Int. Agrophysics, 2008, 22, 201-208

INTERNATIONAL
Agrophysics
www.international-agrophysics.org

Effect of different tillage systems on some microbiological properties of soils under winter wheat*

A.M. Gajda

Department of Agricultural Microbiology, Institute of Soil Science and Plant Cultivation, National Research Institute (IUNG-PIB), Czartoryskich 8, 24-100 Puławy, Poland

Received May 27, 2007; accepted June 20, 2008

A b s t r a c t. The aim of this research was to determine the effect of applied tillage systems on changes of chosen parameters of soil microbiological activity. Analyses of microbiological properties of soil were performed on soil samples collected from long-term field experiments at a private farm in Rogów (Lublin voivodeship) on silt-loam soil and at the IUNG-PIB Experimental Station in Grabów (Masovian voivodeship) on heavy loamy sand. Winter wheat was grown in conventional (CT) and reduced tillage (RT) systems. Analyses of soil taken from experimental fields included the rate of CO_2 evolution using the titration method; microbial biomass C content using the F-I method; dehydrogenase system activity using TTC as a substrate; microbial biomass N content using the F-E method and the Most Probable Number (MPN) of ammonia- and nitrate-forming bacteria. Applied tillage systems affected significantly the analysed parameters of biological activity of tested soils in both experimental years. In general, at both experimental sites, the numbers of specific groups of soil microorganisms estimated on the quantity of biomass C and N were significantly higher in RT soil than in CT soil (by about 20%, on average) at both depths: 0-15 and 15-30 cm. In 2006 and 2007, the dehydrogenase activity, ammonification and nitrification strength of soil reached the highest values mostly in RT soil at both experimental sites. Calculated higher values of microbial quotient and lower values of metabolic quotient in RT soil indicate that the RT system created a more friendly environment for the growth and activity of soil microorganisms, in comparison with the CT system.

K e y w o r d s: microbial respiration, microbial biomass C and N, activity of dehydrogenases, ammonia- and nitrate-forming bacteria, tillage system

INTRODUCTION

Management practices can have major impacts on the content of soil organic carbon (SOC) in soil. Davidson and Ackerman (1993) reported 20% to 40% loss of soil organic matter following the conversion of previously untilled soils to agricultural production. Conversion of land from plough tillage to long-term no-tillage management often increases soil organic C and N content (Buyanovsky and Wagner, 1998; Doran, 1980, 1987; Gajda and Martyniuk, 2005; Gajda *et al*., 2001; McCarty and Meisinger, 1997; McCarty *et al*., 1995, Marinari *et al*., 2006).

The increase of global temperature may affect several major soil processes with a consequent impact on soil quality. Quantity and quality of organic matter in soil, together with products of its biological and biochemical transformations, determine whole complex of biological and biochemical properties influencing soil quality and productivity. Soil microorganisms, the living and active component of soil organic matter (SOM), play an extremely important role in creation of soil quality and productivity through their activity in degradation of plant and animal residues, participation in biogeochemical nutrients cycle and soil structure formation, detoxification of agrochemicals and organic pollutants in the soil environment (Anderson and Domsch, 1989; Brooks *et al*., 2008; Carter *et al*., 1999; Doran *et al*., 1998; Franzluebbers, 1999; Jenkinson, 1988; Rice *et al*., 1994; Sparling, 1992).

Corresponding author's e-mail: ag@iung.pulawy.pl
*The work was done under Programme of the Scientific Network, AGROGAS Project 'Reduction of greenhouse gas and ammonia in agriculture', contract No. 17/E-164/SN-019/2007.

Recent concern about increasing levels of atmospheric CO_2 and consequent global warning has increased interest in the sequestration or storage of C in the form of SOM through the use of conservation management systems in agricultural practice (Lal, 2000; West, 2002).

The objective of this work was to determine the effects of conventional and reduced tillage systems on changes of chosen parameters of microbiological activity of two different soils.

MATERIALS AND METHODS

Analyses of microbiological properties of soil were performed on soil samples collected throughout the growing seasons of 2006 and 2007 from the long-term field experiment (started in 2002) at a private farm (PF) in Rogów (Lublin voivodeship) on a silt-loam soil and at the IUNG-PIB Experimental Station (ES) in Grabów (Masovian voivodeship) on a heavy loamy sand. At both experimental sites winter wheat was grown under two tillage systems: conventional tillage (CT) based on the mouldboard plough and traditional soil tillage equipment with the field surface mulched with chopped wheat straw, and reduced tillage (RT) with the surface mulched with chopped wheat straw based on soil crushing-loosening equipment and a rigid-tine cultivator. All samples were collected from between wheel tracks from soil pits which were dug in the field under the different treatments at both locations. The representative samples, each consisting of 1500 g of soil, were taken from the 0-15, 15-30 cm layers of soil. All fresh soil samples were passed through a 2 mm sieve and stored at 4°C in a refrigerator. Microbiological analyses of 64 soil samples (4 soil depths x 2 tillage systems x 2 locations x 2 samplings x 2 years) included: the rate of CO_2 evolution from soil using the titration method; microbial biomass C content using the F-I (fumigation-incubation) method (Jenkinson and Powlson, 1976) modified by Voroney and Paul (1984); dehydrogenase system activity using TTC as a substrate (Casida *et al*., 1964); microbial biomass N content using the F-E (fumigation-extraction) method (Jenkinson and Powlson, 1976) modified by Keeney and Nelson (1982); the number of ammonia- and nitrate-forming bacteria using the most probable number (MPN) technique according to McCrady (1980). All analyses were performed using fresh soil in 3 replicates of each sample. Statistical analyses were made separately for each experimental year using the ANOVA method and differences at $P<0.05$ were considered as significant.

RESULTS AND DISCUSSION

In both experimental years, 2006 and 2007, the applied tillage systems affected significantly the analysed parameters of the microbiological activity of the tested soils.

In 2006, the largest amounts of CO_2 evolved were measured with the RT soil sampled at 0-15 cm depth in Rogów – 310 μg CO_2-C/g d.w. of soil, on average. Evolution of CO_2 at 15-30 cm depth was about 35% less than at 0-15 cm depth (significant at $P<0.05$) in the RT system, but in the CT the differences between soil depths were not statistically significant (Fig. 1A). In 2007, larger amounts of CO_2 evolved (about 10-20%, on average) were measured with the Rogów CT soil than with the RT soil. At the depths of 0-15 cm and 15-30 cm of CT soil, amounts of CO_2 evolved averaged 226 and 209 μg CO_2-C/g d.w. of soil, respectively, in comparison with RT – 204 μg CO_2-C/g d.w. of soil at 0-15 cm depth and 165.5 μg CO_2-C/g d.w. of soil at 15-30 cm depth, on average (Fig.1A). In the second year of the experiment, the differences in CO_2 evolution between soil depths of CT soil were not statistically significant. Similar trends in CO_2 evolution to the ones reported for the Rogów soil in 2006 were observed in both experimental years in soil taken from the experimental fields in Grabów, but the values obtained were less than 50% of those obtained in the Rogów soil (Fig. 1B). Also Dilly (2001), Doran and Parkin (1996) and Marinari *et al*. (2006) reported a higher rate of CO_2 evolution in soil under reduced than conventional tillage system.

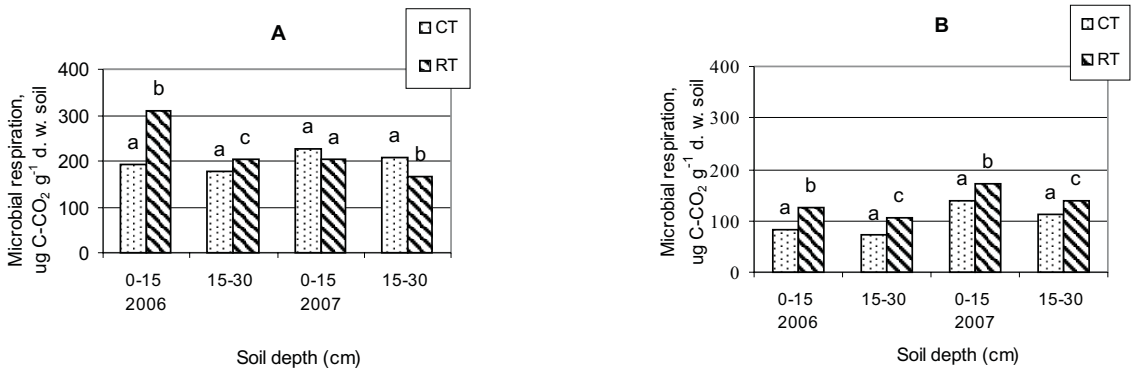

Fig. 1. Rate of CO_2 evolution from soils under winter wheat grown in CT and RT systems in Rogów (A) and Grabów (B) in 2006 and 2007. Values marked with the same character are not significantly different at $P \leq 0.05$

Soil microbial biomass, as the living and most dynamic component of the soil organic matter, may indicate potential for biological activity of soil (Bending *et al*., 2004; Doran and Parkin, 1994). In both experimental years, 2006 and 2007, the highest content of soil microbial biomass C was estimated in RT soil taken from Rogów at the 0-15 cm depth – 430 and 465 μg CO_2-C/g d.w. of soil, respectively (on average). Soil managed conventionally contained a smaller amount of microbial biomass C pool (about 20%) than the RT soil. Microbial biomass C contents were smaller at 15-30 cm depth than at 0-15 cm depth in both CT and RT soil, by about 20% and 30%, respectively (significant at $P<0.05$), as shown in Fig. 2A. Similar trends in microbial biomass C content were observed with soil taken from the experimental fields in Grabów in 2007, but the values obtained in 2006 were less than 50% of those obtained with the Rogów soil. There were no significant differences in soil microbial biomass C content between the two tillage systems in Grabów in 2006 (Fig. 2B). Other authors have also indicated higher results in microbial biomass concentration in soil under reduced tillage, in comparison with the conventional tillage system (Acosta-Martinez *et al*. 2008; Bulluck *et al*. 2002; Doran *et al*., 1998; Fießbach *et al*. 2007; Gajda *et al*., 2001; Liebig and Doran, 1999; Marinari *et al*., 2006).

Numerous studies have shown that the activity of soil enzymes can be used as a sensitive indicator of changes in soil biological activity and fertility in response to various soil management practices (Bending *et al*., 2004; Doran, 1987; Marinari *et al*., 2006). In our studies, the effect of soil tillage system on enzymatic activity of the soils was determined by assessing the activity of dehydrogenase systems, which provides correlative information on the biological activity and microbial populations in soil as well as indicates the rate of organic matter oxidation (Gajda and Martyniuk, 2005; Gajda *et al*., 2001; Martyniuk *et al*., 2001; Włodarczyk, 1998). The activity of the dehydrogenase system in the studied soils was influenced by both the applied tillage systems and soil depth. The greatest activity of dehydrogenases was measured in RT soil in Rogów in the layer of 0-15 cm – 1517.6 mm^3 H_2/100 g d.w. of soil, and 2131.4 mm^3 H_2/100 g d.w. of soil, in 2006 and 2007, respectively. Similar trends were observed in the layer of 15-30 cm. In the CT the measurements of dehydrogenases activity were only about 60% (on average) of those measured with the RT soil. In the RT soil, an effect of soil depth (significant at $P<0.05$) was observed, in both studied years. In the surface layer the measurements of dehydrogenase activity were about 25% (on average) greater than in the subsurface soil in both experimental years (Fig. 3A). The results with the Grabów soil showed similar trends to those obtained with the Rogów soil, but the values in the RT soil in Grabów were only about 35% of those obtained in Rogów (Fig. 3A, B). Similar results have been presented by other authors *eg* Gajda *et al*. (2000), Marinari *et al*. (2006), Martyniuk *et al*. (2001).

An influence of tillage system on the microbial biomass N content in the studied soils was also observed. The greatest content of microbial biomass N was measured in 2006 in RT soil in Rogσw, in both studied layers – 0-15 and 15-30 cm – 33.7 and 28.0 μg N/g d.w. of soil, respectively. In the CT soil the estimations of microbial biomass N were only about 20% (on average) of those measured with the RT soil. In the RT soil, an effect of soil depth (significant at $P<0.05$) was observed in both experimental years. In the surface layer estimations of microbial biomass N were 20% greater than in the subsurface soil (Fig. 4A). The results with the Grabów soil showed similar trends to those obtained with the Rogów soil, but the values in the RT soil in Grabów were only about 20-40% of those obtained in Rogów (Fig. 4A, B). There were no statistically significant differences in the size of the microbial biomass N pools in the CT soil at both experimental sites in 2006, but in the second year of the experiment, 2007, the differences became deeper and statistically significant at $P<0.05$ (Fig. 4A, B). Similar results have been presented by Acosta-Martinez *et al*. (2008), Cookson *et al*. (2008), Doran and Parkin (1996), Gajda and Martyniuk (2005), Mäder *et al*. (1995), Panhurst *et al*. (1998).

Ammonification is a measure of the net N mineralisation, as immobilisation of NH_4^+ by soil microorganisms into new biomass occurs simultaneously with the mineralisation process (Winding *et al*., 2005). Determination of the quantities of soil microorganisms active in decomposition of organic N associations gives the possibility to estimate the ammonification strength of soil. Figs 5A, B and 6A, B show the growth dynamics of ammonia-forming bacteria in soils under winter wheat in 2006 and 2007, respectively, during 7 days of incubation. At the beginning (1-2 days of incubation), the number of ammonia-forming bacteria was very low, especially in experimental year 2006. Differentiation of ammonification strength (significant at $P<0.05$) affected by tillage system and soil depth appeared after 3 days of incubation, but the maximum of differentiation was reached on the 4th day of incubation in both experimental years. In RT soil taken from Rogów in 2006 and 2007, in both soil depths the strength of ammonification was about 3 times greater than the strength of ammonification measured in CT soil (Figs 5A, 6A). Similar results were obtained in soil taken from the experimental fields in Grabów. In the RT soil in 2006 the measurements of the ammonification strength were about 2 times larger in the 0-15 cm depth range and 1.4 times larger in the 15-30 cm depth range, in comparison with the CT soil (Fig. 5B). In 2007, in the RT soil the measurements of the ammonification strength were about 2.5 times larger in the 0-15 cm depth range and about 2 times larger in the 15-30 cm depth range, in comparison with the CT soil (Fig. 6B). Other authors have reported similar results (Bloem and Breure, 2003; Doran, 1987; Doran *et al*., 1998; Gunapala and Scow, 1998; Nsabimana *et al*., 2004; Römbke *et al*., 2002; Schipper and Sparling, 2000).

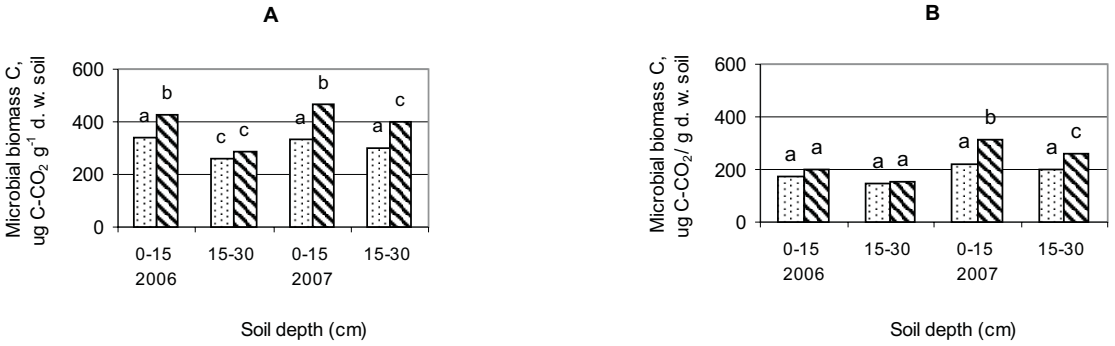

Fig. 2. Microbial biomass C content in soils under winter wheat grown in CT and RT tillage systems in Rogów (A) and Grabów (B) in 2006 and 2007.

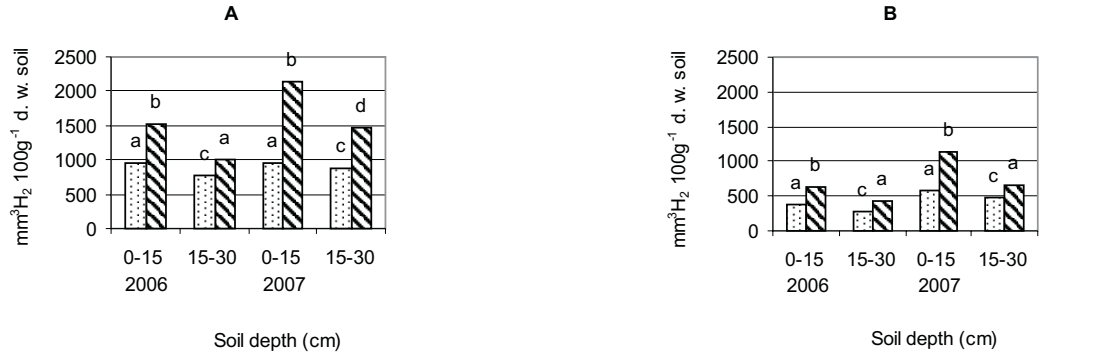

Fig. 3. Dehydrogenase system activity in soils under winter wheat grown in CT and RT tillage systems in Rogów (A) and Grabów (B) in 2006 and 2007.

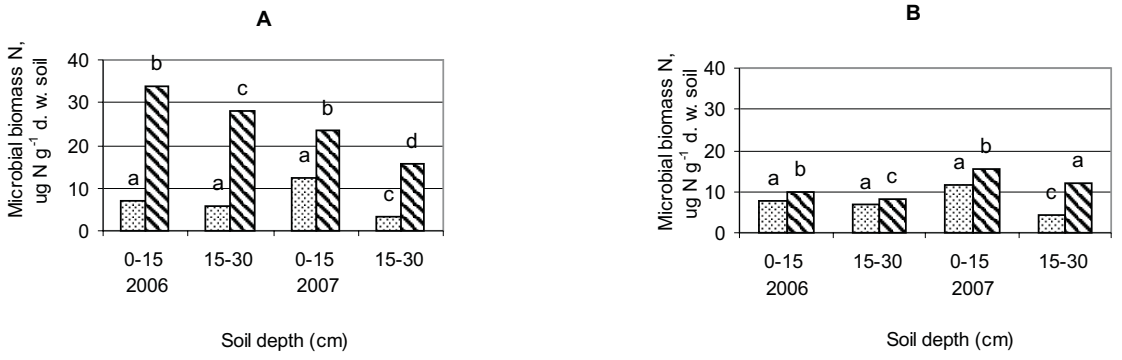

Fig. 4. Microbial biomass N content in soils under winter wheat grown in CT and RT tillage systems in Rogów (A) and Grabów (B) in 2006 and 2007.

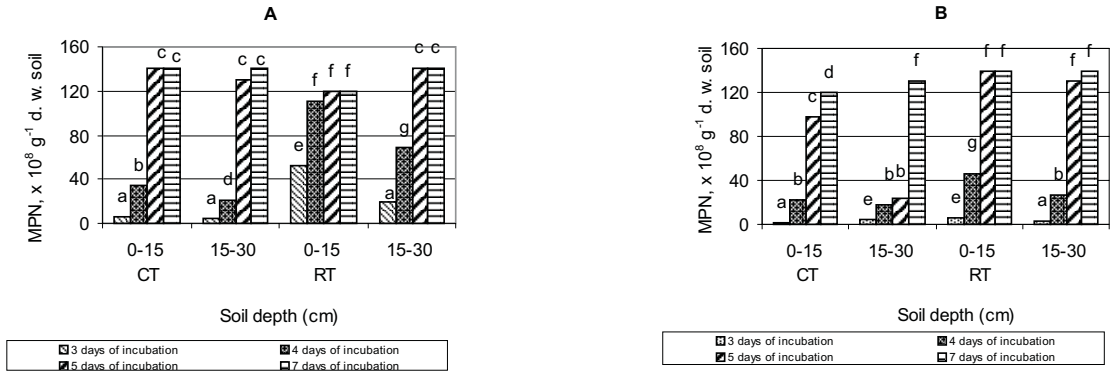

Fig. 5. Most probable number (MPN) of ammonia-forming bacteria in medium inoculated with soils under winter wheat grown in CT and RT in Rogów (A) and in Grabów (B) in 2006.

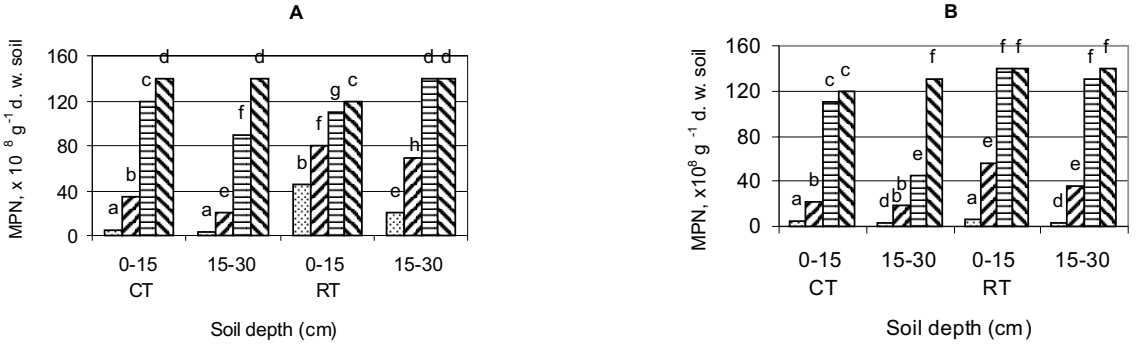

Fig. 6. Most probable number (MPN) of ammonia-forming bacteria in medium inoculated with soils under winter wheat grown in CT and RT in Rogów (A) and in Grabów (B) in 2007.

The next step in the degradation of nitrogen compounds in soil is the process of nitrification. Nitrification measurements reflect the population size of the nitrifiers, for which ammonium is an essential substrate. In both experimental years, at both experimental sites, the tillage system and soil depth affected the number of nitrate-forming bacteria (significant at $P<0.05$). Higher counts of nitrate-forming bacteria (about 1.3 times, on average) were found in the surface layer of reduced- and conventionally-managed soil in Rogów and Grabów, in comparison with the 15-30 cm layer, in both experimental years. The RT soil showed higher counts of nitrate-forming bacteria in both of the studied soil layers (about 1.8 times, on average), in comparison with the CT soil. In general, CT and RT soil taken in Rogów and in Grabów contained similar numbers of nitrate-forming bacteria in both depths ranges. The results show significantly greater nitrification strength of RT soil than soil managed conventionally at both experimental sites in 2006 and 2007 (Fig. 7A, B). Similar results have been published earlier by Winding *et al*. (2005) and Marinari *et al*. (2006).

The metabolic quotient (qCO_2), defined as the ratio of basal respiration to microbial biomass, has been proposed over the past decades as an indicator of ecosystem disturbance and development (Anderson and Domsch, 1989; Dilly, 2006). According to Flieβbach and Mäder (2000), the metabolic efficiency of a microbial community is supposed to be reflected by its specific respiration rate. Differences in qCO_2 are often discussed as a reaction to stress or different community structure. In our studies, the qCO_2 reached lower values under RT systems in 0-15 cm and 15-30 cm layers (RT – 0.50, 0.55 at Rogów; and RT – 0.48, 0.43 at Grabów) in comparison with CT – 0.71, 0.73 at Rogów; and 0.68, 0.63 at Grabów, respectively (Fig. 8). Previous studies by Insam and Domsch (1989), Stolze *et al*. (2000), Nsabimana *et al*. (2004), Dilly *et al*. (2005) have also indicated that values of qCO_2 are greater in disturbed conditions. This suggests that the repeated cultivation was the most regularly disturbed treatment and that the reduced treatment was the least disturbed, especially as the experiment progressed.

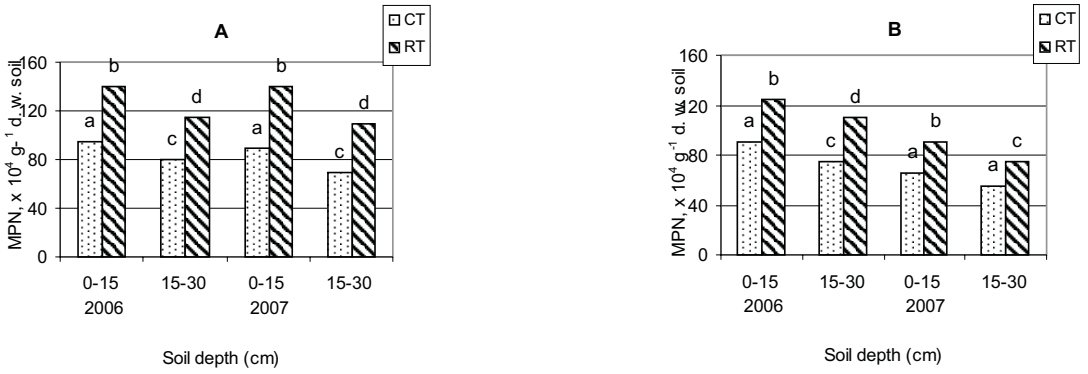

Fig. 7. Most probable number (MPN) of nitrate-forming bacteria (*Nitrosomonas spp., Nitrobacter spp*. i inne) in soils under winter wheat grown in CT and RT in Rogów (A) and Grabów (B) in 2006 and 2007.

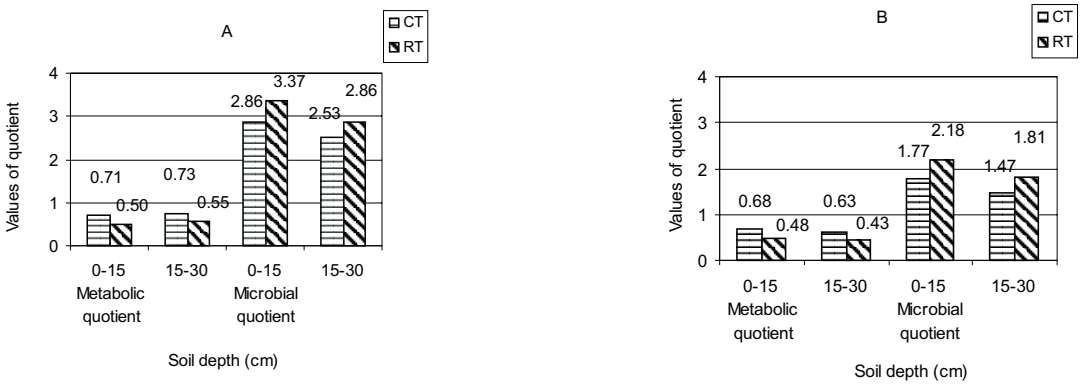

Fig. 8. Obtained values of microbial quotient and metabolic quotient in soils under winter wheat grown in CT and RT in Rogów (A) and Grabów (B).

The microbial quotient (proportion of microbial biomass C to total soil organic C) can be an indicator of changes undergone by the organic matter of the soil (Angers *et al*., 1999). In this field trial the ratio of microbial biomass C/total organic C was higher in the surface and subsurface layers of soil under the RT system 3.37, 2.89 at Rogów and 2.18, 1.81 at Grabów than in soil under the CT system 2.86, 2.53 at Rogów and 1.77, 1.47 at Grabów, respectively (Fig. 8). This indicates that a larger pool of microbial biomass C in RT soil creates beneficial conditions in the soil environment for development, proliferation and activity of soil microorganisms. Results obtained previously by Anderson and Domsch (1989), Marinari *et al*. (2006), and Moscatelli *et al*. (2005) showed similar trends.

CONCLUSIONS

1. Significant effects of tillage systems on quantities of microorganisms active in C and N transformations were found in the studied soils.

2. In general, in both experimental years, at both experimental sites, the number of populations of soil microorganisms estimated on the amount of C and N contained in their biomass was significantly higher in RT soil (about 20-30%, on average) than in CT soil in both depth ranges: 0-15 and 15-30 cm.

3. The dehydrogenases activity, ammonification and nitrification strength of soils reached the highest values mostly in RT soil at both experimental sites.

4. Calculated higher values of microbial quotient and lower values of metabolic quotient in RT soil indicate that the RT system, in comparison with the CT system, was more friendly for the soil environment. It was reflected in increased activity of soil microorganisms – the active pool of the soil organic matter, playing an extremely important role in supplying sources of energy and nutrients in soil necessary for activity of soil biota and growing crops.

5. It was noticed in the 2007 larger measurements that larger amounts of CO_2 were evolved from CT soil than from RT soil in Rogów. This may indicate that repeated tillage results in accelerated oxidation of organic matter by soil organisms, with the untimely release of respired CO_2 back to the atmosphere.

REFERENCES

Acosta-Martinez V., Acosta-Mercado D., Sotomayor-Ramirez D., and Cruz-Rodriguez L., 2008. Microbial communities and enzymatic activities under different management in semiarid soils. Appl. Soil Ecol., 38, 249-260.

Anderson J.P.E. and Domsch K.H., 1989. Ratios of microbial biomass carbon to total carbon in arable soils. Soil Biol. Biochem., 21, 471-479.

Angers D.A., Edwards L.M., Sanderson J.B., and Bissonnette N., 1999. Soil organic matter quality and aggregate stability under eight potato cropping sequences in a fine sandy loam of Prince Edward Island. Can. J. Soil Sci., 79, 411.

Bending G.D., Turner M.K., Rayns F., Marx M.C., and Wood M., 2004. Microbial and biochemical soil quality indicators and their potential for differentiating areas under contrasting agricultural management regimes. Soil Biol. Biochem., 36, 1785-1792.

Bloem J. and Breure A.M., 2003. Microbial indicators. In: Bioindicators and Biomonitors (Eds B.A. Markert, A.M. Breure, H.G. Zechmeister). Elsevier, Oxford, 259-282.

Brooks P.C., Cayuela M.L., Contin M., Nobili De M., Kemmitt S.J., and Mondini C., 2008. The mineralization of fresh and humified soil organic matter by soil microbial biomass. Waste Manag., 28, 716-722.

Bulluck L.R., Brosius M., Evanoylo G.K., and Ristaino J.B., 2002. Organic and synthetic fertility amendments influence soil microbial, physical and chemical properties on organic and conventional farms. Appl. Soil Ecol., 19, 147-160.

Buyanovsky G.A. and Wagner G.H., 1998. Changing role of cultivated land in the global carbon cycle. Biol. Fert. Soils, 27, 242-245.

Carter M.R., Gregorich E.G., Angers D.A., Beare M.H., Sparling G.P., Wardle D.A., and Voroney R.P., 1999. Interpretation of microbial biomass measurement for soil quality assessment in humid temperate regions. Can. J. Soil Sci., 79, 4-16.

Casida L.E., Klein D.A. Jr., and Santoro T., 1964. Soil dehydrogenase activity. Soil Sci., 37, 98-105.

Cookson R.W., Murphy D., and Roper M.M., 2008. Characterizing the relationships between soil organic matter components and microbial function and composition along a tillage disturbance gradient. Soil Biol. Biochem., 40, 763-777.

Davidson E. A. and Ackerman I. L., 1993. Changes in soil carbon inventories following cultivation of previously untilled soils. Biogeochem., 20, 161-193.

Dilly O., 2001. Microbial respiratory quotient during basal metabolism and after glucose amendment in soils and litter. Soil Biol. Biochem., 33, 117-127.

Dilly O., 2005. Ratios of microbial biomass estimates to evaluate microbial physiology in soil. Biol. Fert. Soils, 42, 241-246.

Dilly O., 2006. Microbial energetics in soils. In: Microorganisms in Soils: Roles in Genesis and Functions (Eds F. Buscot, A. Varna). Springer-Verlag, Berlin-Heidelberg, Germany.

Doran J.W., 1980. Soil microbial and biochemical changes associated with reduced tillage. Soil Sci. Soc. Am. J., 44, 765-771.

Doran J.W., 1987. Microbial biomass and mineralizable nitrogen distribution in no-tilled and plowed soils. Biol. Fert. Soils, 5, 68-75.

Doran J.W., Elliott E.T., and Paustian K., 1998. Soil microbial activity, nitrogen cycling, and long-term changes in organic carbon pools as related to fallow tillage management. Soil Till. Res., 49, 3-18.

Doran J.W. and Parkin T.B., 1994. Defining and assessing soil quality. In: Defining Soil Quality for Sustainable Environment. Soil Science Society of America (Eds J.W. Doran, D.C. Coleman, D.F. Bezdicek, B.A. Stewart). American Society of Agronomy, Madison, WI, USA.

Doran J.W. and Parkin T.B., 1996. Quantitative indicators of soil quality: A minimum data set. In: Methods for Assessing Soil Quality (Eds J.W. Doran, A.J. Jones). SSSA Special Publication, 49, Madison, WI, USA.

Flieβbach A. and Mäder P., 2000. Microbial biomass and size-density fraction differ between soils of organic and conventional agricultural systems. Soil Biol. Biochem., 32, 757-762.

Flieβbach A., Oberholzer H.R., Gunst L., and Mäder P., 2007. Soil organic matter and biological soil quality indicators after 21 years of organic and conventional farming. Agric. Ecosys. Environ., 118, 273-284.

Franzluebbers A.J., 1999. Introduction to Symposium – Microbial Biomass: Measurement and role in soil quality. Can. J. Soil Sci., 79, 505-506.

Gajda A.M., Doran J.W., Kettler T.A., Wienhold B.J., Pikul J.L. Jr., and Cambardella C.A., 2001. Soil quality evaluations of alternative conventional management systems in the great plains. In: Assessment Methods for Soil Carbon (Eds R. Lal, J.M. Kimble, R.F. Follett, B.A. Stewart). CRC Press, Boca Raton, FL, USA.

Gajda A.M. and Martyniuk S., 2005. Microbial biomass C and N and activity of enzymes in soil under winter wheat grown in different crop management systems. Polish J. Environ. Studies, 14, 159-163.

Gajda A., Martyniuk S., Stachyra A., Wróblewska B., and Zięba S., 2000. Relations between microbiological and biochemical properties of soil under different agrotechnical conditions and its productivity. Polish J. Soil Sci., 33, 50-57.

Gunapala N. and Scow K.M., 1998. Dynamics of soil microbial biomass and activity in conventional and organic farming system. Soil Biol. Biochem., 30, 805-816.

Insam H. and Domsch K.H., 1989. Relationship between soil organic carbon and microbial biomass on chronosequence of reclamation sites. Microbial Ecol., 15, 177-188.

Jenkinson D.S., 1988. Determination of microbial biomass carbon and nitrogen in soil. In: Advances in nitrogen cycling in agricultural ecosystems (Ed. J.R. Wilson). CAB Press, Wallingford, England.

Jenkinson D.S. and Powlson D.S., 1976. The effect of biocidal treatments on metabolism in soil. V. A method for measuring microbial biomass. Soil Biol. Biochem., 8, 209-213.

Keeney D.R. and Nelson D.W., 1982. Nitrogen: Inorganic forms. In: Methods for analysis (Eds A.L. Page *et al*.). Part 2. Agron. Monogr., 9. ASA and SSSA, Madison, WI, USA.

Lal R., 2000. Soil management in developing countries. Soil Sci., 165, 57-72.

Liebig M.A. and Doran J.W., 1999. Impact of organic production practices on soil quality indicators. J. Environ. Qual., 28, 1601-1609.

Mäder P., Fließbach A., Wiemken A., and Niggli U., 1995. Assessment of soil microbial status under long-term low input (biological) and high input (conventional) agriculture. Proc. Concerted Action Air 3-CT94 'Fertilization Systems in Organic Farming', April 14-16, Darmstadt, Germany.

Marinari S., Mancinelli R., Campiglia E., and Grego S., 2006. Chemical and biological indicators of soil quality in organic and conventional farming systems in Italy. Ecological Indicators, 6, 701-711.

Martyniuk S., Gajda A., and Kuś J., 2001. Microbiological and biochemical properties of soil under cereals grown in the ecological, conventional and integrated systems. Acta Agrophysica, 52, 185-192.

McCarty G.W., Meisinger J.J., and Jennsikens J.M.M., 1995. Relationship between total-N, biomass-N, and active-N in soil under different tillage and fertilizer treatments. Soil Biol. Biochem., 27, 1245-1250.

McCarty G.W. and Meisinger J.J., 1997. Effects of N fertilizer treatments on biologically active N pools in soils under plow and no tillage. Biol. Fert. Soils, 24, 406-412.

McCrady J.E., 1980. The method of calculation of most probably number of bacteria - Handbook of Practical Bacteriology, Edinburgh-London. In: Microbiology of Water and Sewage Sludge (Ed. M. Pawlarczyk-Szpilowa). PWN Press, Warsaw, Poland.

Moscatelli M.C., Lagomassino A., Marinari S., De Angelis P., and Grego S., 2005. Soil microbial indices as bioindicators of environmental changes in poplar plantation. Ecol. Indicators, 5, 171-179.

Nsabimana D., Haynes R.J., and Wallis F.M., 2004. Size, activity and catabolic diversity of the soil microbial biomass as affected by land use. Appl. Soil Ecol., 26, 81-92.

Panhurst C.E., Rogers S.L., and Gupta V.V.S.R., 1998. Microbial parameters for monitoring soil pollution. In: Environmental Biomonitoring – The Biotechnology Ecotoxicology Interface (Eds J.M. Lynch, A. Wieseman). Cambrigde University Press, Cambridge, UK.

Rice C.W., Garcia F.O., Hampton C.O., and Owensby C.E., 1994. Soil microbial response in tallgrass prairie to evaluate CO_2. Plant and Soil, 165, 67-74.

Römbke J., Labes G., and Woiwode J., 2002. Ansätze für biologische Bewertungskonzepte im Bodenschutz. Bodenschutz, 2, 62-69.

Schipper L.A. and Sparling G.P., 2000. Performance of soil condition indicators across taxonomic groups and land use. Soil Sci. Soc. Am. J., 64, 300-311.

Sparling G.P., 1992. Ratio of microbial biomass to soil organic carbon as a sensitive indicator of changes in soil organic matter. Australian J. Soil Res., 30, 195-207.

Stolze M., Piorr A., Häring A., and Dabbert S., 2000. The environmental impact of organic farming in Europe. In: Organic Farming in Europe, Economics and Policy, Hago Druck and Medien Press, Karlsbad-Ittersbach-Hohenheim, Germany.

Voroney R.P. and Paul E.A., 1984. Determination of K_C and K_N in situ for calibration of the chloroform incubation method. Soil Biol. Biochem., 16, 9-14.

West T.O. and Post W.M., 2002. Soil organic carbon sequestration rates by tillage and crop rotation: a global data analysis. Soil Sci. Soc. Am. J., 66, 1930-1946.

Winding A., Hund-Rinke K., and Rutgers M., 2005. The use of microorganisms in ecological soil classification and assessment concepts. Ecotoxicol. Environ. Safety, 62, 230-248.

Włodarczyk T., 1998. Effects of sampling season and storage period on dehydrogenase and catalase activity of an Orthic Luvisol. Polish J. Soil Sci., 31, 2, 59-67.