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Influence of organic and mineral fertilisers on soil biological and physical properties

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Abstract

The aim of this research was to study in a field experiment the influence of different fertiliser applications on soil biological and physical properties. Vermicompost (VC) from biological sludge, stabilised dairy manure or mineral nitrogen fertiliser (NH_4NO_3) were applied to a corn crop (*Zea mays* L.) at 200 kg N ha^{-1}. Soil enzyme activity (acid phosphatase, dehydrogenase and protease BAA) and CO_2 production were measured as indices of soil biological activity. These measures of metabolic activity were correlated to soil physical properties such as soil porosity. The soluble fractions of C and N were taken as indicators of fertiliser effects on soil fertility. There were positive correlations between soil porosity, enzymatic activity and CO_2 production in organic and mineral treatments. The addition of organic fertilisers improved soil physical and biological properties. The increase in macropores, ranging from 50–500 μm, in soil treated with organic fertilisers was mainly due to an increase in elongated pores, which are considered very important both in soil–water–plant relationships and in maintaining a good soil structure. Organic treatments stimulated soil biological activity probably due to an enrichment of soil organic matter. Mineral fertiliser enhanced soil porosity by increasing regular and irregular pores and caused a priming effect of native soil organic matter.

Keywords: *Zea mays*; Vermicompost; Stabilised manure; Mineral fertiliser; Soil enzymes; Porosity

1. Introduction

Soil quality encompasses the interactions of soils and growing plants. An evaluation of soil fertility is generally conducted to optimise the production of agronomic or horticultural crops. In agricultural systems, however, the soil quality includes soil reaction (pH), supply of mineral nutrient elements, water content, composition of soil atmosphere and biotic factors. Mature compost when added to soil directly affects almost all of these factors. In many areas of the world the major benefits derived from compost result from improved soil physical properties. Composted municipal solid waste, composted sewage-sludge or a combination of these materials reduce soil bulk density and increase total porosity in soils over a wide range of textural classes (Mays et al., 1973; Pagliai et al., 1981; Tester, 1990) at rates as low as 50–60 Mg ha^{-1} (Mays et al., 1973; Pagliai et al., 1981; Tester, 1990). The increase in total porosity has been attributed to increased numbers of pores in the 30–50 and 50–500 μm size ranges and a decrease in number of pores greater than 500 μm (Pagliai et al., 1981).

Pronounced shrinkage, sometimes accompanied by surface crusts, is typical of soils with poor structural stability due to clay with a high percentage of exchangeable sodium. Moreover, the internal porosity of aggregates is low especially when, during drying, some pores collapse. Cracks appear where tensile strength of the soil is lowest, which is where the soil is wettest (Oades, 1993). One factor controlling cracking patterns is therefore the uniformity of water distribution, during drying. The drying of surface soils is often controlled by plant roots and major biopores which serve as sinks for water (Oades, 1993).

At the end of the composting process, the compost contains an enormous community of micro-organisms. Thus, application of composts adds organic matter and nutrients and living organisms (Beffa et al., 1995), as well as acting as a nutrient source for indigenous soil micro-organisms. Perucci (1990) showed that microbial biomass carbon, nitrogen, sulphur and phosphorus were

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significantly increased over a 12-month period in a soil treated with 2.5% (w/w) compost made from municipal solid waste.

Despite the importance of pore-size distribution in determining the habitable pore-space for microbes, the interactions between organisms (predation and competition) and the moisture characteristic of soils (Couteux et al., 1988), few researchers have focused upon the correlation between chemical, physical and biological properties (Sequi et al., 1985; Pagliai and De Nobili, 1993). Soil enzymatic activity is generally related to the soil microbial population size and it is positively influenced by the amount of pores ranging from 30 to 200 μm (Pagliai and De Nobili, 1993).

The aim of this study was to assess activities of soil enzyme activities and changes of soil porosity in response to mineral and organic fertilisers under field conditions.

2. Methods

2.1. Soil, fertilisers and field study

The experiment was performed on a maize crop (*Zea mays* L., variety Winner, 12 plants m^2 [EMILSEME, Modena, Italy]) in the Experimental Farm of the University of Tuscia, Viterbo (Italy, latitude 42°25′ and longitude 12°06′). Soil was a sandy clay loam and the treatments applied were: vermicompost (VC) stabilised manure (SM) and mineral nitrogen fertiliser-NH_4NO_3 (AN) (Table 1). VC was obtained from a mixture of two aerobic and one anaerobic sludge from the same municipal sewage-treatment plant serving housing plus paper industry areas (Masciandaro and Garcia, 1997). Earthworms (*Eisenia foetida*) were added to the sludge at 5 kg worms/m^3 sludge. The transformation process lasted 8–10 months after the distribution of the last sludge layer and the warms were removed with a pile of fresh sludge placed in a corner of the windrow which recalled them by attraction of the fresh feed (Masciandaro and Garcia, 1997). SM was produced by composting for 90 days cow-manure mixed with 2% (dry weight of cow-manure) of straw in an open system (windrows), located in the Experimental Farm of the University of Tuscia.

Table 1
Soil and organic fertilisers characteristics[a]

	Unit	Soil	VC	SM
pH (H_2O)		6.40	7.7	8.3
pH (KCl)		5.90	7.0	7.8
Total N	%	0.14	2.0	1.8
Total C	%	1.19	34.2	39.6
N–NO_3	μg N g^{-1}	10.10	813.0	26.7
N–NH_4	μg N g^{-1}	5.60	133.7	16.8
Available P	μg P g^{-1}	20.5	47.0	102
DH[b]	%		96.0	86.4
Clay	%	27.3		
Sand	%	57.1		
Silt	%	15.6		

[a] Values are given as a mean of three replications.
[b] DH = Degree of Humification (percentage of humified compound with respect to total extracted carbon).

Table 2
Dates of soil sampling and agricultural practices in 1996

Descriptions	Dates
VC manure application	30th May
Maize seeding	31st May
Mineral fertiliser application	15th June
Soil sampling	15th October
Maize harvesting	28th October

All fertilisers were applied at 200 kg total N ha^{-1} and were compared with a control (unfertilised). The two organic fertilisers were applied to the soil surface and incorporated into the soil at 0–15 cm depth during seedbed preparation, that was the day before maize seeding; mineral fertiliser was applied two weeks after seeding into the soil surface without incorporation (Table 2).

The treatments were replicated following a random experimental design with three blocks. Each block contained four plots (one for each treatment) and the size of each plot was 21 m^2 with adequate discard. The crop was sown at the end of May and harvested at the beginning of October as shown in Table 1. The experiment was carried out under sub-surface drop irrigation in order to replace the water losses by soil evapotranspiration.

Data on weather during the growing season (from May to October) were not significantly different from the average calculated from 40 yr of records (rain: 352 mm; *T*(max): 26.7°C; *T*(min): 9.3°C).

2.2. Soil sampling

Soil samples were collected from the Ap horizons of each plot in the three blocks 3 months after the application of organic materials. Samples were air-dried at room temperature and stored at 4°C. Soil sub-samples before chemical and biological analysis were screened through a 2 mm sieve and homogenated. For physical analysis, undisturbed soil samples (not sieved) were collected for thin section preparation in order to measure soil porosity by image-analysis. Additional samples were collected to determine soil shrinkage.

2.3. Soil analysis

2.3.1. Chemical analyses

Organic C was determined by dichromate oxidation (Nelson and Sommers, 1982). Total N was determined by sulphuric acid digestion using Se, $CuSO_4$ and K_2SO_4

as catalyst. Total N in the digest was determined by the regular Kjeldahl distillation method (Bremner and Mulvaney, 1982).

Extraction of the water-soluble C fraction from the soil was carried out with distilled water (soil:water 1:10 wt/vol) by incubation at 50°C for 1 h with shaking, followed by centrifugation at 15,000 rpm for 15 min (Garcia et al., 1990). Inorganic nitrogen (NH_4–NO_3) was determined by a colorimetric method using an autoanalyser II Techicon, Braun Luebbe.

2.3.2. Physical analyses

Porosity: Undisturbed soil samples were dried by acetone replacement of water (Miedema et al., 1974; Murphy, 1986), impregnated with a polyester resin and made into thin sections (Murphy, 1986). The photographic method devised by Ismail (1975) was used on thin sections to separate pores from mineral grains. Each photograph was analysed by the image-analysing computer (Quantimet 570) to measure total porosity and to characterise pores according to their shape and size (Pagliai et al., 1983,1984). Pores were measured by their shape as expressed by the shape factor [perimeter^2/(4π area)] and divided into regular (more or less rounded) pores (shape factor 1–2), irregular pore (shape factor 2–5) and elongated pore (shape factor >5) categories. Pores were also sub-divided into size classes according to the equivalent pore diameter for regular and irregular pores and the width for elongated pores (Pagliai et al., 1983, 1984; Giusquiani et al., 1995).

Shrinkage: Soil shrinkage was determined on soil samples handled in the laboratory according to the following methodology. Twenty grams of air-dry soil sample (sieved to <2 mm) were mixed with 20 ml distilled water until they became fluid. The slurry was then poured into a square box (9×9 cm). The drying process was carried out for all soil samples under the same laboratory conditions at constant temperature (25°C), so as to have comparable cracking results. Cracking measurements were carried out optically with a Quantimet 570 apparatus using an electro-optical procedure for image-processing and analysis (Petruzzelli et al., 1976). Briefly, the image of the dried soil sample was scanned by a television camera and displayed on the screen of a monitor. The video signal was passed to a detector where 500.000 picture points (or pixel) on the image were individually analysed for their grey level. Cracks were measured by setting the instrument to detect the corresponding grey level, which was different from the clods. The analysis system gave the percent of cracking area with respect to the total area, and cracks were further sub-divided into different dimensional classes (<500, 500–1000, >1000 μm) which corresponded to average values of the crack width. All determinations were made in triplicate, with a difference, among the three measurements on the same soil sample, of about 0.1% (Pagliai et al., 1980).

Biological analyses: Microbial biomass C was considered an indicator of the amount of the living fraction of organic matter. The activities of acid phosphatase, dehydrogenase, protease BAA enzymes, CO_2 production were measured as indicators of soil activity. Acid phosphatase was assayed according to the methods of Garzillo et al. (1996) and Garcia et al. (1993b). These procedures involve the spectrophotometric determination (wavelength 410) of para-nitrophenol (p-NP) released by 1 g of soil after 20 min at 37°C. Data are expressed as mg p-NP h^{-1} kg^{-1} of soil dry weight. Dehydrogenase activity was determined by the Garcia et al. (1993a) method, which involves the spectrophotometric determination (wavelength 490) of iodonitrotetrazolium formazan (INTF) released by 1 g of soil after 20 h at room temperature. Data are expressed as mg INTF h^{-1} kg^{-1} of soil dry weight. Protease BAA was assayed using the method of Garcia et al. (1993b). This procedure involves determination of NH_4^+ released by 1 g of soil after 2 h at 40°C. Data are expressed as mg NH_4^+ h^{-1} kg^{-1} of soil dry weight. CO_2 production was determined by the method reported in Badalucco et al. (1992) and microbial biomass carbon was established by the fumigation-extraction method (Vance et al., 1987).

2.4. Statistical analysis

Analysis of variance was performed following the General Linear Model (GLM) of SAS. The least significant differences (LSD) among mean values were calculated at $P < 0.05$ confidence level.

3. Results and discussion

3.1. Porosity

Soil total porosity increased significantly with application of both organic and inorganic fertiliser (Table 3). In soil treated with SM, VC and AN total porosities were 46%, 24% and 18% higher, respectively than in the unfertilised soil. Pores ranging from 50 to 500 μm in equivalent pore diameter as elongated and continuous pores are considered the most important in soil–water–plant relationships (Greenland, 1977). The feeding roots need pores ranging from 100 to 200 μm to grow through (Russell, 1978; Tipktter, 1983).

The greater porosity in the soil treated with mineral fertiliser was due to an increase in the amount of rounded pores (Fig. 1), defined as "biopores" (Pagliai, 1988), with 51% more than unfertilised soil (Fig. 2). Conversely, elongated pores, belonging to the 100–200 μm size class, decreased (−32%) with respect to the control soil (Fig. 2).

Table 3
Effects of fertiliser addition on soil porosity expressed as a percentage of area occupied by pores >50 μm per thin section[a]

		Size classes of pores (%)					
	Porosity%	50–100 μm	100–200 μm	200–300 μm	300–400 μm	400–500 μm	>500 μm
Control	10.7 a	3.8 a	41.0 c	17.5 a	18.8 b	8.1 a	10.8 a
Nitram	12.7 b	4.0 a	30.0 b	22.0 b	20.0 b	10.0 b	14.0 a
Manure	15.7 c	2.9 a	30.2 b	19.0 ab	16.2 a	10.0 b	21.7 b
Vermicompost	13.3 b	3.5 a	23.2 a	31.2 c	19.0 b	9.5 b	13.6 a

[a] Size-classes pores distributions are expressed as a percentage of total porosity. Values are given as a mean of three replications. Values with the same letter are not significantly different ($p \leqslant 0.05$).

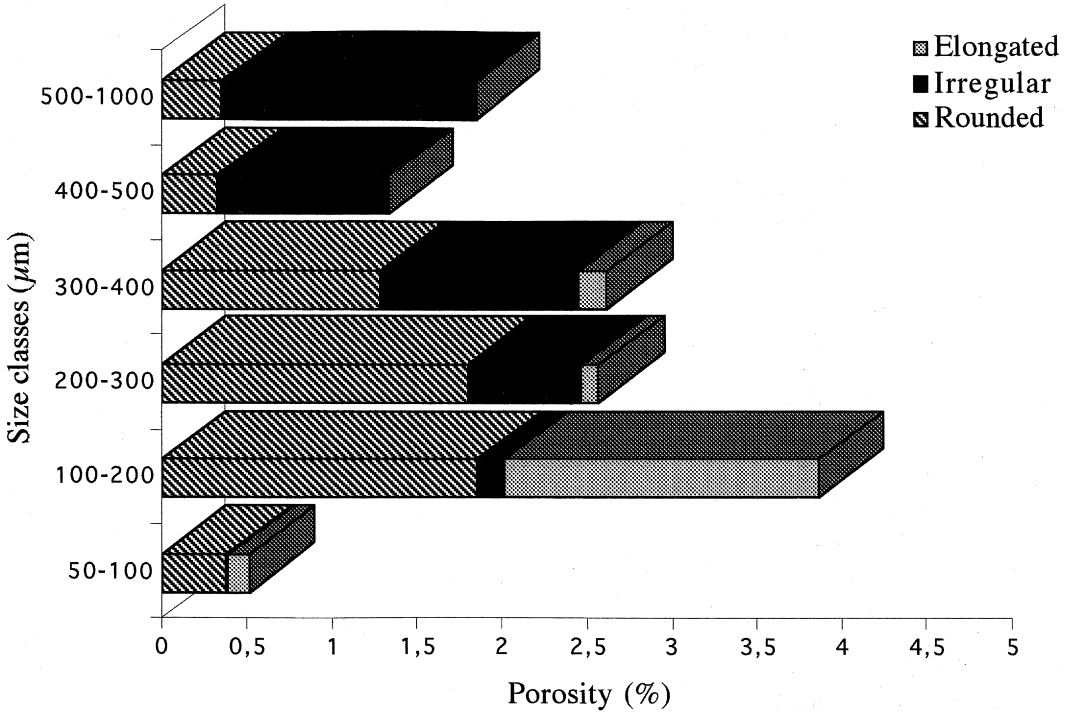

Fig. 1. Pore-size distribution according to the equivalent pore-diameter for regular and irregular pores, and to the width for elongated pores, in a thin section of soil treated with mineral fertiliser (AN).

In soils treated with organic fertilisers an increase of rounded biopores with respect to the control (Fig. 2) soil was detected: (+39% and +32% in SM and VC, respectively) (Figs. 3 and 4). For mineral fertiliser and also with organic fertilisers the above described increase of rounded biopores concerned the 100–500 μm class. In agreement with Giusquiani et al. (1995) in organic treated soils we found a significant increase of the transmission elongated pores (200–300 μm size class) with respect to the control soil. In organic amended soils we also observed an increase of irregular pores greater than 500 μm, especially in manure treated soil.

3.2. Shrinkage

Shrinkage was greater in soil treated with both mineral and organic fertilisers than in control soil (Table 4). A possible explanation is that the addition of the organic or mineral compounds had modified the wettability of soil surfaces (Hartmann et al., 1976) and the main factors controlling cracking could be the non-homogeneity tensile strength of the soil–fertiliser mixture (Oades, 1993). The distribution of size classes of cracks in VC-amended soil was similar to the control soil, with most of the cracks in the class 0–300 μm. Ammonium nitrate and stabilised manure induced a shift to the 300–500 μm class. The organic fertilisers represented a new organic material in the soil, which had different composition and physical properties than native soil organic matter. The addition of mineral fertiliser (AN) caused a higher mineralization of native soil organic matter (priming effect), inducing an increase of water-soluble C (Masciandaro et al., 1996). SM had a lower degree of humification than VC, being not completely stabilised;

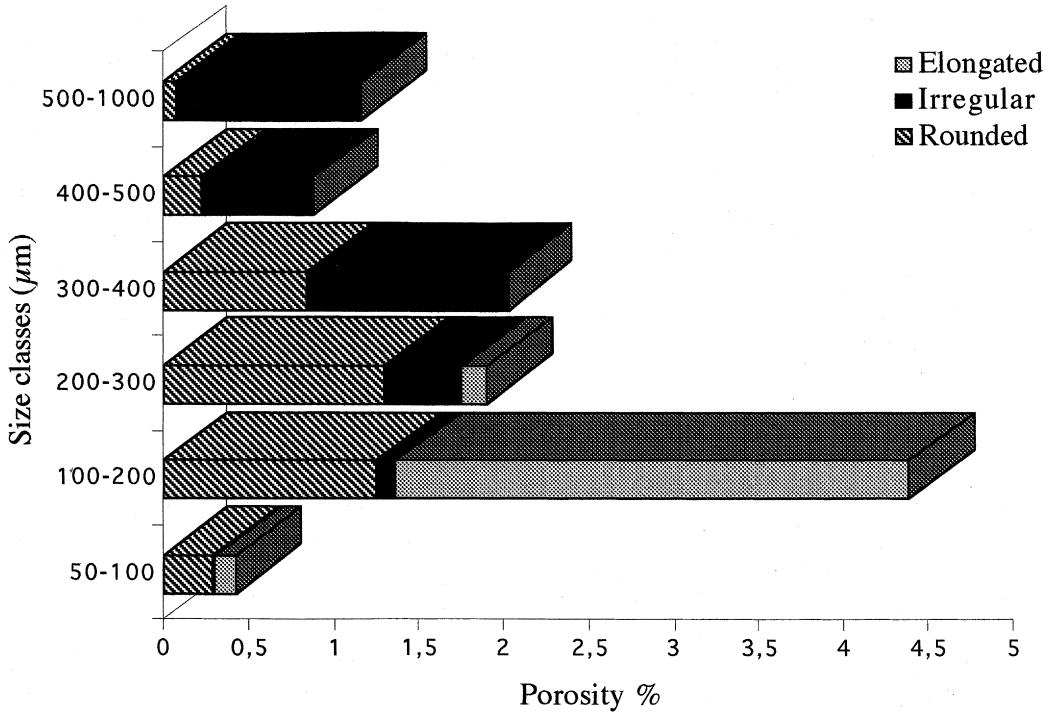

Fig. 2. Pore-size distribution according to the equivalent pore-diameter for regular and irregular pores, and to the width for elongated pores, in a thin section of control soil.

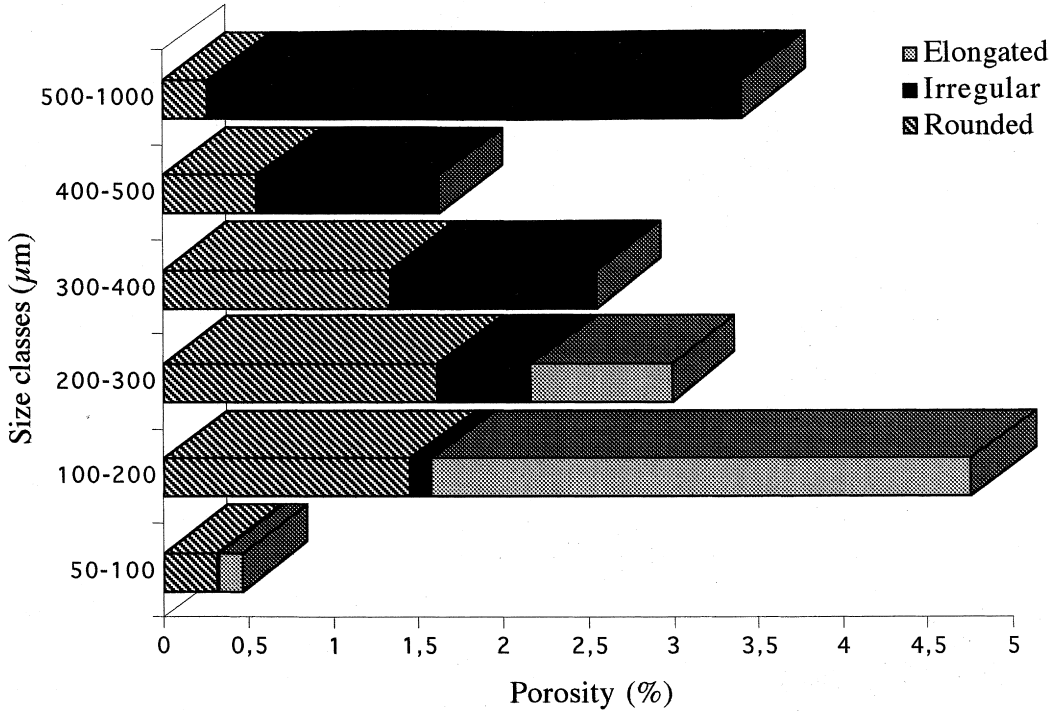

Fig. 3. Pore-size distribution according to the equivalent pore-diameter for regular and irregular pores, and to the width for elongated pores, in a thin section of soil treated with SM.

as reported in Table 1. Both SM and AN caused an increase of soil water-soluble C (Table 5). This was positively correlated with soil total shrinkage yielding the linear equation $y = 0.00952\ x + 9.866$ ($r^2 = 0.6217$, $P < 0.05$, $n = 12$) where y is total shrinkage and x is water-soluble C.

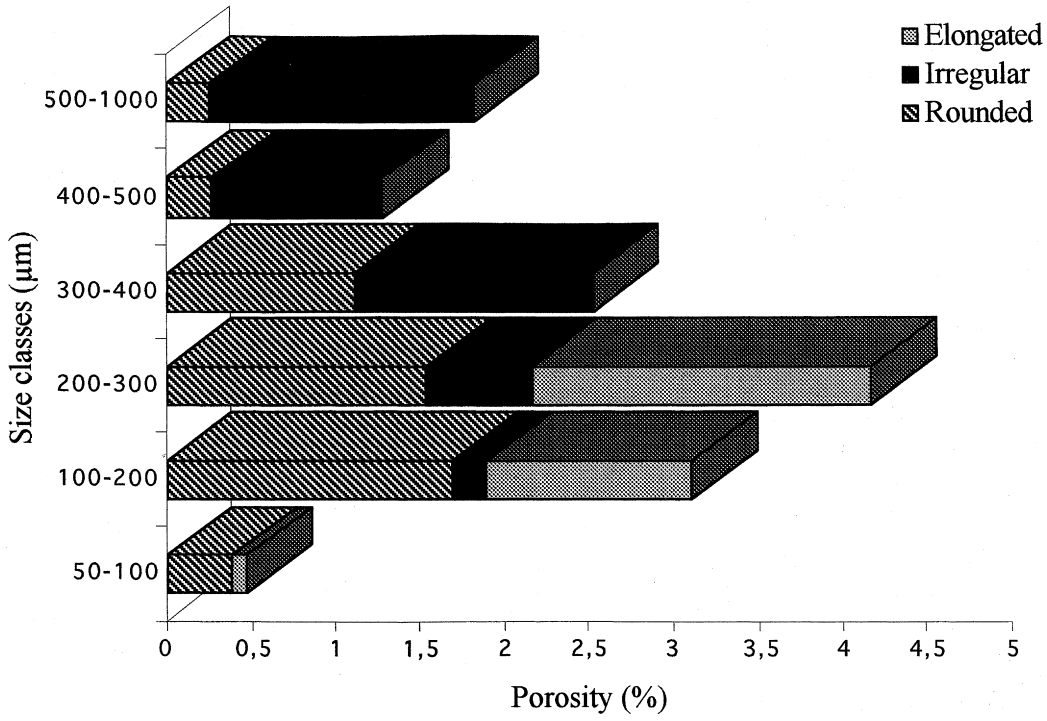

Fig. 4. Pore-size distribution according to the equivalent pore-diameter for regular and irregular pores, and to the width for elongated pores, in a thin section of soil treated with VC.

Table 4
Effects of fertiliser addition on soil total shrinkage expressed as a percentage of area occupied by cracks in the soil surface[a]

		Size classes of cracks (%)					
	Shrinkage %	0–300 µm	300–500 µm	500–700 µm	700–900 µm	900–1100 µm	>1100 µm
Control	9.4 a	99.55 b	0.21 a	0.05 a	0.00 a	0.00 a	0.00 a
Nitram	15.5 c	3.22 a	96.06 b	0.17 b	0.10 c	0.03 b	0.00 a
Manure	15.8 c	1.60 a	97.47 b	0.41 c	0.03 b	0.02 b	0.00 a
Vermicompost	13.7 b	99.27 b	0.39 a	0.02 a	0.00 a	0.02 b	0.07 b

[a] Size-classes cracks distributions are expressed as a percentage of total shrinkage. Values are given as a mean of three replications. Values with the same letter are not significantly different ($p \leqslant 0.05$).

Table 5
Enzyme activities (dehydrogenase, protease BAA, acid phosphatase), C–CO_2 evolution, water soluble carbon (WSC), inorganic nitrogen (IN) in soil fertilised and unfertilised, three months after fertilisation[a]

	Dehydrogenase (µg INTF g^{-1}ds h^{-1})	Protease BAA (µg NH_3 g^{-1} ds h^{-1})	Acid phosphatase (µg pNP g^{-1}ds h^{-1})	C-CO_2 (µg C-CO_2 g^{-1}ds h^{-1})	WSC (µg C g^{-1} ds)	IN (µg N g^{-1} ds)
Control	4.1 a	75.1 a	266 a	0.49 a	195 a	25.7 a
Nitram	6.1 b	87.8 ab	457 b	0.90 b	597 b	34.4 b
Manure	20.7 c	73.5 a	727 d	1.12 c	602 b	45.0 c
Vermi-compost	19.4 c	91.8 b	613 c	0.60 a	177 a	29.9 a

[a] Values are given as a mean of three replications. The values with the same letter are not significantly different ($p \leqslant 0.05$).

3.3. Biological activity

Fig. 5 (A–B–C) reports the significant linear correlation between soil enzyme activities and soil total porosity, giving linear equations where x is the total porosity and $y1$, $y2$ and $y3$ are C–CO_2 production, acid phosphatase, and dehydrogenase activity, respectively. The protease BAA activity was not correlated with any physical parameter, but among treatments, VC caused an increase in soil protease activity (Table 4).

Dehydrogenase activity was positively influenced by the high total porosity of soil and the highest level of dehydrogenase activity was obtained in soil treated with organic fertilisers.

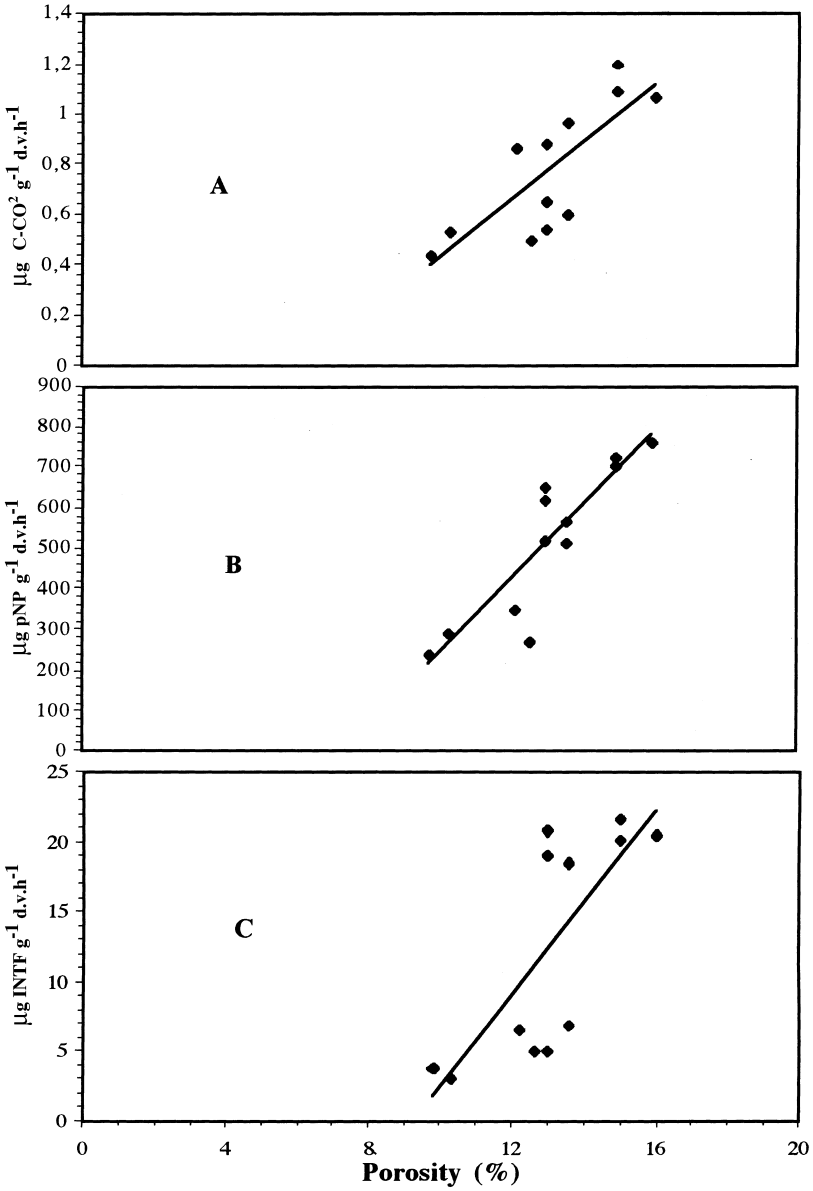

Fig. 5. Determination of the linear regression (biological activity; porosity) (A) C–CO_2 production of soil ($y1$) with different porosity (x) ($P \leqslant 0.05$, $n=12$, $r^2=0.62$, $y1=0.115\ x-0.73$). (B) Acid phosphatase activity of soil ($y2$) with different porosity (x) ($P \leqslant 0.05$, $n=12$, $r^2=0.77$, $y2=90.93\ x-673.89$). (C) Dehydrogenase activity of soil ($y3$) with different porosity (x) ($P \leqslant 0.05$, $n=12$, $r^2=0.56$, $y3=3.28\ x-30.46$).

Many authors have reported that organic fertilisation caused an increase in soil biological activity (Bolton et al., 1985; Fraser et al., 1988; Kirckner et al., 1993). The organic fertilisers supplied phosphate to the soil, giving a more balanced nutritional status than mineral fertiliser.

In the present study we found a higher acid phosphatase activity in soils fertilised with SM, VC and AN. As reported by Nannipieri (1994), phosphatase activity increases when glucose and nitrogen sources are added to the soil, in other words, when the source of nutrients has an equilibrated balance between N and C, as in SM and VC. The increase in soil phosphatase activity with AN could have been due to the soil substrate enrichment (priming effect) caused by the addition of mineral nitrogen to a soil with a high level of native organic matter (SOM 2.05%). Phosphate added to the soil by organic fertiliser application did not depress soil phosphatase activity, which may be ascribed to the stabilised extracellular fraction of enzyme (Nannipieri, 1994).

The considerable difference of inorganic nitrogen availability (N–NO_3 and N–NH_4^+) between VC and SM (Table 1) did not produce any effect on soil biological activity three months after organic fertiliser application (Table 5). An effect of inorganic nitrogen on biological parameters may have been evident after fertiliser addition for a short period. With time nitrogen was distributed in different compartments (soil organic matter,

plants, leaching) without any evident effect on soil biological characteristics and plant production at the end of the experiment (see Section 3.4). Subsurface-drop irrigation and rain at the beginning of the growing season probably caused a severe loss of nitrogen by leaching.

3.4. Corn yield

Maize forage yield was significantly higher in fertilised soils (AN, SM, VC) than in untreated soil (Control). Total maize productions, expressed as g of dry weight m^{-2}, were 1198 in control, 1612, 1866 and 1843 in AN, SM and VC, respectively. The data showed a significant increase of maize productivity on fertilised soil, but differences between fertilisers were not statistically significant.

4. Conclusions

The addition of organic fertilisers improved the soil physical and biological properties; mineral fertiliser apparently induced a similar effect in the soil because it caused an increase in soil porosity, shrinkage and enzyme activity. If we consider the soluble fraction of C and N in soil treated with mineral nitrogen we observe a significant increase of both C and N compared to the control soil.

The remarkable nitrogen input could cause a priming effect of soil native organic matter, as shown by the release of soluble C and N, which become a nutrient source available to the soil microbial biomass, thus increasing soil enzyme activities and CO_2 production.

The main aspects of soil macropores to be considered are not only the pore shapes but also pore-size distribution, especially of elongated continuous pores since they are directly related to plant growth, i.e., for ease of root penetration and storage of water and gases (Greenland, 1977; Giusquiani et al., 1994).

Both mineral and organic treatments improved soil physical properties. Decreased porosity was mostly represented by biopores (100–500 μm), which appeared to be the optimum seat of microbial activity. Finally, organic treatments stimulated soil biological activity probably due to the synergism of soil and organic material micro-organisms or a stimulation of microbial growth by organic compounds added with the VC and manure.

It is clear that physical properties changed after soil organic and mineral fertilisation. It could be interesting to study long-term changes in physical properties after repeated mineral and organic nitrogen applications, along with the dynamics of soil organic matter quality and soil biological activity.

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