Soil Biology & Biochemistry 40 (2008) 608–615

Soil Biology & Biochemistry

www.elsevier.com/locate/soilbio

Changes in chemical and biochemical soil properties induced by 11-yr repeated additions of different organic materials in maize-based forage systems

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Received 9 May 2007; received in revised form 17 August 2007; accepted 7 September 2007
Available online 15 October 2007

Abstract

The repeated addition of organic materials to the soil greatly affects the physical, chemical and biological characteristics. In the present work, we analyzed changes in soil quality properties of the tilled layer caused by different agronomic managements of maize which supply different amounts of carbon (C) and nitrogen (N) through the addition of slurry, farmyard manure or plant residues. The agronomic history of the analyzed soils, which derived from a medium-term (11 yr) field experiment located in NW Italy, represents typical managements of maize for this region. The area is characterized by highly intensive agriculture, with consequent risks to soil degradation that could be limited by the efficient utilization of organic inputs and by recycling within cropping systems, the large amounts of manure that are produced from the many animal breeding farms in this region. We used a combination of both different chemical (soil organic C and total N) and biochemical indicators (potential soil respiration, potentially mineralizable N (PMN) and potential soil microbial biomass (SMB)). We considered the suitability of the selected biochemical indicators to describe the changes in soil characteristics resulting from the past management.

The results showed that the application of the different organic materials, in addition to urea-N fertilizer, increased SOM contents and altered the selected soil biochemical properties compared with the unfertilized treatment, especially in the upper 15 cm of the 0–30 cm tilled soil layer. Farmyard manure applications caused the greatest increase in SOM content, PMN and potential SMB, whilst return of maize straw produced the largest increase in potential soil respiration, but had less effect on total soil organic C and SMB. The use of slurry only caused a moderate increase in SOM and showed intermediate changes in biochemical properties. Also, the rate of C accumulation in the soil per unit of C applied was higher for farmyard manure application than for slurry and straw incorporation in the soil. Fertilization with only mineral N did not induce an increase in C_{org} and N_{tot} and even reduces soil N mineralization potential.

Because of the high variability in the data, potential SMB carbon could be considered as a less successful indicator for differentiating between past agronomic histories and effects on soil quality, whilst microbial activity (measured by potential soil respiration) and PMN, gave a more reliable and useful indication of the amount of easily decomposable organic carbon.

Keywords: Soil quality; Biochemical indicators; Nitrogen availability; Soil organic matter; Manure management

1. Introduction

Intensive agriculture has increased the productivity and efficiency of agricultural systems over past decades, but has also caused negative effects on the environment (e.g. loss of SOM, soil erosion, water pollution) (Matson et al., 1997). These problems have led to the adoption of measures for the protection of non-renewable natural resources, such as agricultural soils and groundwater, as a main framework for modern agricultural policies (EC, 1999).

Soil conservation is now a major concern because more frequent tillage and low inputs of organic materials balanced with the use of mineral fertilizers have contributed to a general reduction in SOM content, with a consequent decline in the quality of agricultural soils

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0038-0717/$ - see front matter © 2007 Published by Elsevier Ltd.
doi:10.1016/j.soilbio.2007.09.015

(Magdoff and Ray, 2004). This negative effect of agricultural practices could be reversed by the correct utilization of manures and/or crop residues within cropping systems, either alone or in combination with mineral fertilizers (Powlson et al., 1987; Jarvis et al., 1996; Breland and Eltun, 1999; Doran et al., 1998; Haynes, 2000; Nardi et al., 2004).

Recent concerns over climate change and greenhouse gas emissions have also raised interest in improving the management of the C balance of agro-ecosystems, since SOM represents an important sink for C fixed by plants (Buyanovsky and Wagner, 1998; Vleeshouwers and Verhagen, 2002; Smith, 2004). Nevertheless, processes controlling the soil organic C cycle are complex, especially in agricultural soils, where the equilibrium of biogeochemical cycles is continuously and rapidly altered by human actions, such as soil tillage, fertilization and irrigation. Therefore, any increase in SOM content may be slow and also difficult to measure against the large background of organic matter already present (Powlson et al., 1987; Sparling, 1992). However, whilst the amount of C stored in soil is a good indicator of soil quality, it does not necessarily reflect the complexity of the organic compounds present and the influence that these may have on the microbiological processes controlling nutrient availability (Herrick and Wander, 1997; Mahmood et al., 1997).

To overcome these limitations, different authors have proposed several soil indicators to study the effects of repeated organic matter applications on soil C accumulation and C and N turnover (Doran and Parkin, 1994; Gil-Sotres et al., 2005). Some are based on soil physical and chemical properties, but the majority focus on biochemical properties that reflect the size and activity of microbial processes. This is because biologically mediated processes in soils are central to their ecological functions (Haynes, 1999) and play a key role in the mineralization of organic C and in nutrient cycling. Moreover, changes in the size and activity of the soil microbial biomass (SMB) occur more rapidly in response to changes in environmental conditions, land use and management than most physical and chemical parameters (Powlson et al., 1987; Sparling, 1992).

Techniques used to measure changes in biochemical properties must show several characteristics that allow assessment of their reliability. They should be tested across a wide range of soil types and soil conditions and should have generally accepted scientific validity. In addition, the natural annual variation of the parameters, such as weather patterns and crop development, should not affect the results of the measurement, especially in long-term experiments (Francaviglia et al., 2004). This implies that laboratory techniques, performed under optimal or standardized conditions with set protocols, are to be preferred to field techniques. However, laboratory techniques must be compared with field data from medium/long-term agronomic studies in order to demonstrate their practical application and scientific merit.

The aim of this work was to evaluate the effects, after 11 yr, of different agronomic managements on SOM accumulation and soil quality changes in maize-based forage systems, using selected chemical and biochemical indicators related to the pools and cycling of C and N. The selected treatments represent typical managements of maize in the region, which received different amounts of organic C and N through the incorporation of slurry, farmyard manure or plant residues in the soil. The changes in soil properties induced by these agronomic treatments were compared with the use of urea alone and with soil which had never received fertilizer N. We tested the suitability of the selected biochemical indicators to describe the changes in the SOM turnover resulting from previous types of management.

2. Materials and methods

2.1. Experimental site and treatments

The soil samples analyzed in the present work were collected in 2004 from five plots ($10 \times 7.5\,m^2$) which are part of a large field experiment established in 1993 in the Agri-environmental experimental station of the Agronomy, Forest and Land Management Department of the University of Turin (NW Italy), aimed at evaluating different fertilization managements in maize-based forage systems in terms of environmental sustainability (Grignani et al., 2007).

The site is located in the western area of the Po river plain (229 m a.s.l.) and is characterized by a scarcely weathered alluvial soil, classified as Typic Udifluvent (USDA, 1977). The texture of the Ap horizon (0–40 cm) is loam (48.4% sand, 43.1% silt and 8.5% clay), with a dry bulk density of $1.47\,g\,cm^{-3}$, pH of 7.9 and total C and total N of 11.6 and $1.7\,g\,kg^{-1}$, respectively. The exchangeable K is low (0.22 meq), whilst Olsen P is high ($29.4\,mg\,kg^{-1}$). The climate is temperate sub-continental, characterized by two main rainy periods in spring and autumn, and by a cold winter and warm summer. From 1993 to 2003, during the period of the experiment, the mean annual precipitation was 792 mm with a mean annual temperature of 11.8 °C.

The five selected treatments, under continuous cultivation of irrigated maize (*Zea mays* L.) from 1993, represented different quantities and nature of C and N inputs supplied to the soil for 11 yr. Specifically, treatments were (1) MsU, maize for silage, fertilized with $200\,kg\,ha^{-1}\,y^{-1}$ of urea-N before sowing and $100\,kg\,ha^{-1}\,y^{-1}$ of urea-N at ridging and harvested as a whole crop; (2) MgU, maize for grain, fertilized as MsU, with, on average, $12.6\,Mg\,D.M.\,ha^{-1}\,y^{-1}$ of straw (i.e. leaves, stalks and stowers) returned to the soil when the grain was harvested; (3) MsS, maize for silage, fertilized with $100\,Mg\,ha^{-1}\,y^{-1}$ of cattle slurry before sowing and $100\,kg\,ha^{-1}\,y^{-1}$ urea-N at ridging; (4) MsF, maize for silage, fertilized with $40\,Mg\,ha^{-1}\,y^{-1}$ of composted farmyard manure before sowing and $100\,kg\,ha^{-1}\,y^{-1}$ of urea-N at ridging and (5) Ms0, maize for silage, without any N fertilizer supply, utilized as the control treatment. The selected treatments represent typical managements of maize in the region, which received different amounts of C and N

Table 1
Carbon and nitrogen inputs from different sources in different treatments

Treatment	C inputs ($Mg\,ha^{-1}\,y^{-1}$)				N inputs ($kg\,ha^{-1}\,y^{-1}$)				
	Farmyard manure	Slurry	Straw	Total	Farmyard manure	Slurry	Straw	Urea	Total
Ms0	0	0	0	0	0	0	0	0	0
MsU	0	0	0	0	0	0	0	305 (15)	305 (15)
MgU	0	0	5.73 (0.75)	5.73 (0.75)	0	0	92 (17)	305 (15)	397 (22)
MsS	0	2.17 (1.10)	0	2.17 (1.10)	0	226 (45)	0	100 (0)	326 (45)
MsF	3.03 (1.46)	0	0	3.03 (1.46)	284 (65)	0	0	100 (0)	384 (65)

Shown are annual means of the period 1993–2003, standard deviation between years is shown in parentheses.

inputs that were kept constant throughout the experiment (Table 1). Soil cultivation, weed control and irrigation were common to all five treatments. In spring, organic or urea-N fertilizers were spread and incorporated into the soil by a spading machine. Soil tillage was 30 cm deep. Then, the seedbed was prepared using a rotavator and the crop was sown in mid-April to mid-May. Maize was harvested for whole-crop silage at the beginning of September and for grain between the end of September and beginning of October. In the MgU treatment, maize straw (including leaves, cob, bracts and stalks) was chopped in November–December and incorporated into the soil by tillage in the subsequent spring.

2.2. Soil sampling and storing

Soil samples used for the experiment were collected in February 2004 from the tilled layer at 0–15 and 15–30 cm depth, combining several soil cores taken randomly from the experimental plots. Samples were air-dried, sieved to 2 mm and stored at room temperature in closed plastic bags. The residual soil moisture was determined by oven-drying three sub-samples from each treatment for 24 h at 105 °C.

We measured the soil water content at saturation by wetting soil cores contained in steel cylinders closed with a disk of fine tulle fixed with rubber bands. Samples were initially wetted from the bottom by capillarity and were then left immersed in water to half of the cylinder height, for 4 days; the water content was determined by oven-drying the soil cores (105 °C, 24 h).

We employed air-dried soil samples throughout in testing various indicators of soil quality, both to maintain uniformity between samplings and also consistency in experimental protocols when applied to repeated measurements over different years.

2.3. Soil analyses

All the analyses were carried out on three sub-samples for each plot. Soil organic C (C_{org}), total N (N_{tot}), C:N ratio, potentially mineralizable N (PMN), potential soil respiration and potential SMB carbon (C_{SMB}) measurements were used to evaluate soil quality related to the agronomic history of the treatments.

C_{org} and N_{tot} were analyzed using an elemental analyzer (TERMOQUEST NC 2005). C_{org} was analyzed after removal of carbonate (as CO_2) by adding 4 ml of a 10% solution of HCl per 1 g of soil sample, in two successive additions.

Potentially mineralizable N was estimated from the NH_4^+-N accumulated under water-logged conditions after 7 days at 40 °C in an anaerobic environment (Keeney, 1982). At the beginning and at the end of incubation, soil inorganic N was extracted with 2 M KCl. Soil extracts were filtered through a Whatman No. 1 paper, frozen for storage and later analyzed for NH_4^+-N by automated colorimeter (Scalar autoanalyzer).

Potential soil respiration was measured using a modification of the method proposed by Isermeyer (1952), whereby the CO_2 released during soil incubation is trapped in NaOH and determined by titrimetric analysis. Briefly, air-dried soil (25 g) was weighed into a 100 ml beaker, water added to bring the soil to 70% of saturation and placed in a jar containing a beaker with 10 ml of 0.5 M NaOH. The jars were sealed (air-tight) and incubated at 30 °C in the dark. At fixed intervals (t), the jars were opened (1, 2, 4, 7, 10, 14, 17, 21, 28 days), and BaCl was added to the NaOH solution to remove the trapped CO_2 by precipitation. Residual NaOH was determined by titration with 0.25 M HCl in the presence of phenolphthalein indicator. Daily soil respiration rates at each interval t (CR_t) and the cumulative amount of respiration after 10 days (C_{10}) and 28 days (C_{28}) of incubation were then calculated.

For C_{SMB} measurement, air-dried soil samples (150 g) were incubated in the dark for 10 days at 30 °C and 70% of saturation to allow SMB growth which was assessed using the fumigation–extraction method (Vance et al., 1987). Briefly, the amount of C extracted with 0.5 M of K_2SO_4 from fumigated and unfumigated soil samples was determined by chromic acid digestion and titration. C_{SMB} was calculated as 2.64 times the difference between organic C contents in fumigated and unfumigated soil samples.

2.4. Statistical analysis

An ANOVA procedure was used to analyze C_{org}, N_{tot}, C:N ratio, CR_t values for each interval, C_{10}, C_{28}, PMN and C_{SMB}, using soil treatment and depth as fixed factors and soil sub-samples as replicates. Mean separations were obtained by Bonferroni's protected LSD.

The relationships between biochemical indicators were analyzed using the Pearson bivariate correlation.

3. Results

The agronomic history of the soils caused significant differences between treatments for C_{org}, N_{tot}, PMN, C_{10}, C_{28} and for C_{SMB} (Tables 2 and 4). A significant effect of depth was also detected for all the measured parameters. Also, the interaction of treatment × depth was significant for C_{org}, N_{tot}, C:N ratio and PMN.

In the upper 0–15 cm layer, C_{org} ranged from 10.4 g kg^{-1} (MsU) to 15.7 g kg^{-1} (MsF) and N_{tot} from 1.03 g kg^{-1} (Ms0) to 1.48 g kg^{-1} (MsF) (Table 2). Soils that received farmyard manure application (MsF) or maize straw (MgU) had statistically higher amounts of both C_{org} and N_{tot} compared with the unfertilized soil (Ms0) and the urea-N fertilized soil (MsU). In contrast, C_{org} and N_{tot} measured on MsS and MsU were not significantly different from the control (Ms0). Considering only the treatments with additional inputs of organic C, i.e. MgU, MsS and MsF, C_{org} was higher after the application of farmyard manure (MsF) than slurry (MsS) or maize straw (MgU), although the latter treatment actually received the highest input of total C. In the 15–30 cm layer, C_{org} and N_{tot} were, on average, lower than in the upper layer and the only difference detected was between MsF and MsU for both parameters.

The application of farmyard manure caused a higher C accumulation rate (calculated as the difference between the unfertilized treatment) when compared with slurry and maize-straw treatments. Specifically, it was equal to 0.48, 0.25 and 0.11 Mg C recovered in soil per Mg C supplied in 11 yr, for MsF, MsS and MgU, respectively ($P = 0.002$, Bonferroni LSD = 0.20). Moreover, the amount of N accumulated in soil per unit of N input was higher in MsF (0.31 kg N kg^{-1} N) than in MsS (0.03 kg N kg^{-1} N), whilst it showed an intermediate value in MgU (0.18 kg N kg^{-1} N) ($P = 0.006$, Bonferroni LSD = 0.18).

The C:N ratio ranged from 9.1 (MgU) to 11.0 (MsS) in the upper layer and from 8.7 (Ms0) to 10.0 in the lower layer (MsS). Whilst the soil depth and the treatment × depth interaction effects were statistically significant, no simple treatment effect could be detected for this parameter.

In the 0–15 cm layer, PMN was significantly higher in MsF, MsS and MgU in comparison with Ms0 and MsU (Table 4). Although the MsU treatment received a high amount of N, it did not show an increase in PMN compared with the control. Treatments MsF, MsS and MgU had higher PMN values in the upper soil layer than in the lower, whilst there were no significant differences between layers in Ms0 and MsU. Furthermore, in the 15–30 cm layer, only the MsF value was statistically higher than all the other treatments.

The results for potential soil respiration measurements showed that the treatment effect was significant at all sampling intervals during incubation, with the exception of the last period (days 20–28) (Table 3). As would be expected, the measured respiration rates showed an exponential decrease as the time of incubation progressed and tended to stabilize after 10 days of incubation (Fig. 1). The respiration rates in MsF, MsS and MgU treatments were generally higher than in Ms0 and MsU, which in turn, were not significantly different from each other. For those treatments that received additional organic inputs, MgU generally had higher respiration rates than MsF and MsS although these differences were only statistically significant on the first day of incubation. Also, higher respiration rates were detected in the surface layers than in the deeper ones throughout the experiment. Cumulated values of CO_2-C production (C_{10} and C_{28}) were also effective in differentiating between soil treatments and soil depths (Table 4). In detail, the C_{10} values were highest in MgU, intermediate in MsF and MsS and lowest in Ms0 and MsU. Considering the whole period of incubation (C_{28}), the ranking between treatments did not change, but differences were not large. It was only possible to detect a significantly higher amount of CO_2-C produced in MgU, compared with MsU and Ms0, and in MsS compared with MsU.

With regard to potential SMB measurements (Table 4), C_{SMB} was higher after the addition of farmyard manure in MsF than when only urea was applied (MsU), but no

Table 2
Soil organic C, total N and C:N in the 0–15 and 15–30 cm layers, sampled in February 2004 after the 11 y different management

Depth (cm)	Treatment	C_{org} (g kg^{-1})	N_{tot} (g kg^{-1})	C:N
0–15	Ms0	10.7c,d	1.03d	10.4a,b
	MsU	10.4c,d	1.06d	9.8a,b
	MgU	12.8b	1.41a,b	9.1a,b
	MsS	12.6b,c	1.14c,d	11.0a
	MsF	15.7a	1.48a	10.6a,b
15–30	Ms0	10.1c,d	1.16b,c.d	8.7b
	MsU	9.4d	0.96d	9.8a,b
	MgU	11.2c,d	1.15c,d	9.7a,b
	MsS	11.0c,d	1.10c,d	10.0a,b
	MsF	12.5b,c	1.31a,b,c	9.5a,b
0–30	Ms0	10.4	1.10	9.6
	MsU	9.9	1.01	9.8
	MgU	12.0	1.28	9.4
	MsS	11.8	1.12	10.5
	MsF	14.1	1.39	10.1
0–15	Average	12.4	1.22	10.2
15–30	Average	10.8	1.14	9.5
Source of variation				
Treatment		<0.001	<0.001	0.072
Depth		<0.001	0.008	0.019
Treatment × depth		0.003	0.006	0.032

Different letters show differences for $P<0.05$ (Bonferroni LSD test, $n = 3$).

Table 3
Levels of probability for treatment, depth and treatment × depth effects derived from the ANOVA of the respiration rates (CR_t, mg CO_2-C kg^{-1} day^{-1}) measured at different intervals of incubation

Source of variation	Interval of incubation (day)								
	1	2	4	7	10	14	16	20	28
Treatment	<0.001	0.005	0.002	0.016	0.008	0.030	0.043	0.005	0.065
Depth	<0.001	<0.001	0.001	0.004	<0.001	<0.001	0.001	0.001	0.003
Treatment × depth	0.343	0.466	0.366	0.263	0.173	0.237	0.105	0.151	0.016

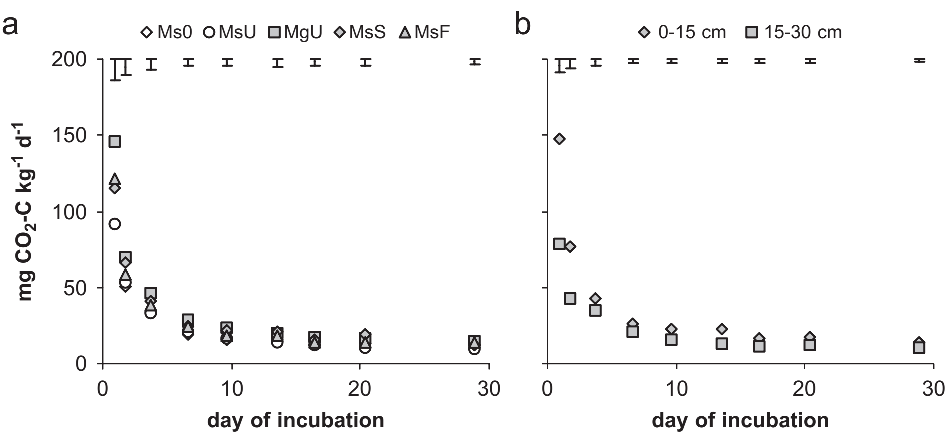

Fig. 1. Respiration rates at different intervals of incubation (CR_t, mg CO_2-C kg^{-1} day^{-1}), measured in different treatments, average of the 0–30 cm (a), and in different depths, average of the treatments (b). The bars in the upper part of the graph represent the Bonferroni LSD and are referred to the ANOVA reported in Table 3.

Table 4
Effect of treatment on cumulated amount of C-CO_2 produced after 10 and 28 days (C_{10}, C_{28}), potentially mineralizable N (PMN) and on soil microbial biomass C (C_{SMB})

Depth (cm)	Treatment	PMN (mg N kg^{-1})	C_{10} (mg C-CO_2 kg^{-1})	C_{28} (mg C-CO_2 kg^{-1})	C_{SMB} (mg C kg^{-1})
0–15	Ms0	15.4c,d	341.1	569.0	630.4
	MsU	8.3d	377.7	642.2	584.9
	MgU	29.6a,b	524.7	920.7	587.8
	MsS	37.2a,b	445.0	815.3	716.9
	MsF	37.9a	423.8	744.4	757.7
15–30	Ms0	15.4c,d	250.2	519.3	467.8
	MsU	15.3c,d	227.2	391.0	507.5
	MgU	12.9c,d	351.0	589.4	598.5
	MsS	17.7c	310.0	549.0	599.0
	MsF	28.8b	298.2	537.4	583.4
0–30	Ms0	15.4	295.7c	544.2b,c	549.1a,b
	MsU	11.8	302.4c	516.6c	546.2b
	MgU	21.2	437.9a	755.1a	593.2a,b
	MsS	27.4	377.5a,b	682.1a,b	657.9a,b
	MsF	33.4	361.0b	640.9a,b,c	670.5a
0–15	Average	25.7	422.4a	738.3a	655.5a
15–30	Average	18.0	287.3b	517.3b	551.2b
Source of variation					
Treatment		<0.001	<0.001	0.001	0.010
Depth		<0.001	<0.001	<0.001	<0.001
Treatment × depth		<0.001	0.470	0.108	0.165

Different letters show differences for $P<0.05$ (Bonferroni LSD test, $n = 3$).

Table 5
Correlation coefficients (*R* Pearson), and significance of measured parameters ($n = 10$)

		PMN	C_{28}	C_{10}	C_{SMB}
C_{org}	*R*	0.86	0.67	0.65	0.80
	Sig.	0.002**	0.035*	0.041*	0.005**
N_{tot}	*R*	0.73	0.64	0.59	0.45
	Sig.	0.017**	0.047*	0.070	0.194
C:N	*R*	0.41	0.22	0.28	0.83
	Sig.	0.235	0.543	0.428	0.003**
PMN	*R*		0.63	0.57	0.69
	Sig.		0.049*	0.088	0.028*
C_{28}	*R*			0.98	0.60
	Sig.			0.000**	0.067
C_{10}	*R*				0.64
	Sig.				0.045*

Correlations were considered significant (*) at $P<0.05$ and highly significant (**) at $P<0.001$.

significant differences were detected between the treatments with additional inputs of organic C, i.e. MgU, MsS and MsF, with respect to Ms0. As with the other parameters, C_{SMB} also decreased significantly with increased soil depth.

Considering the correlations between the measured parameters (Table 5), PMN, C_{10}, C_{28} and C_{SMB} were all positively and significantly correlated with C_{org}, but the correlation coefficients were higher for PMN and C_{SMB} than for C_{10} and C_{28}. Also, C_{SMB} was positively correlated with C:N ratio, PMN and C_{10}.

4. Discussion

One of the greatest problems posed by the use of soil quality indicators is the lack of reliable reference values to accommodate regional variations (Sparling et al., 2004; Gil-Sotres et al., 2005). Results from this work demonstrate both the agronomic relevance and the feasibility of using particular chemical and biochemical indicators in a soil with a clearly defined agro-environmental history.

In general, the soil treatments which received repeated applications (11 yr) of the different organic materials, in addition to urea-N fertilizers, increased not only SOM content and soil total N, but also potential N supplying capacity, potential soil respiration and C_{SMB} when compared with soil that received no fertilizer N (Ms0) and soil that received urea alone (MsU). Comparisons made between the surface and deeper soil layers showed soil stratification. While the soil was tilled to a depth of 30 cm, the organic sources applied were not completely mixed within the two layers; consequently, the greatest differences across the various soil treatments were found in the upper soil layer.

The treatment in which farmyard manure was incorporated in the soil was found to increase SOM content, PMN and C_{SMB} to the greatest extent. This coincides with the positive effect of manure applications on soil health indicators in arable cropping systems documented by others (Breland and Eltun, 1999; Nardi et al., 2004; Zaller and Köpke, 2004). Furthermore, MsF was found to store the maximum amount of C and N per unit of C and N received throughout the experimental period. The soil respiration values confirm that C supplied with farmyard manure is more stable and less decomposable than straw-C.

The use of slurry resulted in a lower accumulation of C and N in the soil per unit of C and N received than farmyard manure. With respect to the control treatment, the liquid manure applications did not change the amount of total N in the soil, but did significantly increase the fraction of easily mineralizable organic N. These results were consistent with those found by Grignani et al. (2007), based on the experimental trial to which these selected treatments belong. They found that farmyard manure, applied at two different levels, markedly increased the soil C content, whereas the effect of slurry was modest.

The incorporation of maize straw into the soil, in addition to urea, caused an increase in C_{org}; however, given the large C inputs, the accumulation was limited and lower than in the farmyard manure treatment. This finding agreed with the measured respiration rates found to be highest in MgU. The higher value of N_{tot}, relative to the control treatment, suggests that straw inputs contribute to N accumulation in the soil.

The low rate of C immobilization when high quantities of straw were added to the soil indicates that crop residues can be rapidly decomposed by the microbial biomass (Jenkinson, 1981) and only a modest amount of the C supplied could be recovered in the soil. In this study, straw mineralization was likely to have been further accelerated by the mineral N fertilizer addition as also found by Recous et al. (1995). However, after 11 yr, fertilization with urea alone yielded no significant differences in the soil characteristics measured when compared with unfertilized soil.

Potentially mineralizable N measured after water-logging air-dried soil is frequently used as a reliable indicator of the potential N supplying capacity of a soil (Curtin and McCallum, 2004; Nayyar et al., 2006; Russell et al., 2006). Our measurements found that manures and straw applications to the soil created conditions that promoted an increase in the easily mineralizable organic-N pool. Moreover, the values of the PMN/N_{tot} were equal to 0.78%, 1.49%, 2.10%, 2.57% and 3.25% ($P<0.001$, LSD = 0.82), respectively, for MsU, Ms0, MgU, MsF and MsS in 0–15 cm layer and showed that the applications of slurry or farmyard manure increased the mineralizable pools of organic N proportionately more than soil total N.

With regard to soil respiration measurements, it is acknowledged that air-drying soil leads to an increase in readily mineralizable C compounds (Davidson et al., 1987) and subsequently causes a flush in CO_2 after soil rewetting (Jenkinson, 1988). Others have suggested that the rapid C mineralization after soil core disturbance (via freeze-thawing, dry-rewetting or sieving) is indicative of the labile fraction of organic matter which is closely associated with the agronomic history of soils (Franzluebbers, 1999; Haney et al., 2001; Herrmann and Witter, 2002). Our results confirm this interpretation and also show that this early flush of C is effective in differentiating between treatments. In the treatments with additional inputs of organic C, we found that the higher the respiration value was (755.1, 682.1 and 640.9 $mg\,C\text{-}CO_2\,kg^{-1}$ for MgU, MsS and MsF, respectively), the lower was the amount of C remaining in the soil per unit of C inputs (0.11, 0.25 and 0.48 $Mg\,C\,Mg^{-1}\,C$ for MgU, MsS and MsF, respectively). We also found the respiration of SOM to be affected by the nature of the C input; it was lower when the C was partially humified before soil input (manure $<$slurry$<$straw). Measurements taken after a longer incubation (up to 28 days) did not change the information derived after only 10 days.

In contrast to the findings of other investigators (Jordan et al., 1995; Alvarez et al., 1998), we found C_{SMB} to be the least effective indicator for differentiating among agronomic histories in the investigated treatments, albeit they used different soil types in different climates. Absolute values are consistent with the other indicators used to describe the changes in chemical and biochemical properties of our soils, but the high variability of C_{SMB} reduced its power in showing significant differences.

5. Conclusions

All the indicators selected for evaluation of the effect on soil properties of the different agronomic histories provided valuable and consistent information on C and N turnover and accumulation in soil. The analysis of the differences between treatments leads us to conclude that (i) PMN, measured under water-logged conditions, not only estimates the increase in readily mineralizable organic N compounds, but also rapidly and reliably indicates the nature of soil C and N, allowing us to assume that a high PMN value as a proportion of N_{tot} is a good indicator of a fertile and well-managed soil; (ii) the first flush of respiration after the soil is rewetted, efficiently differentiates between treatments as it increases when C inputs are higher and unstable and (iii) potential SMB, measured after soil drying and rewetting/fumigation, is highly variable and therefore is a less sensitive indicator of the effect of past agronomic management.

Acknowledgment

The authors would like to thank Ms. Elizabeth Dixon for her assistance in carrying out the experiment.

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