united nations
educational, scientific
and cultural
organization

international atomic
energy agency

the
abdus salam
international centre for theoretical physics

H4.SMR/1304-3

"COLLEGE ON SOIL PHYSICS"

12 March - 6 April 2001

The Quantification of the Effect of Subsoil Compaction on Soil Porosity and Related Physical Properties under Conventional to Reduced Management Practices

M. Pagliai

Istituto Sperimentale per lo Studio
e la Difesa del Suolo
Firenze, Italy

THE QUANTIFICATION OF THE EFFECT OF SUBSOIL COMPACTION ON SOIL POROSITY AND RELATED PHYSICAL PROPERTIES UNDER CONVENTIONAL TO REDUCED MANAGEMENT PRACTICES

M. Pagliai[1], S. Pellegrini[1], N. Vignozzi[1], S. Rousseva[2], O. Grasselli[1]

[1]) Istituto Sperimentale per lo Studio e la Difesa del Suolo, MiPA. Piazza D'Azeglio 30, 50121 Firenze, Italy
[2]) N. Poushkarov Institute of Soil Science and Agroecology, Agricultural Academy, Chaussee Bankya 7, 1080 Sofia, Bulgaria

Abstract

Micro and macroporosity, pore shape and size distribution, aggregate stability, saturated hydraulic conductivity and water content were analysed in a loam soil where a long term field experiment was carried out to investigate different types of soil tillage and traffic for maize cultivation.

Micro and macroporosity decreased in the 0-10 cm layer of compacted areas of soil after the passage of tractor for fertilisation and herbicide treatments. This decrease was due to a reduction of all larger pores but mainly the elongated pores, which can negatively affect water infiltration. The hydraulic conductivity was, in fact, strongly reduced.

In the 20-30 and in the 40-50 cm layers of soil ploughed to a depth of 20 and 40 cm, respectively, the macroporosity strongly decreased, 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. Also in these layers the hydraulic conductivity significantly decreased. Such a subsoil compacted layer was not present in soil under alternative tillage systems like ripper subsoiling, in which the porosity was homogeneously distributed along the profile. Also the microporosity and aggregate stability were higher compared to conventional ploughing.

Keywords: Soil structure, Soil pore system, Soil tillage, Ploughpan, Image analysis

Introduction

It is widely demonstrated that intensive cultivation of some agricultural soils can lead to a deterioration in soil structure and other physical properties of the soil and, consequently, decreased crop yield and caused environmental degradation. One of the most important factors responsible for such degradation is just soil compaction. 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.

In order to evaluate the impact of management practices on the soil environment it is necessary to quantify the modifications to soil structure.

Porosity is the best indicator of soil structure conditions and pore space measurements are increasingly being used to quantify soil structure because it is the size, shape and continuity of pores that affect many of the important processes in soils. 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, 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, regarding both sample preparation and image analysis, have improved the methods for direct quantification of soil pores. Such methods allow the quantification of the effects of tillage practices on soil porosity and structure and, in turn, on the optimum tillage needs for sustainable agriculture.

The aim of this study was to evaluate the effects of different types of tillage practices and traffic on soil structural characteristics through the quantification of soil porosity and some related physical properties on a loam soil (Eutric Fluvisol), representative of the hilly environment of Central Italy, where maize is the most widespread and economically significant crop.

Materials and Methods

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 Eutric Fluvisol according to the Food and Agriculture Organization (FAO, 1988), cultivated with maize. Three replications of each of four management practices were tested in 50 m × 10 m plots. The tillage treatments were: 1) minimum tillage (harrowing with a disc harrow to a depth of 10 cm) (MT); 2) shallow tillage (mouldboard ploughing to a depth of 20 cm) (SP); 3) conventional deep tillage (mouldboard ploughing to a depth of 40 cm) (DP) 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 fertilisation has been mineral alone without any addition of farmyard manure or other organic materials.

The pore system was characterised by image analysis on thin sections from undisturbed soil samples to measure pores >50 μm (macroporosity). Six undisturbed samples were collected in the surface layer (0-10 cm) and in the 10-20, 20-30, 40-50 cm layer of each plot in October 1996. Additional samples were collected in the surface layer (0-10 cm) of areas compacted by tractor for fertilisation and herbicide treatments. Samples were dried by acetone water replacement, impregnated with a polyester resin and made into 6×7 cm vertically oriented thin sections (Murphy, 1986). The sections were analysed by means of image analysis techniques (Pagliai, 1988) using a PC-IMAGE-PRO PLUS software (Media Cybernetics, Silver Spring – USA). Total porosity and pore distribution were measured according to the shape and size of the pores. 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). 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, 1988). Microstructure was also examined in the thin sections using a Zeiss "R POL" microscope.

For characterising pores <50 μm, 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 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 the pore size distribution were determined in the range 0.007-50 μm.

The hydraulic conductivity was also measured by collecting six undisturbed cores (5.68 cm diameter and 9.5 cm deep) from the 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).

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 (0-10 cm) of all plots, were placed in 0.25 mm mesh sieves and moistened by capillary rise from a layer of wet sand, then immersed in deionised 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-C)*100, where A is the mass of air-dried soil aggregates, B is the oven-dry mass of aggregates remained in the sieve and C is the mass of sand fraction. Each determination was made at least in triplicate.

Results and Discussion

The macroporosity significantly decreased in the 0-10 cm layer of compacted areas of soil after the passage of tractor for fertilisation and herbicide treatments (Fig. 1). In these areas the porosity did not show significant differences between the different tillage systems, apart from ripper subsoiling were the porosity was significantly higher, and it was confirmed that the compaction caused about four-fold decrease in soil porosity between the wheel tracks and may further decrease under the wheel tracks compared to the adjacent sites with uncompacted soil. In these sites the porosity in the SP and DP soils was significantly lower than in the soils under MT and RS. The micromorphological observations revealed that a more developed surface crust in SP and DP soils that may cause the decrease of soil porosity. 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).

In the 10-20 cm layer, in the MT soils the porosity was significantly lower that in soil under the other tillage systems, indicating a more compact soil structure that also caused a decrease of hydraulic conductivity. In the 20-30 and in the 40-50 cm layers of soil ploughed to a depth of 20 and 40 cm, respectively, the macroporosity strongly decreased, thus indicating that the structure became rather compact (massive) and a ploughpan at the lower limit of cultivation was well developed.

The values of saturated hydraulic conductivity along the cultivated profile are reported in Fig. 2 and showed the same trend of macroporosity.

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 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 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.

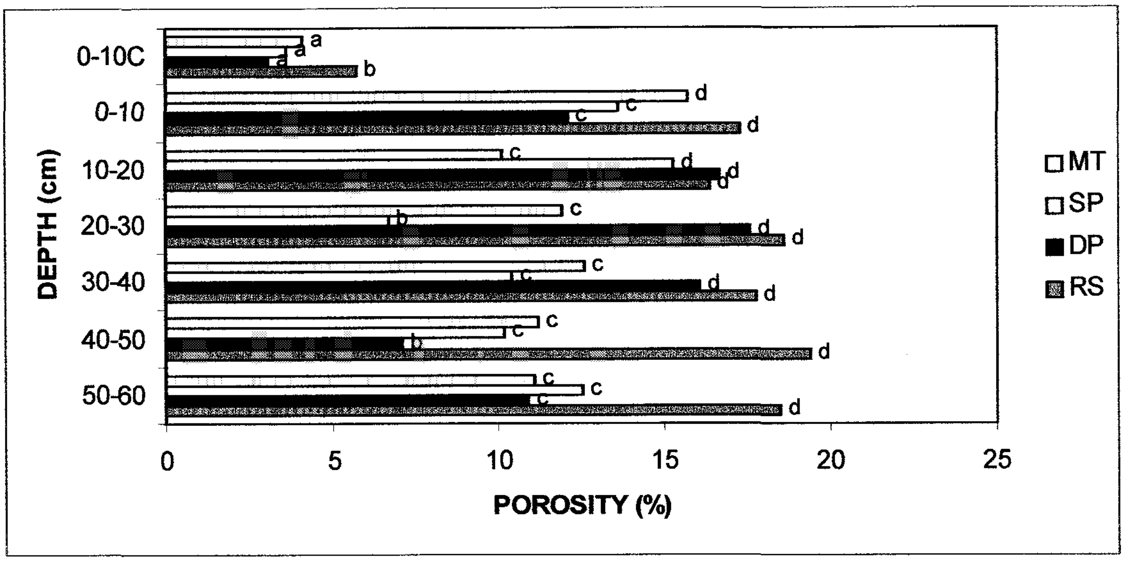


Fig. 1 – Effects of tillage systems on macroporosity distribution along soil profile and traffic in the surface layer (0-10C) expressed as a percentage of total area occupied by pores >50 µm per thin section (MT, minimum tillage; SP, shallow ploughing; DP, deep ploughing; RS, ripper subsoiling). Macroporosity values differ significantly when followed by different letters at P ≤0.05 employing the Duncan's Multiple Range Test.

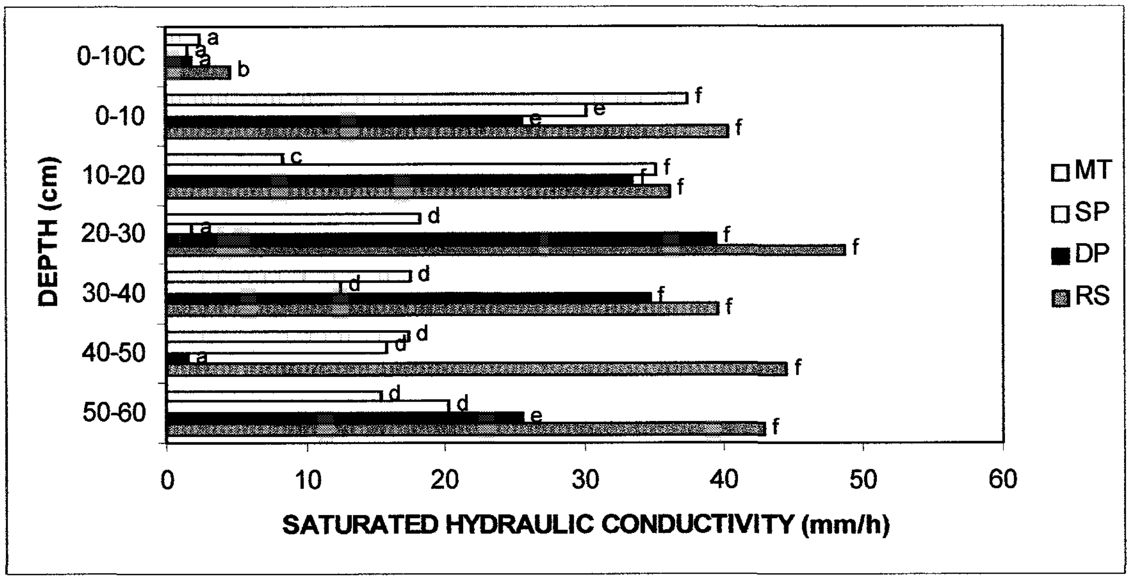


Fig. 2 – Effects of tillage systems on saturated hydraulic conductivity distribution along soil profile and traffic in the surface layer (0-10C) (MT, minimum tillage; SP, shallow ploughing; DP, deep ploughing; RS, ripper subsoiling). Hydraulic conductivity values differ significantly when followed by different letters at P ≤0.05 employing the Duncan's Multiple Range Test.

Fig. 3 shows that the lower values of soil porosity in the surface layer (0-10 cm) of conventionally ploughed soils was mainly due to a reduction of elongated pores both in the range of transmission pores (50-500 µm) as well as in pores > 500 µm. In the compact areas in this layer the strong reduction of elongated pores is even more evident and this explains the strong decrease of hydraulic conductivity (Fig. 2) thus indicating a positive correlation between this parameter and elongated pores (Pagliai et al., 1998b). As in the case of macroporosity the pore shape and size distribution was rather homogeneous throughout the soil profile tilled by RS, while the decrease of porosity in the sublayers (20-30 and 40-50 cm) of the soil under conventional tillage also indicated a reduction of elongated pores (Fig 4). These compact layers strongly reduced the continuity of elongated pores and this leads, as a consequence, to a significant decrease of hydraulic conductivity. Such subsoil compacted layers were not present in soil under alternative tillage systems, like ripper subsoiling, in which the porosity was homogeneously distributed and the hydraulic conductivity was uniform along the profile.

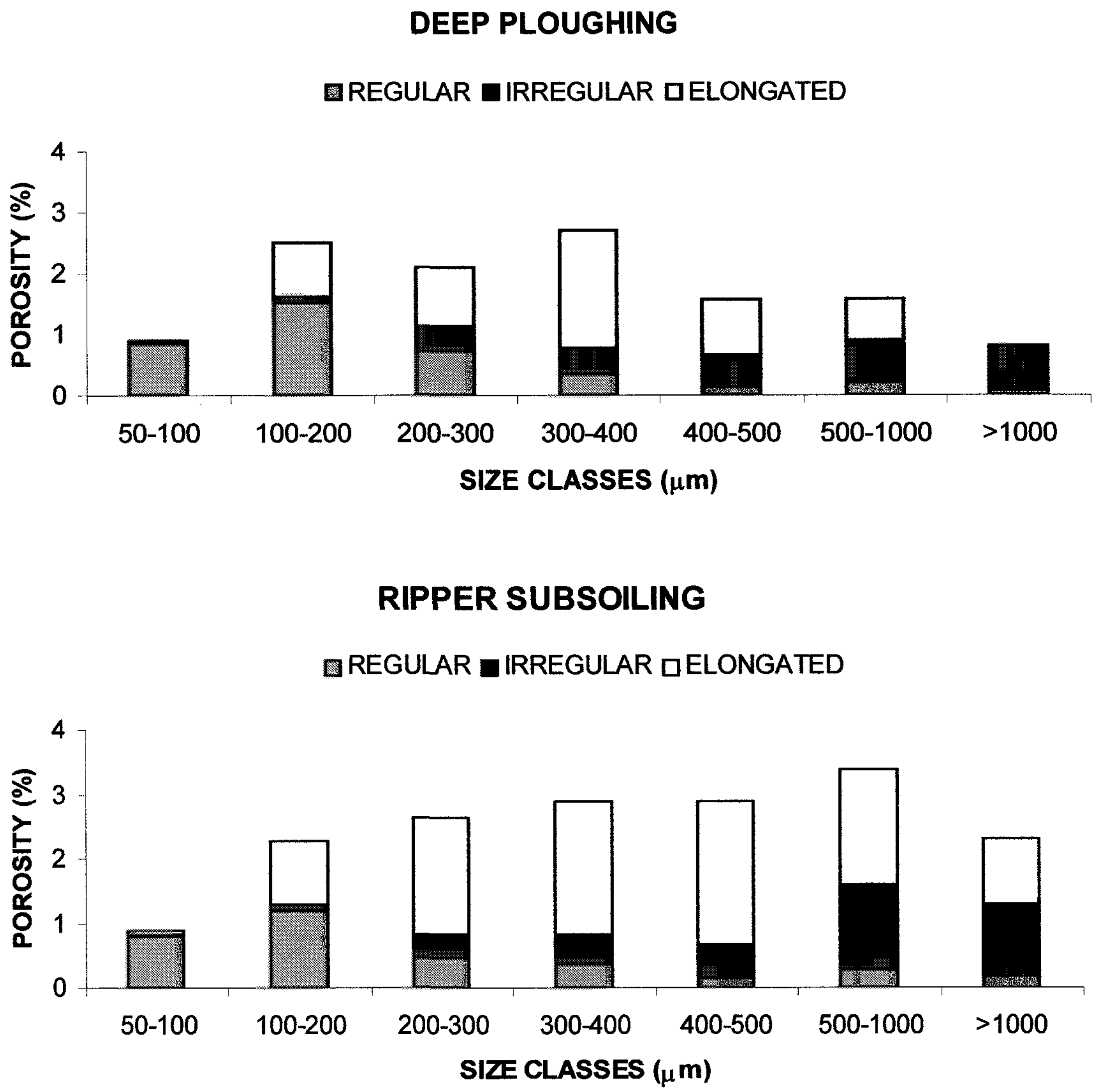
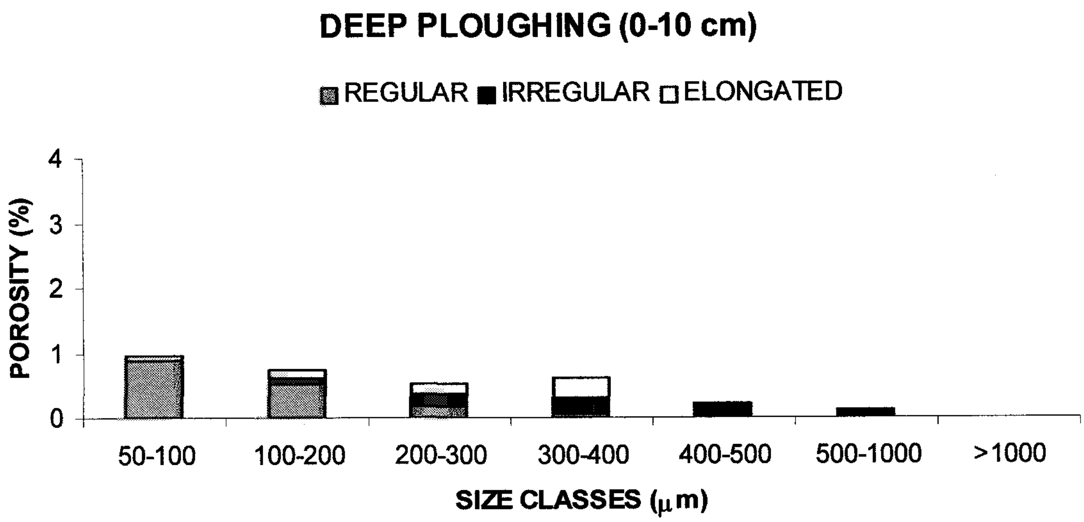


Fig. 3 – Pore size distribution, expressed as equivalent pore diameter, for regular and irregular pores and width for elongated pores in the surface layer (0-10 cm) in the uncompacted areas.

Also the microporosity and aggregate stability were higher compared to conventional ploughing (Table 1). The wheel traffic also caused a significant decrease of microporosity inside the aggregates while, in this soil, did not seem to significantly influence the aggregate stability. The higher microporosity in RS and MT 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).



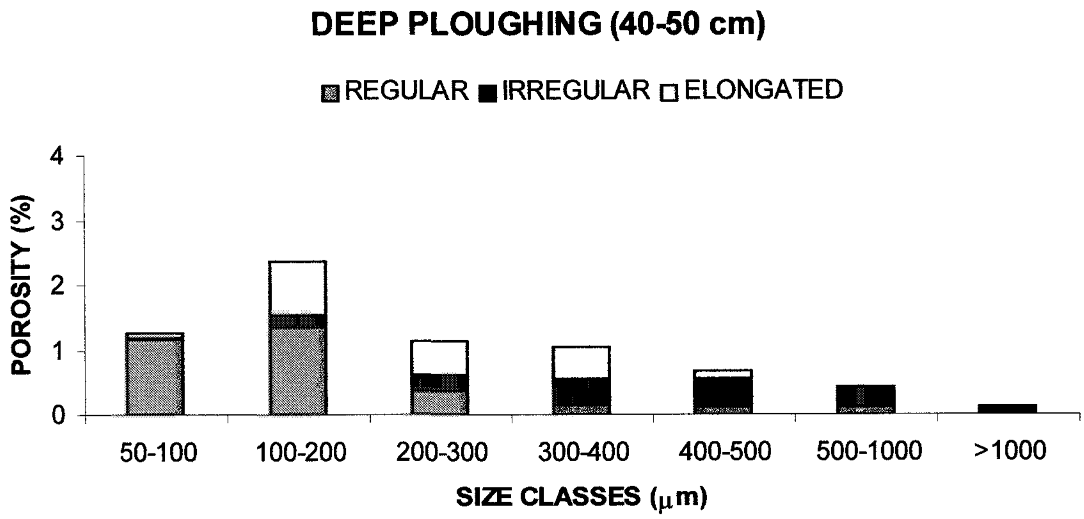


Fig. 4 – Pore size distribution, expressed as equivalent pore diameter, for regular and irregular pores and width for elongated pores in the surface layer (0-10 cm) of compacted areas and in the ploughpan (at the lower limit of ploughing).

Table 1. Effects of tillage systems on microporosity inside the aggregate measured by mercury intrusion and aggregate stability in the surface uncompacted and compacted layer (0-10 cm). Values in each parameter differ significantly ($P \leq 0.05$) when followed by different letter employing the Duncan's Multiple Range Test.

Tillage	Microporosity (%, v/v)		Water Stability Index	
	Uncompacted	Track	Uncompacted	Track
Minimum tillage	30.3c	25.4b	14.7b	14.2b
Shallow ploughing	24.5b	20.7a	11.3a	10.1a
Deep ploughing	27.4b	22.1a	10.4a	10.2a
Ripper subsoiling	32.9c	28.2c	15.3b	14.8b

Conclusions

The results of this study confirmed that conventional ploughing (both shallow and deep ploughing) induced the more relevant modifications of soil physical properties resulting in damage to soil structure. The main negative aspects associated with these management systems are the subsoil compaction (ploughpan) at the lower cultivation limit and the formation of surface crusts. The formation of the ploughpan and the decrease of porosity in the ploughed soil, besides a reduction in water movement, may also hamper root growth. The formation of surface crusts, that may induce surface runoff, is related to the lower aggregate stability in the SP and DP soils with respect to soils under MT and RS. Moreover the damage caused by wheel traffic, in terms of decrease of micro and macroporosity and hydraulic conductivity, is more pronounced in conventionally ploughed soils. The ripper subsoiling, in this type of soil, seems to be the most efficacious tillage system to prevent soil structure degradation and to reduce the negative effects of the compaction due to wheel traffic.

The combination of mercury intrusion porosimetry-image analysis 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 and to quantify aspects of soil degradation such as soil and subsoil compaction.

References

Food and Agriculture Organisation, 1988. FAO/UNESCO soil map of the world, revised legend. World Resources Report 60. FAO, Rome, 138 pp. 11.

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. and 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.

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. International Agrophysics, 4, 215-232.

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

Pagliai, M., Rousseva, S., Vignozzi N., Piovanelli C., Pellegrini S. and Miclaus, N., 1998a. Tillage Impact on Soil Quality. I. Soil Porosity and Related Physical Properties. Italian Journal of Agronomy, 2: 11-20.

Pagliai, M., Torri, D. and Patruno A., 1997. Stabilità e distribuzione dimensionale degli aggregati. In: Metodi di analisi fisica del suolo (M. Pagliai Editor). Franco Angeli, Roma.

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

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.