported nutrients, particularly nitrogen and potassium. For example, the losses of potassium amounted to 25% of the quantity applied as fertilizer (150 kg ha^{-1} per year of K_2O) (Pagliai, 1992).

Management practices can also affect biological activity and can therefore affect both the formation and preservation of biopores, important for water movement and root development. Pagliai and De

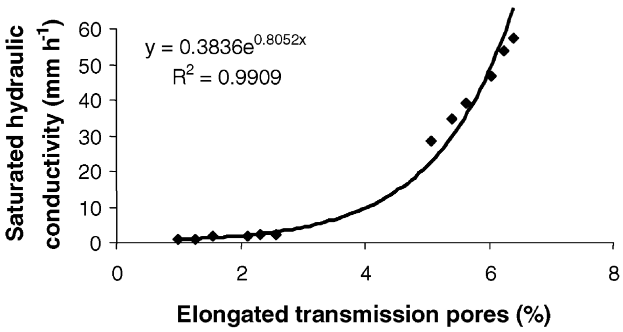

Fig. 8. Correlation between soil porosity, formed by elongated pores, and saturated hydraulic conductivity in the ploughpan (400–450 mm) (elongated pores less than 3%) and in the area just above the ploughpan (350–400 mm) (elongated pores greater than 5%) of the soil under conventional tillage.

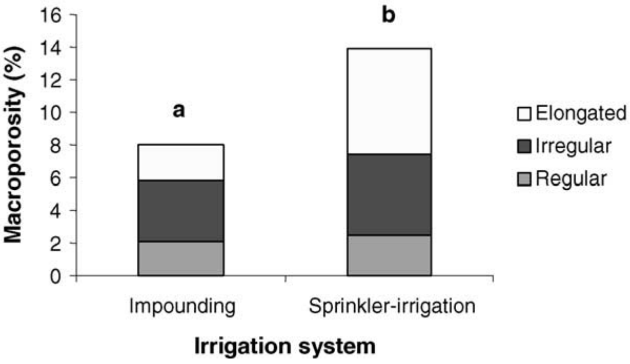

Fig. 9. Effect of two irrigation systems on soil macroporosity (>50 μm) of a peach orchard sandy loam expressed as a percentage of total area of pores per thin section; mean of six replicates. Total porosity values followed by the same letter are not significantly different at the 0.05 level as determined by Duncan's multiple range test. (Modified by Pagliai, 1992).

Nobili (1993) found a positive correlation between soil enzyme activity and the presence of pores in the range from 30 to 200 μm which were more numerous in minimally tilled soils.

3.2. Application of manures

The application of organic materials to the soil has also been shown to enhance both soil porosity and pore size distribution. Results obtained in long-term field experiments on different types of soils showed that soil pore space (microporosity and macroporosity) significantly increased after treatment with sewage sludges, composts from urban refuse, livestock effluents and the traditional farmyard manure compared with treatment with chemical fertilization alone (Pagliai and Vignozzi, 1998).

Table 2
Effect of different treatments on total and elongated macroporosity

Treatment	Total macroporosity (%)	Elongated pores (%)
Control (C)	20.96 a	11.69 a
Manure (M)	21.76 a	13.34 a
Compost 10 Mg ha^{-1} (LC)	22.05 a	14.74 a
Compost 40 Mg ha^{-1} (HC)	22.33 a	14.84 a

Values differ significantly ($P \leq 0.05$) when followed by different letters employing the Duncan's multiple range test.

These results were generally confirmed in a recent experiment in the alluvial plain of the Taro river (northern Italy). Two months after seedbed preparation, different treatments did not exhibit significant differences in total macroporosity values (Table 2).

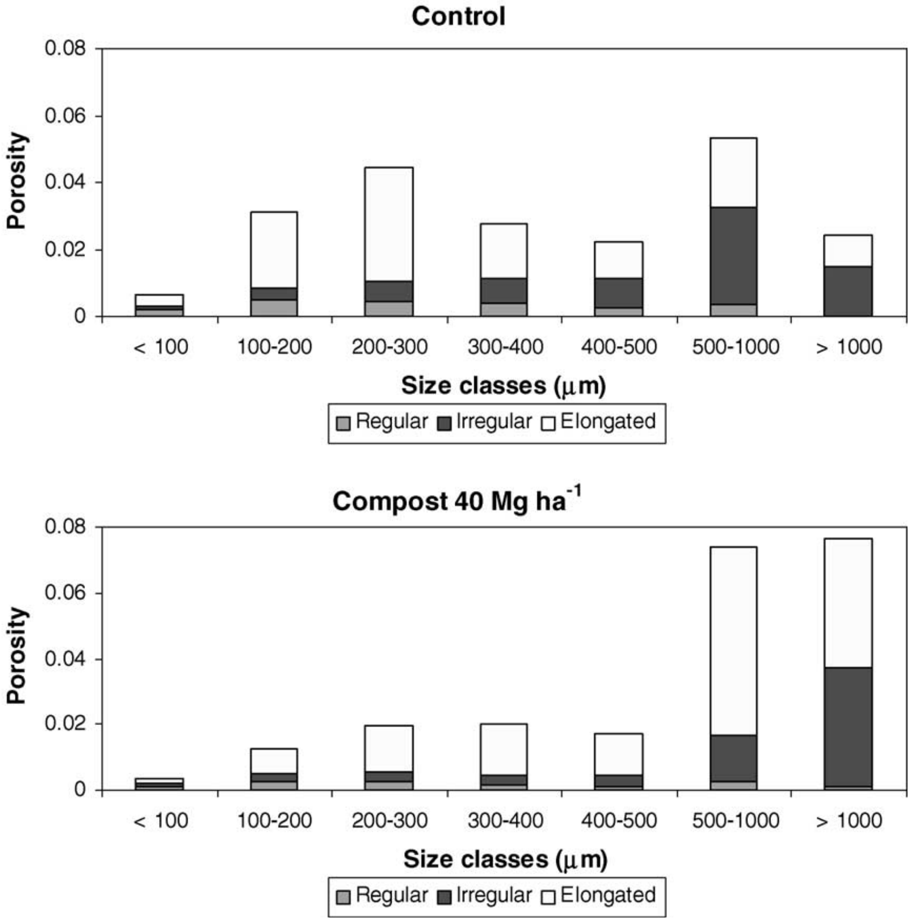

Fig. 10. Pore size distribution, expressed as equivalent pore diameter, for regular and irregular pores and width for elongated pores, in the control and in soil treated with the high rate of compost two months after seedbed preparation.

Even without a significant difference, the control always showed lower values either for total or elongated porosity when compared with amendment-added treatments.

Pore shape and size distribution analysis revealed that proportion of elongated pores in the 50–300 μm range was significantly higher in the control plot, while pores belonging to size classes >500 μm (fissures) were much more represented in high and low rate of compost and livestock manure treatments (Fig. 10). It seems that organic matter provided by manure and compost effectively reacted with soil matrix, making aggregates produced by tillage more stable. A higher percentage of pores in this size class is particularly useful for water infiltration and drainage in this fine-textured soil. Micromorphological observation showed crust formation in the control plot, thus indicating that the addition of organic material plays an important role in preventing soil crust formation (Fig. 11).

There was an evident effect of amendments at the second sampling date. Total macroporosity values are reported in Table 3. The highest percentage of macropores was observed in soils treated with livestock manure, but were not significantly different between high and low rates of compost. On the other hand, the control treatment showed the lowest porosity. The effect of various treatments on total macroporosity dynamics is quite evident between the two sampling dates. The maximum porosity decrease occurred in the control plot and to a lesser extent, in the compost-added soils irrespective to the addition rate. Livestock manure had a better effect in improving soil porosity, making the topsoil structure more stable. Dramatic macroporosity decrease in the control plot could be due to the lack of organic matter addition and to its progressive mineralization, particularly intense under the Mediterranean climatic conditions.

Table 3
Macroporosity values observed at the end of the growing season and variations respect to the previous sampling date

Treatment	Total macroporosity (%)	Porosity variation
Control (C)	8.58 b	−12.4
Manure (M)	18.16 a	−3.6
Compost 10 Mg ha^{-1} (LC)	16.17 a	−5.9
Compost 40 Mg ha^{-1} (HC)	16.70 a	−5.6

Values differ significantly ($P \leq 0.05$) when followed by different letter employing the Duncan's multiple range test.

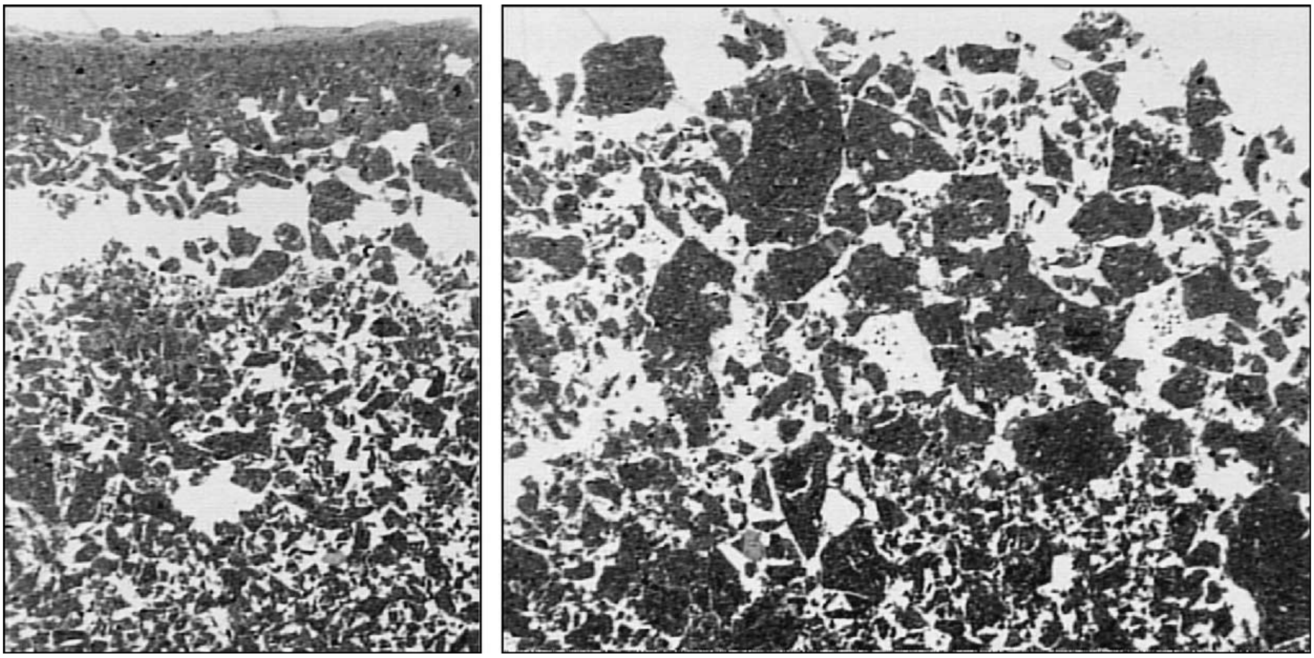

Fig. 11. Macrophotographs of vertically oriented thin sections prepared from undisturbed samples from the surface layer (0–100 mm) of the control (left) and high rate compost (right) treatments. Frame length 21 mm × 28 mm (left) and 35 mm × 28 mm (right).

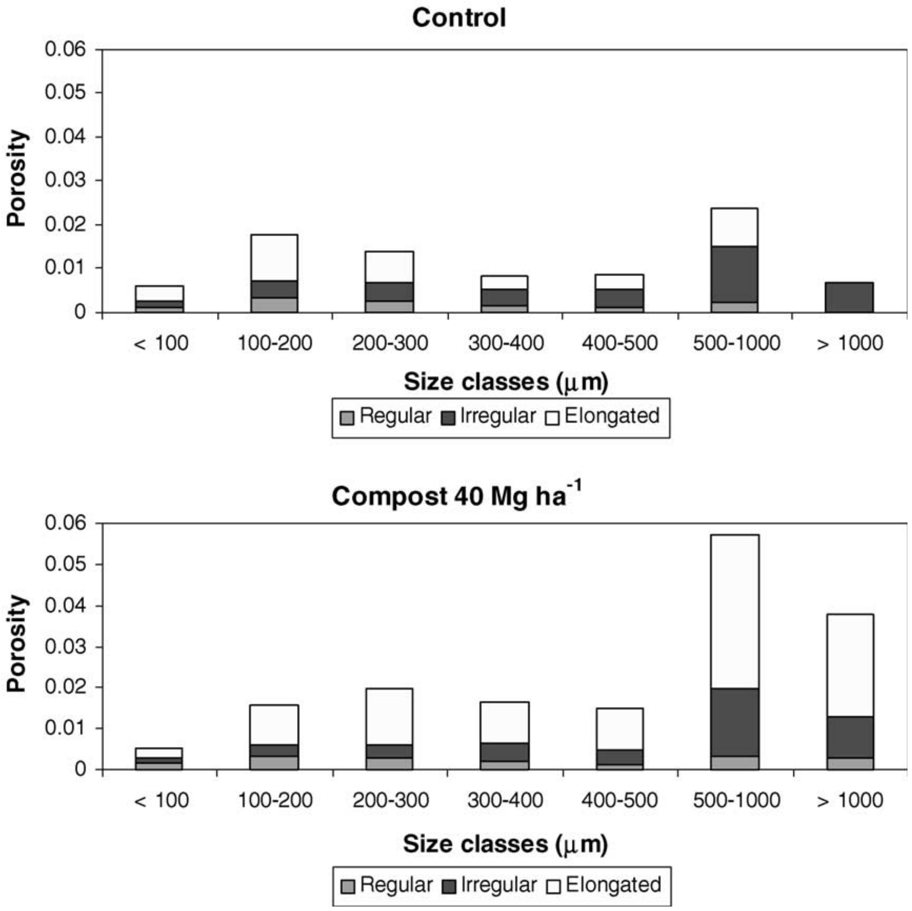

Fig. 12. Pore size distribution, expressed as equivalent pore diameter, for regular and irregular pores and width for elongated pores, in the control and in soil treated with the high rate of compost at the end of the growing season.

With regard to pore shape and size distribution, there were a significantly higher percentage of total elongated pores in amended treatments than in the control (Fig. 12). Elongated pores belonging to size classes 50–500 μm (transmission pores), important to define soil structural quality, reached the highest value in soil treated by livestock manure, but differences between high and low rates of compost addition were not significant. Moreover, in soil treated with the high rate of compost a higher occurrence of pores larger than 500 μm was observed.

4. Conclusions

The characterisation of the soil pore system gives essential indications about soil quality and vulnerability in relation to degradation events mainly connected with human activity. The quantification of the shape, size, continuity, orientation and irregularity of pores allows the prediction of the changes that can be expected following soil structural modifications induced by management practices, or following soil degradation due to compaction, formation of surface crusts, etc. It also allows the modelling of water movement and solute transport. The quantification of the damage caused by degradation processes also makes it possible to predict the risk of soil erosion.

The results of this study confirmed that conventional ploughing induced the more relevant modification of soil physical properties resulting in damage to soil structure. The negative aspects associated with this management system are the formation of surface crusts and ploughpan at the lower cultivation limit. The formation of the ploughpan and the decrease of porosity, in particular the continuous elongated pores, in the surface layers of conventionally tilled soil, besides a reduction of water movement, may also hamper root growth. Minimum tillage and ripper subsoiling could be a good alternative to conventional ploughing. The soil degradation following a decrease of soil porosity can also be induced by wheel traffic and other non-sustainable management practices, like irrigation by impounding. The combination image analysis–micromorphological observations on thin sections prepared from undisturbed soil samples allows the quantification of the above-mentioned aspects of soil degradation and can also help to explain differences in water movement and aggregate stability between different management practices.

Soil amendment with compost and livestock manure showed clear positive effects on soil structure. Compost, when applied at the same rate of manure, similarly improved soil pore system characteristics. At the end of the growing season, the control treatment exhibited the lowest total macroporosity values, probably due to a more intense mineralization of soil organic matter.

For a successful solution of problems related to sustainable soil management, agricultural production and environmental protection, knowledge of soil hydraulic functions and parameters is required. Future work should be focused on the promotion of research on soil hydraulics, soil structure and soil micromorphology in order to reach a better understanding on relationships between aggregation, *n*-modal porosity, configuration of pores and soil hydraulic properties. A detailed quantification of the size, continuity, connectivity, orientation and irregularity of pores could allow more precise modelling of soil water movement.

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References

Bajracharya, R.M., Lal, R., 1999. Land use effects on soil crusting and hydraulic response of surface crusts on a tropical Alfisol. Hydrological Process. 13 (1), 59–72.

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.

Cannell, R.Q., Hawes, J.D., 1994. Trends in tillage practices in relation to sustainable crop production with special reference to temperate climates. Soil Till. Res. 30, 245–282.

Danielson, R.E., Sutherland, P.L., 1986. Porosity. In: Klute, A. (Ed.), Methods of Soil Analysis, Part 1, second ed. Am. Soc. Agron. Publ, Madison, WI, pp. 443–460.

Dexter, A.R., 2002. Soil structure: the key to soil function. Adv. GeoEcology 35, 57–69.

Di Carlo, D.A., Bauters, T.W.J., Steenhuis, T.S., Parlange, J.Y., Bierck, B.R., 1997. High-speed measurements of three-phase flow using synchrotron X-rays. Water Resources Res. 33 (4), 569–576.

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.

FAO-IUSS-ISRIC, 1998. World Reference Base for Soil Survey. FAO report n° 84.

Gomez, J.A., Giraldez, J.V., Pastor, M., Fereres, E., 1999. Effects of tillage method on soil physical properties, infiltration and yield in an olive orchard. Soil Till. Res. 52, 167–175.

Greenland, D.J., 1977. Soil damage by intensive arable cultivation: temporary or permanent? Philos. Tran. R. Soc. Lon. 281, 193–208.

Hermavan, B., Cameron, K.C., 1993. Structural changes in a silt loam under long-term conventional or minimum tillage. Soil Till. Res. 26, 139–150.

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

Lal, R., Mahboubi, A.A., Fausey, N.R., 1994. Long-term tillage and rotation effects on properties of a central Ohio soil. Soil Sci. Soc. Am. J. 58, 517–522.

Langmaack, M., 1999. Earthworm communities in arable land influenced by tillage, compaction, and soil. Z. Ökol. Natursch 8, 11–21.

Marsili, A., Servadio, P., Pagliai, M., Vignozzi, N., 1998. Changes of some physical properties of a clay soil following the passage of rubber and metal tracked tractors. Soil Till. Res. 49, 185–199.

Mathieu, C., 1982. Effects of irrigation on the structure of heavy clay soils in north east Morocco. Soil Till. Res. 2, 311–329.

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, UK.

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

Pagliai, M., 1992. Losses of Potassium through run-off, erosion and 'slash and burn' agriculture. In: Proceedings of the 23rd IPI Colloquium, Praga, Czechoslovakia 12–16 October 1992, pp. 345–362.

Pagliai, M., De Nobili, M., 1993. Relationships between soil porosity, root development and soil enzyme activity in cultivated soils. Geoderma 56, 243–256.

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., Marsili, A., Servadio, P., Vignozzi, N., Pellegrini, S., 2003. Changes in some physical properties of a clay soil in central Italy following the passage of rubber tracked and wheeled tractors of medium power. Soil Till. Res. 73, 119–129.

Pagliai, M., Pellegrini, S., Vignozzi, N., Rousseva, S., Grasselli, O., 2000. The quantification of the effect of subsoil compaction on soil porosity and related physical properties under conventional to reduced management practices. Adv. GeoEcology 32, 305–313.

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.

Pagliai, M., Rousseva, S., Vignozzi, N., Piovanelli, C., Pellegrini, S., Miclaus, N., 1998a. Tillage Impact on Soil Quality. I. Soil Porosity and Related Physical Properties. Ital. J. Agronomy 2, 11–20.

Pagliai, M., Torri, D., Patruno, A., 1997. Stabilità e distribuzione dimensionale degli aggregati. In: Pagliai, M. (Ed.), Metodi di analisi fisica del suolo. Franco Angeli, Roma, Parte V, 1–9.

Pagliai, M., Vignozzi, N., Pellegrini, S., 1998b. The quantification of soil degradation problems in relation to the impact of agricultural management practices. In: Proceedings of the 16th World Congress of Soil Science, Montpellier, 19–27 August 1998.

Pagliai, M., Vignozzi, N., 1998. Use of manure for soil improvement. In: Wallace, A., Terry, R.E. (Eds.), Handbook of Soil Conditioners, Marcel Dekker, Inc., New York, USA, pp. 119–139.

Pezzarossa, B., Pagliai, M., Xiloyannis, C., 1991. Effetti di differenti sistemi di irrigazione su alcune caratteristiche fisiche di un terreno investito a pescheto. Rivista di Frutticoltura, 7-8, 71-75.

Ringrose-Voase, A.J., 1996. Measurements of soil macropore geometry by image analysis of sections through impregnated soil. Plant Soil 183, 27–47.

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 3, 216–227.

Servadio, P., Marsili, A., Pagliai, M., Pellegrini, S., Vignozzi, N., 2001. Effects on some clay soil qualities following the passage of rubber-tracked and wheeled tractors in central Italy. Soil Till. Res. 61, 143–155.

Sumner, M.E., Stewart, B.A., 1992. Soil Crusting: Chemical and Physical Processes. Lewis Publisher, Boca Raton.

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

Unger, P.W., Stewart, B.A., Parr, J.F., Singh, R.P., 1991. Crop management and tillage methods for conserving soil and water in semi-arid regions. Soil Till. Res. 20, 219–240.

USDA-NRCS, 1999. Soil Taxonomy, a Basic System of Soil Classification for Making and Interpreting Soil Surveys, second ed. Agriculture Handbook N° 436, Washington, DC.

Vogel, H.J., 1997. Morphological determination of pore connectivity as a function of pore size using serial sections. Eur. J. Soil Sci. 48, 365–377.

Zeng, Y., Gantzer, C.J., Peyton, R.L., Anderson, S.H., 1996. Fractal dimension and lacunarity of bulk density determined with X-ray computed tomography. Soil Sci. Soc. Am. J. 60, 1718–1724.