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Seasonal changes in labile organic matter, mineral nitrogen, and N_2O emission in a loamy sand Orthic Luvisol cultivated under three management practices

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A b s t r a c t. Valid evaluation of soil quality requires better understanding of short- and long-term responses of key biochemical and microbiological soil properties to seasonal changes and types of management practice. In our study we evaluated the effects of growing of winter wheat on seasonal changes in the state of a loamy sand Orthic Luvisol cultivated under the conventional, monoculture and organic management practices. The extent of seasonal changes in soil organic matter (SOM) was more pronounced in terms of its labile forms - particulate organic matter (POM) and microbial biomass carbon (MBC) than of its total content. The management practices contributed to the formation of an equilibrium state of SOM, mainly towards the end of the growing season. Seasonal variations in the total amount of NO_3^--N showed weak correlations to those of N_2O emission (r=0.31-0.49, p<0.50) from the soil for all the management practices. However, we observed stronger correlations between the seasonal changes in N_2O emission and MBC content, whereas the organic management practice, compared to the monoculture and conventional practice, had the strongest influence on these relationships (r=0.89, p<0.01), probably as a result of higher content of microbial biomass N. Moreover, differences in N_2O emission induced by the management practices alone were also highly correlated to changes in the MBC content in April and July (r=0.71, p<0.05).

K e y w o r d s: labile organic matter, mineral nitrogen, N_2O emission, management practices, growing period

INTRODUCTION

A reasonable selection of sensitive and robust soil indicators is required to distinguish the trends in improvement and deterioration of soil quality in various agro-ecosystems (Karlen *et al*., 1997; Nortcliff, 2002). Identification and monitoring of the key soil quality indicators can be unsuccessful due to the lack of interdisciplinary approaches (Arshad and Martin, 2002; Herrick, 2000).

Microorganisms (bacteria and fungi) playing a main role in processes of soil organic matter (SOM) and nitrogen transformation, and soil structure formation are key driving forces of soil resilience defined as 'an ability of soils to return to a new dynamic state after damage' (Szabolcs, 1994). Therefore, among approaches to evaluating soil quality, a high priority is now given to integrated microbiological, physicochemical, biochemical, and biophysical studies (Cambardella and Elliott, 1992; Dąbek-Szreniawska *et al*., 2002; Six *et al*., 2004; Väisänen *et al*., 2005).

Because the C and N pools are tightly linked in soils, comprehensive studies of SOM sequestration, nitrification and denitrification are very useful tools for the evaluation of unfavourable losses of different N and C forms from arable soils to the atmosphere, surface water and groundwater. Soil temperature, pH, oxygen availability, redox potential, moisture content, pools of mineral, microbial N and easily available C, freezing and thawing processes, affect the rates of nitrification and denitrification in soils (Dobbie and Smith, 2001; Kaiser *et al*., 1998; Morkved *et al*., 2006; Włodarczyk *et al*., 2003). That is why efforts are being currently undertaken to reduce N_2O and CO_2 emissions from soils by: (1) increasing the efficiency of mineral and organic fertilisers, (2) selection of rational timing and location of application of tillage and fertilisers, and (3) incorporation of plant residues with wide C/N ratios (Huang *et al*., 2004; Velthof *et al*., 2002).

Organic and mineral (inorganic) farming systems can have different effects on the soil quality and crops. Firstly, organic and mineral fertilisers differ from each other in duration of nutrients release and thus have indirect and direct effects on plants. Secondly, there are differences in

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the influence of the organic and mineral management practices on the size and composition of soil microbial community and, as a result, on soil physicochemical and structural properties (Böhme *et al*., 2005; Dąbek-Szreniawska *et al*., 2002; Väisänen *et al*., 2005). Despite the information about the effects of different farming systems on soils being well documented, there is still little site-specific information on: (1) time scale of response of key soil quality indicators to agricultural soil disturbances and (2) behaviour of soils under disturbance regimes. Therefore, long-term interdisciplinary studies are still required to increase the effectiveness of use of soil quality indicators under different land uses and management practices.

The aim of the present studies was to evaluate the effects of growing of winter wheat on seasonal changes in the biochemical, physicochemical, and microbiological quality indicators of a loamy sand Orthic Luvisol cultivated under organic and mineral management practices.

MATERIALS AND METHODS

Disturbed samples of a loamy sand Orthic Luvisol were taken on the territory of the Experimental Station of the Institute of Soil Science and Plant Cultivation (IUNG) in Puławy, Poland. Soil samples were collected from the depth of 0-20 cm in April, July and November of 2004, on plots with growing winter wheat plants, and several weeks after their harvesting (August and September), soil harrowing (September) to a depth of ~5 cm, application of mineral fertilisers (September), and sowing (September). Three management practices are currently used for growing of several crop species at this experimental station. The monoculture management practice (MP) includes amendments with mineral fertilisers (120 kg N, 80 kg P_2O_5 and 100 kg K_2O ha^{-1} yr^{-1}) with continuous winter wheat. The conventional management practice (CP) consists of amendments with the above-mentioned rates of mineral fertilisers in crop rotation with rape, winter wheat and spring barley. The organic management practice (OP) includes an incorporation of manure compost only, at the rate of 33 t ha^{-1}, once in 3 years in crop rotation with potato, spring barley, red clover for two years, and winter wheat. Content of organic C, total N, available P and K in the manure compost was equal to 93.1 g C kg^{-1}, 4.5 g N kg^{-1}, 1.4 g P kg^{-1} and 1.3 g K kg^{-1} of dry matter, respectively.

SOM content in samples was measured by the Tiurin wet oxidation method (Rastvorova *et al*., 1995). To measure the basal respiration (BR) in terms of CO_2 emission rates, we moistened 4-g air-dried soil samples to field capacity and incubated them in glass jars (40 cm^3) for 24 h at 30°C. The CO_2 production was measured with a gas chromatograph equipped with an electron-capture detector that enabled us to simultaneously determine the N_2O emission rates from the soil samples. Afterwards we added glucose (5 mg g^{-1} soil) into the same soil samples and incubated them again for 3 h at 22°C to determine the rates of substrate-induced respiration (SIR) and N_2O emission. Calculations of microbial biomass carbon (MBC) content based on the rates of SIR were made according to an equation proposed by Anderson and Domsch (1978). We determined the content of free particulate organic matter (POM), with a density <1.6 g cm^{-3} and total size fraction of >53 μm, using a technique of wet sieving proposed by Cambardella and Elliott (1992). Mineral NO_3^--N and NH_4^+-N concentrations and pH values were measured in 1:5 ratio soil/water extracts by an ionmeter equipped with relevant ion-selective and glass electrodes. All the measurements of soil properties were made in three replicates. The results were subjected to analysis of variance (ANOVA) for each sampling time, and the means, standard deviations (SD) and coefficients of linear correlations between soil properties were determined at a confidence limit of up to 95%.

RESULTS AND DISCUSSION

There were no significant seasonal changes in the SOM content under all the management practices. Nevertheless, we observed a higher contribution of the OP and CP, compared with the MP, to the SOM sequestration during the growing period. The values of SOM content varied in a range of 7.4-8.9 g C kg^{-1} (MP), 9.4-10.0 g C kg^{-1} (CP) and 10.6-11.7 g C kg^{-1} of soil (OP). These results are in agreement with our previous data on greater positive influence of the OP on the SOM accumulation in this soil (Dąbek-Szreniawska *et al*., 2004).

Different size fractions of the POM are weakly decomposed organic substances derived from plant residues and occluded outside or inside soil aggregates (Cambardella and Elliott, 1992; Yamashita *et al*., 2006). The POM is considered to be one of the labile forms of SOM and therefore its studies enable the understanding how different farming systems can enhance the humification of plant residues, nitrogen transformation, and stabilisation of soil structure on a short- and long-term scale (Compton and Boone, 2002; Six *et al*., 2004).

Our results showed that the POM content demonstrated significant seasonal changes (Fig. 1). Regarding the management practices, we observed a permanent increase in the POM content with time under the MP and CP, except the OP. Decrease in the POM content in July under the OP is likely explained by higher mineralisation of root residues in the soil which could be still present as a high quantity of residue of red clover as continuous preceding crop of winter wheat. The root residues of red clover (C/N ratio < 20) are rich with easily available N compounds and therefore have a higher degree of microbial decomposition than those of winter wheat (C/N ratio > 60) under the MP and CP. The contribution of C in the POM to SOM was greater under the MP (10.8-16.5%) and OP (9.3-13.0%) than under the CP (8.1-10.7%). As reported by Marriott and Wander (2006), long-term organic farming systems also based on the use of manure and legumes have great quantities of C in the POM.

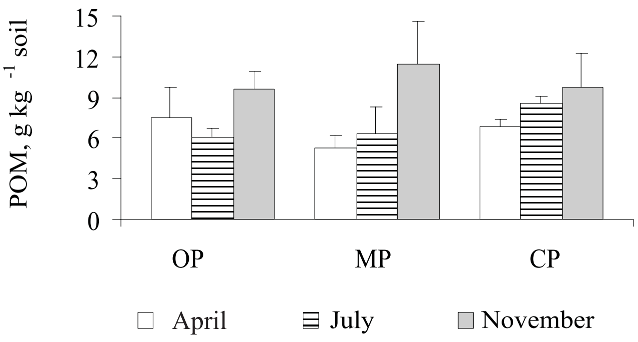

Fig. 1. Dynamics of POM content in Orthic Luvisol under OP, MP and CP during growing period of 2004 (vertical bars are SD at p<0.05).

Compared to the SOM content, we distinguished more pronounced but insignificant changes in the MBC content in the soil during the growing period. As also reported in our recent paper (Balashov and Dąbek-Szreniawska, 2005), there was also a greater accumulation of the MBC under the OP (140-200 mg C kg^{-1} soil) than under the CP (130-190 mg C kg^{-1} soil) and the MP (120-180 mg C kg^{-1} soil). Such small differences in MBC content between the management practices can be explained by weak stabilisation and protection of the POM and MBC in this soil with a low amount of clay particles and water-stable aggregates (Anderson and Domsch, 1978; Dąbek-Szreniawska *et al*., 2004). Therefore, despite the consistent seasonal changes in the POM content, we did not observe its significant contribution to the MBC content in the soil in the OP, MP and CP treatments during the growing period (r= 0.37-0.48, p<0.35).

MBC/SOM ratios as useful indicators of an equilibrium state of SOM had insignificant seasonal changes under all the management practices. The equilibrium state of SOM at the MBC/SOM ratios equal to ~2% (Anderson and Domsch, 1989) was observed in the middle (CP) or only by the end (OP and MP) of growing season.

The MBC/SOM ratios strongly correlated to the MBC content under the MP (p<0.001), OP and CP (both at p<0.0001), as presented in Fig. 2. This data shows that if it is necessary to maintain the equilibrium state of the SOM in this soil, the MBC content has to be managed at a level of >200 mg C kg^{-1} soil.

The metabolic quotient, qCO_2 (BR/MBC ratio), is considered to be a measure of specific metabolic activity of soil microorganisms and is induced by their physiological state, availability of C and nutrients, and other factors (Anderson and Domsch, 1990). Although the qCO_2 did not show any significantly pronounced seasonal changes, we observed management-induced significant differences in its values. The values of the qCO_2 ranged between 9.1-10.1 mg C-CO_2 g^{-1} MBC h^{-1} (CP), 5.3-8.4 mg C-CO_2 g^{-1} MBC h^{-1} (OP) and 3.1-4.0 mg C-CO_2 g^{-1} MBC h^{-1} (MP). The results demonstrated that among these three management practices the soil microbial community in the MP treatment had a higher amount of easily decomposable organic substrates as sources of energy for its activity.

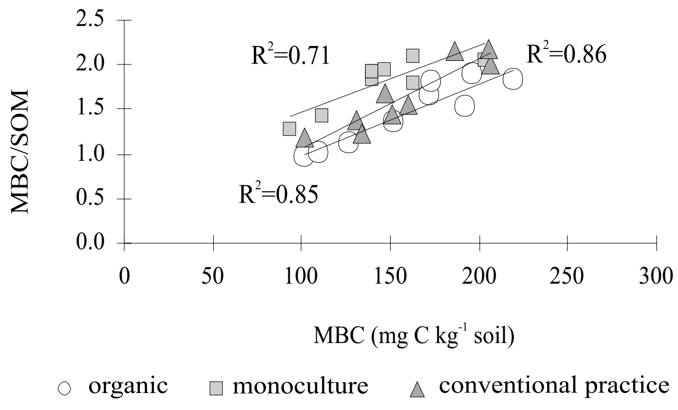

Fig. 2. Relationships between MBC/SOM ratios and MBC content in Orthic Luvisol under OP, MP and CP during growing period of 2004.

As mentioned above, the N_2O emission from soil samples was determined simultaneously with the measurements of BR and SIR. Therefore, we were able to evaluate the N_2O emission at different amounts of C available for soil microorganisms.

Soil pH (H_2O) varied in the ranges of 6.0-6.1 (OP), 5.3-6.5 (MP) and 5.2-5.5 (CP), and showed that better conditions for nitrification were observed in the soil under the OP. Mineral NO_3^- -N concentrations in the soil were comparatively higher under the OP than under the CP and MP, and demonstrated mostly significant seasonal changes (Fig. 3).

NH_4^+- N concentrations in soil were significantly lower than those of NO_3^--N and significantly varied in ranges of 3.1-8.5 mg NH_4^+ kg^{-1} (OP), 1.7-4.7 mg NH_4^+ kg^{-1} (MP), and 2.9-4.8 mg NH_4^+ kg^{-1} soil (CP) during the growing season. The lowest NH_4^+-N concentrations were observed in July, presumably as a result of increased nitrification in this month.

N_2O emission from the soil (without glucose) did not show significant seasonal changes in the management treatments except for the MP (Fig. 4). We observed stronger correlations between the N_2O emission and mineral NO_3^--N concentration under the MP (r=0.49, p<0.20) than under the OP (r=0.32, p<0.50) and CP (r=0.31, p<0.50). This data probably reflects a slightly higher influence of nitrification on N_2O emission from soil under the MP. Compared to the NO_3^--N concentration, N_2O emission under the MP had stronger correlation to the POM (r=0.59, p<0.10) and SOM (r=0.74, p<0.05) content, as well as to BR (r=0.73, p<0.05). However, the N_2O emission had weak correlations to these parameters under the OP and CP. This is likely due to: (1) differences in the composition of soil microbial community in the soil under the MP, OP and CP (Dąbek-Szreniawska *et al.*, 2002), and (2) differences in the biochemical composition of plant residues or easily decomposable organic substrates in the soil in these management treatments (Bending *et al.,* 2002).

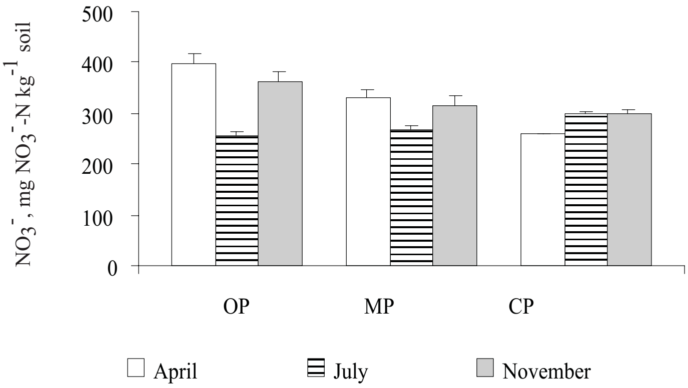

Fig. 3. Dynamics of NO_3^- content in Orthic Luvisol under OP, MP and CP during growing period of 2004 (vertical bars are SD at p<0.05).

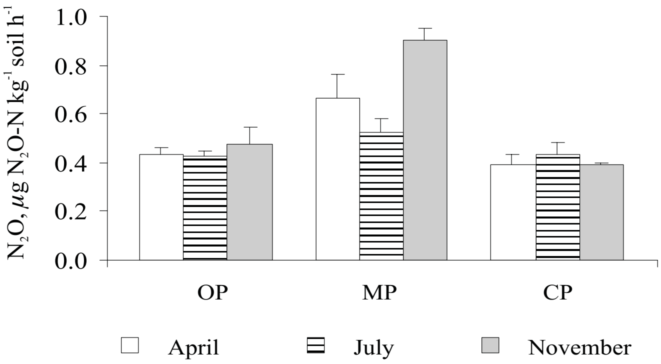

Fig. 4. N_2O emission from Orthic Luvisol under OP, MP and CP during growing period of 2004 (vertical bars are SD at p<0.05).

There were consistent differences in the values of glucose-induced N_2O emission from the soil under the CP (1.4-2.1 mg N_2O-N kg^{-1} soil h^{-1}) and the two other management practices (1.1-1.6 mg N_2O-N kg^{-1} soil h^{-1}). Thus, the soil in the CP treatment showed the highest sensitivity to the input of easily available C. Such an input might have enhanced denitrification in which glucose was oxidized to CO_2 and H_2O, whereas NO_3^- ions (as electron acceptors) were reduced to N_2O and N_2. Higher availability of mineral and biomass NO_3^--N for soil denitrifying microorganisms could be a likely reason for greater increase in N_2O emission after the addition of available C into soil samples taken from the CP treatment than from the MP and OP treatment (Morkved *et al*., 2006; Williams *et al*., 1998). Nevertheless, there were rather weak positive correlations between the seasonal N_2O emission and MBC content under the MP ($r=0.41$, $p<0.30$) and CP ($r=0.59$, $p<0.10$), except the OP ($r=0.89$, $p<0.01$). Decomposition of red clover residues with a high content of easily available N could contribute to enrichment of microbial biomass with N. Therefore, the seasonal relationships between the glucose-induced N_2O emission and MBC content in the soil under the OP were stronger than those under the MP and CP with winter wheat and rape having a wide C/N ratio.

Moreover, we observed strong correlations (at $p<0.05$) of the glucose-induced N_2O emission with MBC content between the OP, MP and CP treatments when winter wheat plants were still growing in April and July (Fig. 5).

This data indirectly supports the above-mentioned importance of microbial biomass N for the control of N_2O emission from soils.

The addition of available organic C with glucose also showed a different sensitivity of the soil to internal impacts in terms of the ratio of N_2O emission rates measured simultaneously with SIR and BR. The values of the N_2O (SIR) to N_2O (BR) emission ratio varied in the ranges of 1.6-2.9 (MP), 2.7-3.2 (OP) and 3.5-5.5 (CP). The data demonstrate that the less favourable soil disturbance regime (in terms of the increased qCO_2 values) under the CP might result in a higher sensitivity of the soil (in terms of increased N_2O emission) to the input of available organic C, possibly in any form (glucose, farmyard or green manure). Therefore, better soil conditions for the microbial community under the MP and OP, compared to the CP, presumably resulted in a decrease of sensitivity *ie* an increase of sustainability of this soil to such internal impacts as the input of available organic C because of its more efficient utilization by soil microorganisms.

CONCLUSIONS

1. The extent of the seasonal changes in SOM was more pronounced in terms of its labile forms (POM and MBC) than its total content. There were insignificant seasonal changes in N_2O emission and significant seasonal variations in the NO_3^- -N and NH_4^+ -N concentrations in the soil.

2. The critical level of MBC content in the soil was equal to approximately 200 mg C kg^{-1} of soil for the maintenance of equilibrium state of SOM under the OP, MP and CP.

3. A mitigation of N_2O emission from this soil can be achieved by improvement of soil conditions for microbial community in terms of its size, specific metabolic activity, and content of mineral and microbial biomass N.

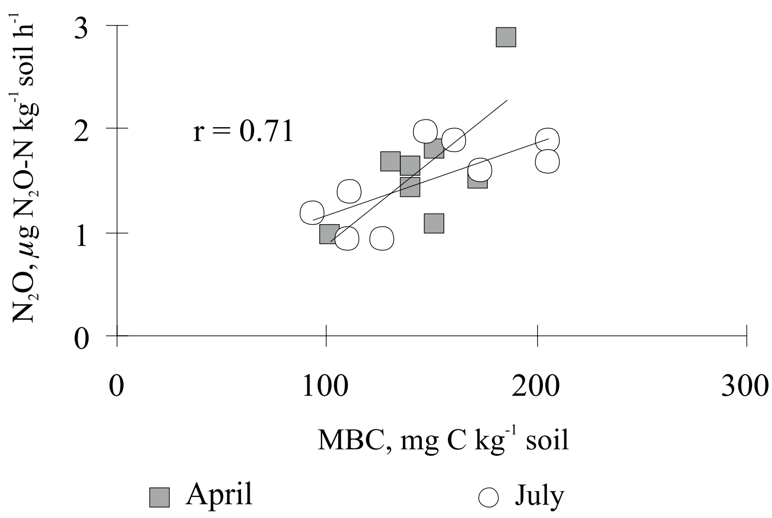

Fig. 5. Relationships between N_2O emission and MBC content in OrthicLuvisol between OP, MP and CP treatments in April and July of 2004.

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