Relationships between winter wheat yields and soil carbon under various tillage systems

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ABSTRACT

Soil quality and fertility are associated with its productivity, and this in turn is connected to the soil biological activity. To study these effects, well designed long-term field experiments that provide comprehensive data sets are the most applicable. Four treatments (tillage methods) were set up: (1) conventional tillage (CT); (2) no tillage (NT); (3) minimum tillage + straw (MTS), and (4) no tillage + mulch (NTM). Our objective was to assess the relationships between soil microbial characteristics and winter wheat yields under these different techniques of conservation tillage within a field experiment, originally established in 1995. The differences in average grain yields over time period 2002–2009 between the variants were not statistically significant. Organic carbon in the topsoil was higher in plots with conservation tillage (NT, MTS, and NTM), than in the conventional tillage plots. There was a statistically significant correlation ($P \leq 0.01$) between the grain yields and organic C content in topsoil.

Keywords: soil tillage; *Triticum aestivum*; soil organic C; microbial biomass C

Soil quality, which determines the soil fertility and productivity of agroecosystems, is an important objective of sustainable agriculture (Melero et al. 2006, Roger-Estrade et al. 2010). Arable lands under cultivation differ dramatically from native soils. The periodic utilization of conventional tillage practices affects the top soil layer, and may lead to both a decline of the soil's organic matter as well as to soil erosion. In addition, excessive tillage can produce compaction, soil crusting, and damage to the soil biota (Kladivko 2001). To mitigate these problems, conservation soil tillage technologies (no-till and reduced tillage) have been adopted worldwide. Nevertheless, practical experience has shown that they are not universally applicable (Friedrich 2003). In Europe, conservation agriculture was less widely adopted than in other regions of the world, and the reduced tillage is more often used than the no tillage (Lahmar et al. 2006). Van den Putte et al. (2010) reviewed and assessed the effects of soil tillage on crop yields, using 47 studies from 75 sites all over Europe. Their analysis showed that the introduction of conservation tillage in Europe may have some negative effect (ca. 4.5%) on yields. However, no significant crop yield reduction was observed with deep reduced tillage (RT). On average, for deep RT, the yields are even somewhat higher than for the conventional tillage; except with maize.

Sustainable soil management systems not only require the proper choice of cropping methods, tillage techniques, as well as ensuring a supply of nutrients; but they also require subsequent soil quality evaluations. It is well known that soil quality and fertility are connected to the biological activity of a soil. The biochemical properties of soil are widely used to evaluate soil quality. Among the general parameters, the microbial biomass C is considered to be the most reliable. In the Czech Republic, conventional tillage is the predominant method of land preparation. Nevertheless, about 18% of the agriculturally used land by 2005 was converted to reduced tillage, and about another 3.5% to no tillage (Lahmar et al. 2006). Past research on conservation agriculture focused on both the effects of the tillage practices on the crop yields (Šíp et al. 2009) and the soil quality (Mikanová et al. 2009). To study such effects, well designed long-term field experiments that can provide comprehensive data sets are the most

Supported by the Ministry of Agriculture of the Czech Republic, Project No. MZE 0002700604.

suitable. Based on these, both short and long-term changes in soil and crop traits can be evaluated, and specific trends characterizing conversion and the stationary phase of conservation tillage can be defined. Our objective was to assess the relationships between soil microbial characteristics and winter wheat yields under different techniques of conservation tillage and crop management in a field experiment, originally established on an orthic Luvisol in 1995.

MATERIAL AND METHODS

Field experimental design. Since 1995, the experiment has been continuously conducted in an area with a temperate semiarid climate, 338 m a.s.l., annual mean air temperature of 8.2°C, and an annual mean precipitation of 477 mm. The field experiment was established as a rotation of three crops: winter wheat (*Triticum aestivum* L.), spring barley (*Hordeum vulgare* L.), and pea (*Pisum sativum* L.). A split plot method, with four replications, was used. Four different treatments (tillage methods) were set up: (1) conventional tillage (CT), i.e. mouldboard ploughing to a depth of 0.20 m, usual seed bed preparation and sowing; (2) no tillage (NT), i.e. sowing with a special drill machine into non-tilled soil; (3) minimum tillage (MTS), i.e. shallow tillage (about 10 cm deep) and chopped straw with the post-harvest residues of the catchcrop incorporated; (4) no tillage + mulch (NTM), i.e. direct drilling into non-tilled soil, covered with the catchcrop post harvest residues and chopped straw. The field site has a soil of clay-loam texture (Orthic Luvisol, FAO Taxonomy), with a bulk density within the range from 1.57 (CT) to 1.65 g/cm^3 (NT) in the upper layer (0–0.1 m) of the topsoil, pH_{KCl} 7.7, electrical conductivity 12.5 mS/m, total N 0.164%. All crop stands (including CT) were sown with a John Deere 750A drill machine. Mineral nitrogen fertilization was used for all crops (i.e. 100 kg N per ha for winter wheat). In the MTS treatment, the straw from the cereals were incorporated into the soil with nitrogen (ammonium form) at a dosage of 1 kg per 100 kg of straw. In the MTS and NTM treatments, 30 kg nitrogen fertilization was used for catchcrop. The catchcrop was harvested and post harvest residues were incorporated into the soil. The P and K fertilizer doses were determined and applied according to the P, K content in the soil. Standard herbicides were used, depending on the intensity of weed infestations. Grain yields were determined on a 24 m^2 test area, at the time of harvest.

Soil sampling and sample processing. Soil sampling from 2002–2009 was carried out annually at the beginning of October from the CT, NT, MTS, and NTM treatments from the topsoil, at depths of 0–0.1 m, at three sites from each individual plot. The moist field soil samples from each plot were mixed together (1 kg total per plot), sieved to 2 mm, and then stored in a refrigerator at 4°C. Microbial biomass carbon (C-biomass) was determined by the fumigation extraction method (Vance et al. 1987). Total organic C (C_{org}) was determined on a VARIO MAX analyser (Elementar Analysensysteme GmbH, Hanau, Germany) on air-dried soil samples.

Averages and correlations between the individual characteristics were calculated using Microsoft Excel and Statistica CZ software. Tukey *HSD* tests were used for determining significant mean differences. Columns which are designed by the same letter did not differ significantly ($P = 0.05$). The correlation matrix of different properties was based on Pearson correlation coefficients ($P < 0.01$ and $P < 0.05$). The relationships were tested by means of linear regression.

RESULTS AND DISCUSSION

Average values of winter wheat grain yields in the selected tillage treatments during the period from 2002 to 2009 are shown in Figure 1.

The wheat yields are presented from 2002 because we started our investigations of the biological soil properties in that year. There were rather high fluctuations in the grain yields until 2006, due to adaptations of the soil properties to the conservation tillage, and weather conditions in individual years. Grain yields apparently had stabilized by 2006, which is eleven years after the beginning of the experiment; thereafter, they steadily grew in variants under conservation tillage. As shown in Figure 1, the differences in grain yields among the treatments did not differ significantly. These differences were mainly dependent on the weather conditions in the given years. The mean grain yields ranged from 3.9 t/ha to 8.45 t/ha until 2006. Several authors point to large variations of grain yields during the first years after setting up soil conservation technologies, as a result of both the adaptation to the soil properties and variations of the weather conditions. Significant effects of the year on the yield are widely documented in long-

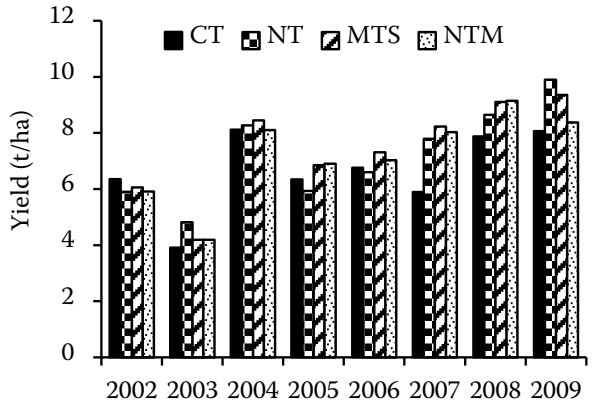

Figure 1. Average values of winter wheat grain yields in four tillage treatments. CT – conventional tillage; NT – no tillage; MTS – minimum tillage + straw; NTM – no tillage + mulch over the time period from 2002 to 2009

term field studies (Šíp et al. 2009, Videnovič et al. 2011). Lahmar (2010) summarized the results of the KASSA project, which showed that within Europe conservation agriculture does not necessarily generate increases in yields. In northern Europe, on average, yields on poor and medium fertile soils did not change dramatically (±10%); on very fertile soils they slightly decrease with a highly intensive level of production. It is always important to keep in mind the introduction of soil conservation technologies, that the favorable effects are exhibited later, after the stabilization of the soil properties. The length of this period depends on several factors, primarily on soil fertility, as well as on the local soil and climate conditions.

Figure 2 shows the sum of precipitation and the average temperatures during the growing seasons (IV–IX) during the period 2002–2009. The first distinct difference in grain yields between the conventional tillage and conservation tillage was found in 2003. All variants of reduced tillage performed better than the conventional one did. The weather in 2003 was characterized by drought (264.2 mm; the long-term mean being 356 mm) and high temperatures during the vegetation period (16.7°C; the long-term mean being 15.7°C). Another example of the beneficial effects of conservation tillage on the yields of winter wheat grain was seen in 2007. The very low grain yield in the conventional treatment (CT – 5.9 t/ha), compared to soil conservation technologies (NT – 7.8 t/ha, MTS – 8.2 t/ha, and NTM – 8.0 t/ha) was due to the very low precipitation in March (14.5 mm; the long-term mean being 36.0 mm) and April (2.4 mm; the long-term mean being 34.5 mm). Other observed years did not differ from the long-term average (annual mean air temperature of 8.2°C, and an annual mean precipitation of 477 mm). The advantage of soil conservation technologies in dry years were also mentioned by Josa and Hereter (2005), who found a higher amount of precipitation accumulated in the soil under no-tillage, than under conventional tillage. The amount of the water in the top 0.2 m of the soil decreased significantly from system to system in the following sequence: NT > MT > CT. However, this increased quantity of water did not deliver any increased crop production. Also Moreno et al. (1997) reported that the yields of the wheat crop, and also of sunflower, were slightly higher in the conservation tillage treatment than in the traditional tillage. They concluded that the conservation tillage seems to be highly effective in enhancing both soil water recharge and water conservation, particularly in those years with precipitation that is much lower than average. These results indicate that the main driving force in the spread of soil conservation technologies is the better utilization of soil water, and a reduction of non-productive evaporation due to mulching of the soil surface with crop residues. Figure 1 also shows that from 2006 (which is 11 years after the experiment was established) there was continuous growth of the grain yields on the soil conservation treatments; except for NTM in 2009. Grain yields were greater than 8 t/ha (even reaching 10 t/ha in the NT treatment while it fluctuated between 6–8 t/ha in the CT treatment. The mean grain yields ranged from 5.9 t/ha to 10.0 t/ha from 2006. In accordance with our results, Arrúe et al. (2007) documented that the yields of crops were generally 10–15% higher under no tillage, in most studies that were carried out in Spain, especially in dry years. So et al. (2009) also found yield stabilization 5 years after the establishment of their experiment. They showed that over the first 5 years the

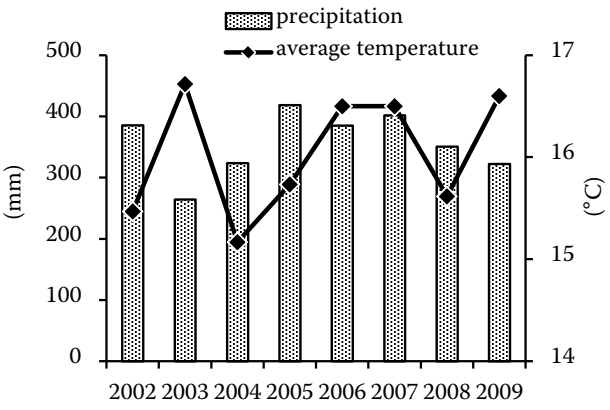

Figure 2. Sum of precipitation, and average temperatures during growing season (IV–IX) throughout 2002–2009

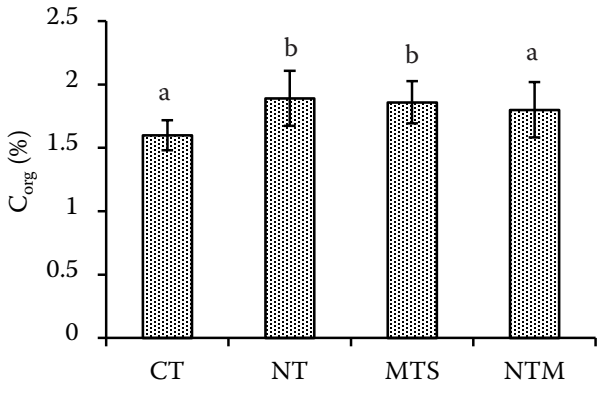

Figure 3. Average values of organic C content in topsoil under different tillage systems over the time period from 2002 to 2009. CT – conventional tillage; NT – no tillage; MTS – minimum tillage + straw; NTM – no tillage + mulch. Columns which are designed by the same letter did not differ significantly (P = 0.05)

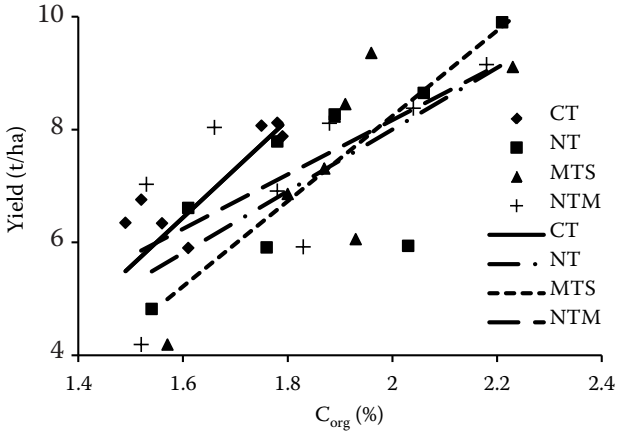

Figure 4. Relationship between winter wheat yields and values of organic C content in topsoil under different tillage systems during the period 2002 to 2009. CT – conventional tillage; NT – no tillage; MTS – minimum tillage + straw; NTM – no tillage + mulch

annual soybean yields of the NT treatments were consistently less than, or equal to, those resulting from CT. However, CT was unable to sustain the greater yields; and from 5 years, onwards, the yields of the NT treatments were typically greater than those of the CT.

Organic carbon content (C_{org}) in the topsoil in individual treatments is presented in Figure 3.

Organic carbon in the topsoil was higher in the plots with conservation tillage (NT, MTS, and NTM), than in the conventional tillage (CT) plots over the entire time period. A statistically significant and higher C_{org} content was found in the NT and the MTS systems, when compared to the CT. Relationships between winter wheat yield and organic C content are presented in Figure 4. Linear regression lines show positive relationships between the organic C content in soil and winter wheat grain yields in all treatments.

These close relationships are supported by correlation coefficients between the two datasets shown in Table 1. There was a significant correlation (at the 0.01 level) between the yields and C_{org} contents in the topsoil.

Table 1. Pearson correlation matrices among the winter wheat grain yields, organic C content and microbial biomass in topsoil during the period 2002 to 2009

	Yield	C_{org}
C_{org}	0.571**	–
$C_{biomass}$	–0.107	0.124

**indicate a significant correlation at the 0.01 level of significance

Microbial biomass content ($C_{biomass}$) in the topsoil in individual treatments is presented in Figure 5.

Average values of microbial biomass C content in topsoil were again higher in plots with conservation tillage (NT, MTS, and NTM) than in the conventional tillage (CT) plots. A statistically higher biomass C content was found in the MTS and NTM treatments.

A higher variability of biomass C values probably caused lower values of correlation coefficients between $C_{biomass}$ and C_{org} contents, as well as between $C_{biomass}$ and grain yields. They are not statistically significant (Table 1). Microbial C dynamics are more dependent on the fluctuations of the organic matter input, temperature, and moisture during the vegetation period; a time while the crop yields and total organic C content in the soil are more

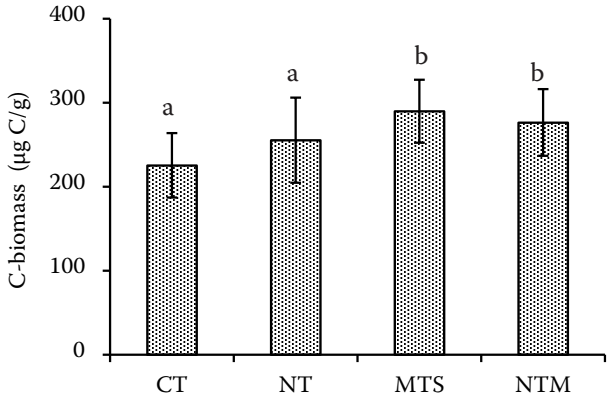

Figure 5. Average values of microbial C-biomass in topsoil under different tillage systems over the time period from 2002 to 2009. CT – conventional tillage; NT – no tillage; MTS – minimum tillage + straw; NTM – no tillage + mulch. Columns which are designed by the same letter did not differ significantly (P = 0.05)

stable. $C_{biomass}$ and C_{org} were decreasing in the conventional tillage treatment, probably due to a more intensive mineralization of the soil organic matter, and lesser inputs of substrate and energy from the crop residues. On the other hand, there was an increase in both C_{org} and $C_{biomass}$ in no till with mulch treatments (NTM). Apparently, the input of organic matter was higher and the mineralization processes were less intensive in this variant, compared to the CT treatment. The beneficial effect of crop residues in the no till system, in which crop residues remain on the surface, and soil organic matter accumulates in the upper layer, was also cited by Mikanová et al. (2009). Lipavský et al. (2008), who showed that the cereal straw and mineral nitrogen fertilizers may substitute for farmyard manure in its effect on crop yields and organic C content in the topsoil.

Our earlier studies (Mikanová et al. 2009, Šimon et al. 2009), as well as some studies by other authors (Mijangos et al. 2006, Madejón et al. 2009, Wang et al. 2012) showed that soil conservation tillage improves the biological properties of soils.

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Received on July 31, 2012

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