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Soil physical properties as affected by traditional, reduced and no-tillage for winter wheat**

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Abstract. The aim of this research was to determine the effects of traditional, reduced and no-tillage systems on the soil physical properties: bulk density, water content, stability in water and soil physical quality. Traditional tillage involved soil inversion whereas reduced tillage and no-tillage were non-inversion systems. Soil physical properties were measured on samples collected from the field throughout the growing season and harvest times. These included: particle size distribution, soil water content and bulk density. Soil stability was measured in terms of the content of readily-dispersible clay (RDC) in the soil samples. From water retention curves, an index of soil physical quality (*S* index) was calculated. The effect of tillage systems on the values of the physical properties was significant. The non-inversion plots (reduced tillage and no-tillage) increased water content and bulk density in the top layer in comparison with traditional tillage. Reduced tillage and no-tillage reduced the amount of RDC and therefore increased soil stability, especially in the top layer in comparison with traditional tillage. Reduced tillage and no-tillage also decreased the *S* index after the first year in comparison with traditional tillage. However, after 4 years, the non-inversion plots (reduced tillage and no- tillage) showed some improvement in soil physical quality and soil stability in water.

Keywords: tillage systems, bulk density, water content, soil stability in water, readily-dispersible clay, soil physical quality

INTRODUCTION

Sustainable agriculture must protect the environment and at the same time produce good soil conditions for crop production. Therefore, there is growing interest in developing systems of reduced tillage with mulching (conservation tillage) and no-tillage as alternative technologies to traditional tillage. Before introduction of soil conservation tillage several steps should be taken: the structure and fertility of the soil should be improved, pests including perennial weeds, insects and pathogens should be suppressed, and finally, the appropriate knowledge must be acquired (Dzienia *et al.,* 2006). Reduced and no-tillage systems have effects on soil physical properties: bulk density, water content, soil stability (Czyż and Dexter*,* 2008; Gațe *et al.,* 2005, 2006a, b; Lipiec and Nosalewicz, 2004; Pabin *et al.,* 2003) and soil physical quality (Dexter, 2004; Wereszczaka *et al.,* 2009). Conservation tillage protects the subsoil against compaction and erosion by water. It can reduce run-off throughout the year (Dexter *et al.,* 2004) reduce evaporative losses and can increase infiltration and can also increase the stability of the surface soil through increased organic matter content and increased biological activity. We are looking for soil physical conditions that give good plant production whilst at the same time protecting the environment.

The aim of the research was to compare three different tillage systems (traditional, reduced and no-tillage) on some soil physical properties.

MATERIALS AND METHODS

Field experiments were done in 2003-2009 on a private farm at Rogów, in the Lubelskie voivodeship of Poland (50° 48'N, 23° 29'E, 230 m a.s.l.) on a silt loam soil that had been formed on loess, 60 km east from Lublin. A long-term field experiment with three tillage treatments was established in the autumn of 2002 (Czyż and Dexter, 2008). The soil is a silt loam formed on loess which is typical in this region and considered to be sensitive to erosion and compaction.

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Winter wheat was grown in three systems:

- traditional tillage (TT) with straw incorporation (chopped wheat straw) based on mouldboard ploughing (to 25 cm depth) and traditional soil management equipment,
- reduced tillage (RT) with surface mulching with straw based on a rigid-tine cultivator (to 10 cm depth),
- no-tillage (NT) with surface mulching with straw and direct sowing. TT involved soil inversion whereas RT and NT were non-inversion systems. Soil physical properties were measured on samples collected from the field at harvest time.

The long-term tillage experiment was set up in 2002 on 1 ha experimental plots with three replicates. The soil tillage treatments were established in October 2002 and sampled in each of the years 2003-2009. Winter wheat was sown in October and harvested in August.

The particle size distributions of the soils studied were determined by Casagrande's hydrometer method modified by Prószyński (Lityński *et al.,* 1976). The organic matter content of the soils was measured by wet oxidation by the Tiurin method (Ostrowska *et al.,* 1991). The annual precipitation is 588 mm on average with 376 mm within the growing season and temperature 7.6 and 14.4°C, respectively (Table 1). Comparison of monthly air temperatures for the period 2003-2008 with the 120-year mean show, that from April to August were warmer than the long-term average, except for 2004. Comparison of monthly precipitation for the periods 2003-2008 with the 120-year mean shows, that the period from April to August was drier than average in the 3 years: 2003-2005 and wetter than average in the 3 years: 2006-2008.

From each tillage treatment at the farm at Rogów, undisturbed soil cores of 100 cm^3 volume were collected after harvest (in the period August - October) in 2003-2008. Soil samples were taken from the 0-5, 5-10, 10-15, 20-25, 30-35 cm layers so as to include the cultivated layer, the pan and the non-tilled layers in 4 replicates.

For determination of bulk density (Mg m^{-3}), and water content (%, m^3 m^{-3} or kg kg^{-1}) soil samples collected from the field were used. The soil samples were collected from soil pits that were dug in the field in the different treatments. For the above, 4 replicates were collected from each of the depth layers. The depth of sampling was selected to coincide with the depths of layers corresponding with the different tillage practices. Undisturbed soil cores were taken by pushing stainless steel cylinders of 100 cm^3 vertically into the soil, and for each layer and location 4 replications were sampled. The cylinders were then closed and were placed in polythene bags to prevent water loss. Dry bulk density and water content of the soils were measured in the laboratory by standard

Table 1. Comparison of mean monthly air temperatures (°C) and precipitation (mm) for the periods 2003-2009 with the 120-year means (1871-1990)

Years	Months													
	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	IV-IX	I-XII
	Air temperatures (°C)												Mean	
2003	-4.3	-6.6	1.0	6.8	15.2	16.5	19.2	18.3	13.4	16.8	5.2	0.5	14.9	8.5
2004	-5.3	-1.2	2.2	8.0	11.9	15.9	17.9	18.0	12.7	9.9	3.4	1.2	14.1	7.9
2005	-0.5	-4.3	-0.7	8.7	12.7	15.5	19.8	17.0	14.1	8.6	2.4	-0.8	14.6	7.7
2006	-8.5	-4.9	-1.2	8.5	13.2	16.4	20.1	18.0	14.8	10.3	5.0	2.9	15.2	7.9
2007	2.8	-1.5	6.0	8.1	14.7	18.5	18.8	18.9	12.7	8.1	0.5	-1.4	15.3	8.8
2008	-0.2	1.9	3.5	9.0	13.1	17.3	18.2	18.5	12.6	10.0	4.4	0.4	14.8	9.1
2009	-3.2	-1.2	2.2	10.7	13.5	16.4	19.7	18.1	14.9	–	–	–	15.5	–
1871-1990	-3.5	-2.5	1.5	7.7	13.4	16.7	18.3	17.3	13.2	7.9	2.7	-1.4	14.4	7.6
	Precipitation (mm)												Total	
2003	14.3	20.3	19.1	37.9	44.7	60.0	24.6	42.5	28.4	76.1	16.1	37.8	238.1	421.8
2004	14.7	25.5	22.1	95.3	31.3	33.7	59.7	61.3	42.2	35.5	69.3	19.3	323.5	509.9
2005	12.3	17.6	11.8	25.9	44.4	50.8	44.9	59.7	54.4	8.9	7.7	25.3	280.1	363.7
2006	5.7	14.2	29.2	38.0	58.9	40.2	35.7	214.6	28.8	16.3	32.5	7.3	416.2	521.4
2007	68.8	22.3	38.3	28.3	23.4	67.5	47.5	66.8	178	40.4	30.6	5.7	411.5	617.6
2008	20.5	19.8	52.9	67.6	81.9	62.2	93.8	115.2	88.2	32.4	21.4	19.3	508.9	675.2
2009	23.8	29.9	76.8	0.6	57.5	117.9	117.8	74.6	32.3	–	–	–	400.7	–
1871-1990	31	29	30	39	57	71	85	75	49	45	39	38	376	588

procedure. The determinations were done immediately after returning from the field so that further water loss was avoided. The dry bulk density was calculated as the mass of dry soil per unit volume of moist soil.

Soil stability was measured by a turbidimetric method using samples from 5-10, 15-20 and 30-35 cm depths. Soil stability was measured in terms of the content of readily-dispersible clay (RDC) in the soil samples. The turbidimeter was a Hach model 2100AN as described in Czyż and Dexter (2008). The method used for determination of readily-dispersible clay, RDC (NTU/(g l)$^{-1}$) and RDC (g 100 g^{-1} soil), is that described by Czyż *et al.* (2002); Dexter and Czyż (2000), and is rather similar to that described by Kay and Dexter (1990); Watts and Dexter (1997) but was adapted for Polish sandy soils. Turbidity values are linearly proportional to the concentration of colloids (clay) in suspension (Dexter and Czyż, 2000). The turbidimeter readings were expressed as NTU (Nephelometric Turbidity Units) and were normalized by dividing by the concentration of the original soil in the water to give NTU/(g l^{-1}). The mass of soil was corrected to dry mass for this calculation. Ten replicates were used for each tillage system and depth at each place.

It was also considered the proportions of the soil clay content that are readily dispersible. We did this by using high energy inputs (30 min of intense stirring) to disperse all the clay followed by 18 h of sedimentation and measurement of turbidity (as described above) to obtain the normalized turbidity, T (NTU/(g l^{-1})), due to the total clay. We then calculated a factor, *K*, as follows:

$$K = \left[\frac{C}{T}\right], \tag{1}$$

where: *C* is the total clay content (%) as measured in the particle size analysis, *K* is a calibration factor that relates turbidity measurements to amounts of clay in suspension. *K* may be expected to be different for different soils because of differences in clay mineralogy (Czyż and Dexter, 2008).

For estimation of the soil physical quality (*S*) values, we measured water retention on undisturbed cylinder samples. Cylinder samples were wetted from below to saturation and then drained to water pressure, *h*, of 10, 20, 40, 80, 250 hPa. For pressures of 500, 1 000, 2 000, 4 000, 8 000, and 15 000 hPa, the measurements were made on crumbled soil fragments. The water contents, θ, were measured gravimetrically. The mean water contents for every value of pressure were then fitted to the van Genuchten (1980) equation. The non-linear van Genuchten equation was fitted iteratively to the experimental data for each sampling depth and date using the Levenberg-Marquardt method (Marquardt, 1963). The Mualem (1976) restriction fixing the relationship ($m = 1-1/n$) between the van Genuchten parameters n and m was applied.

The van Genuchten equation, when plotted as θ against *ln*(h) has an inflection point at which the curvature changes sign. From the parameters of the fitted van Genuchten equation, we calculated the water content at the inflection point, θ_{INFL}, using the equation of Dexter and Bird (2001):

$$\theta_{INFL} = (\theta_{sat} - \theta_{res})\left[1 + \frac{1}{m}\right]^{-m} + \theta_{res}\,, \tag{2}$$

where: θ_{sat} and θ_{res} are the gravimetric water content at saturation and the residual water content, respectively, and *m* is a shape parameter. θ_{INFL} can be used as an estimate of the optimum soil water content for tillage.

The slope of the water retention curves at the inflection point, *S*, was calculated according to Dexter (2004):

$$S = -n(\theta_{sat} - \theta_{res})\left[1 + \frac{1}{m}\right]^{-(1+m)}. \tag{3}$$

The *S* values were compared between the different tillage systems. The relationship between *S* and soil bulk density is significant. As shown by Dexter (2006) and Dexter and Czyż (2007), values of *S* can be used to predict a range of other properties including: hydraulic conductivity, clod production during tillage, soil strength and root growth. *S* is also related to the stability of soil in water as measured by the content of readily-dispersible clay (Gațe *et al.*, 2006a,b).

The literature presented above shows that the *S* index is a useful addition to the range of approaches available to soil and tillage scientists. Use of the *S* index enables us to identify soil management practices for sustainable agriculture and for environmental protection.

The results were expressed as mean values: mean SEM. The results enable comparison of the inversion (TT) system with the non-inversion (RT and NT) systems. Statistical analysis of the measured values of soil bulk density, water content and the soil stability in water (measured as the content of readily-dispersible clay) were done using the MiniTab$^{©}$ program. Differences at $P<0.05$ were considered to be statistically significant.

RESULTS AND DISCUSSION

The particle size distribution of the experimental soil in 2003 was: 5% clay, 81% silt, 14% sand and 1.56% organic matter. Maps of organic matter and clay content (%) of the arable layer in 2003 at Rogów are shown in Figs 1 and 2.

The effect of tillage system on soil bulk density was different in the 7 years studied. The no-tillage systems (NT) had higher mean values of soil bulk density than traditional (TT) and reduced tillage (RT) at all depths measured (Figs 3-5). The effects of different tillage practices on soil bulk density after 7 years are shown in Fig. 3. This figure shows that after 7 years of different tillage, the mean values of soil bulk density show a similar trend, and that the RT and NT systems had decreased soil bulk density in the top layer, especially at 2.5 cm depth, in comparison with the TT system. For the wet year 2006, mean values of soil bulk density at 0-15 cm depth were lower in the NT system, than in the TT and RT systems (Fig. 4). During the drier-than-average period in the years 2007-2009, mean values of soil bulk density were lower in the TT system at 0-15 cm depth than in either of the other tillage systems: RT and NT.

Analyzed values of soil bulk density for depth 0-15 cm confirm that on NT plot the highest values were at depth 7.5 cm and the lowest at 2.5 cm depth (Fig. 5). There were also trends showing decreased bulk densities after 7 years of use of the NT system. Here also we can see how decreased values of bulk densities in the NT treatment occurred after 4-years use of this system tillage in comparison with TT and RT.

The results with the bulk density showed similar trends to those obtained with heavy soil observed in earlier research by Czyż (2005). In this reference, the effects of different tillage systems on physical properties of heavy soil in a 3-year field experiment were presented. The soil physical properties (bulk density, water content) in the 0-25 cm layer in the three different tillage systems: traditional (mouldboard ploughing), reduced tillage and direct sowing. The value of bulk density, mean of three years, was highest with direct drilling (1.58 Mg m^{-3}), lower with reduced tillage (1.39 Mg m^{-3}), and the lowest with conventional (ploughing) tillage (1.24 Mg m^{-3}). Also Pranagal *et al.* (2005) presented results after 7 years of use of different tillage systems. Several authors have shown an increase in soil bulk density with reduced tillage or no-tillage system in comparison with the traditional tillage (plough) system. Some authors have shown in their experiments that such is the case with their soils *eg* Fabrizzi *et al*., 2005; Moreno *et al.,* 1997; Niedźwiecki and Pecio, 2008. However, some researchers have not found significant differences in bulk density between tillage treatments (Ferreras *et al.,* 2000). Also Czyż and Dexter (2008) found that differences in bulk density were not significant with the loamy and loamy silt soils at the 0-10 cm depth. However, bulk density was greater in the 10-20 cm layer of loamy silt soils with NT in comparison with the TT and RT systems.

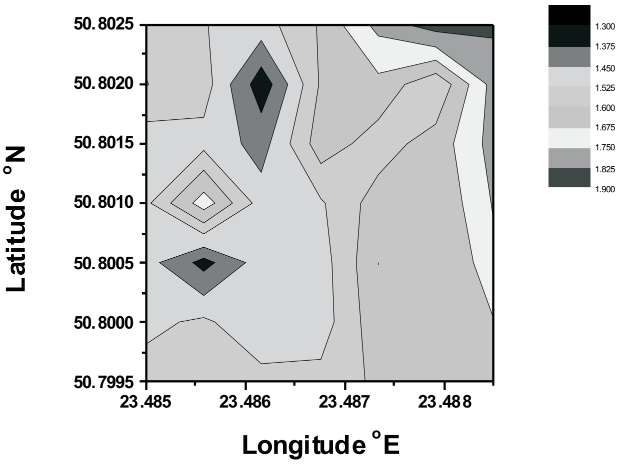

Fig. 1. Map of organic matter content (%) of the arable layer in 2003 at Rogów.

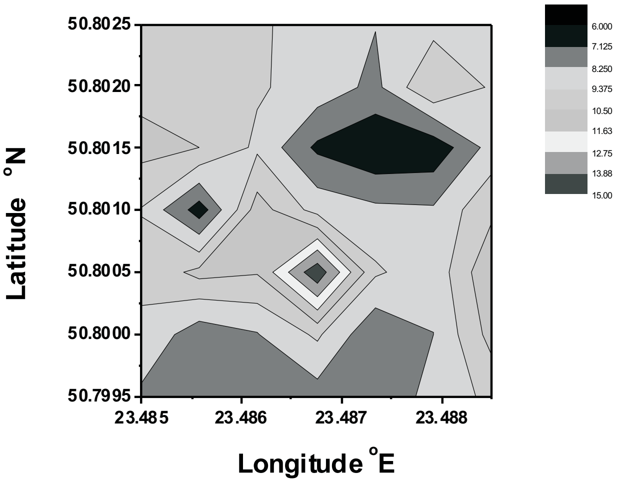

Fig. 2. Map of clay content (%) of the arable layer in 2003 at Rogów.

The effect of tillage system on water content at Rogów is shown in Fig. 6. There were no consistent effects of tillage on water contents at the times of sample collection. Comparison of the effects of different tillage practices on water content after 7 years show that RT and NT both had greater water contents in the top layer in comparison with the TT system.

The RT and NT systems decreased mean values of readily-dispersible clay (RDC) throughout the whole profile and increased soil stability in comparison with traditional tillage (TT), especially in the top layer 5-10 cm (Fig. 7).

The results show effects of tillage systems on soil physical quality, *S*, at 5-10 cm depth after 4 years (Fig. 8). After conversion from a soil inversion system (TT) to a non- inversion system (RT or NT), the soil physical quality deteriorates for the first 3 years before starting to improve. After one and two years, the RT and NT systems had smaller values of *S* in comparison with TT. However, after four years both the RT and NT systems showed significantly increased values of *S*.

The relationship between the index of soil physical quality, *S*, and the content of readily-dispersible clay (RCD) has been published earlier by Gațe *et al.* (2004) (Fig. 9). The boundaries between good and poor physical quality (S = 0.035) and between poor and very poor (S = 0.020) of the soils was suggested by Dexter (2004) and Dexter and Czyż (2007). Values of *S* that were measured on samples collected in the years 2003 and 2004 mainly followed the regression lines obtained for *S* values measured on samples collected in the previous year, except for the *S* values from Rogów that were well above the regression lines. At this location, the factor that had more significant effects on the dispersibility of clay minerals was the field water content of the soil samples. In 2003, the values of *RDC* were obtained on soil samples having around 0.10 kg kg^{-1} water content, whereas the values of *RDC* in the year 2004 were obtained on soil samples having around 0.24 kg kg^{-1} water content. Although the silt loam soils from Rogów had quite good physical condition as quantified by the *S* index, higher water contents at the time of collection of the soil samples led to the release of more dispersible clay in the year 2004.

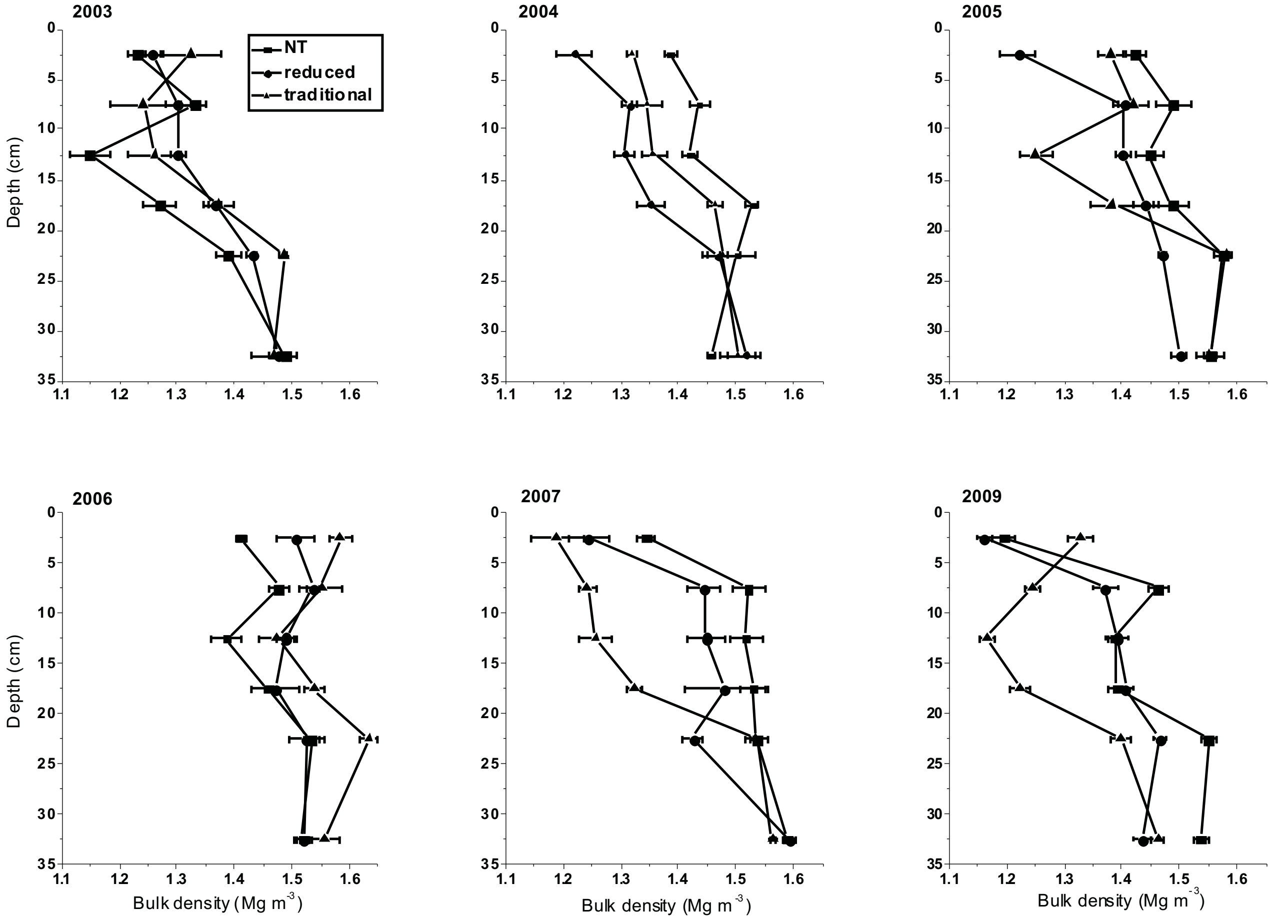

Fig. 3. Effects of different tillage systems on soil bulk density (error bars show ±s.e.).

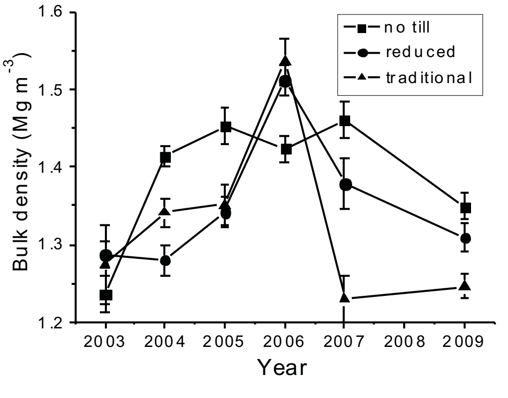

Fig. 4. Effects of different tillage systems on mean soil bulk densities in the 0-15 cm layer (error bars show ±s.e.).

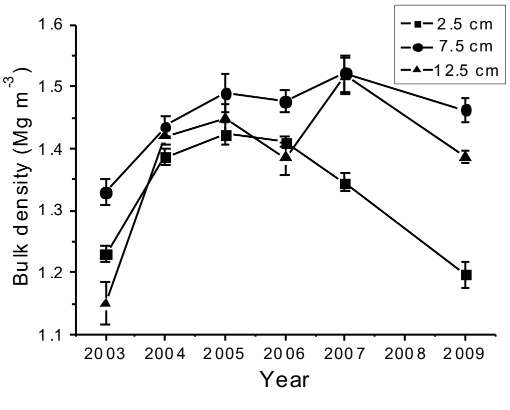

Fig. 5. Trends in bulk density on the no till plot at three different depths (error bars show ±s.e.).

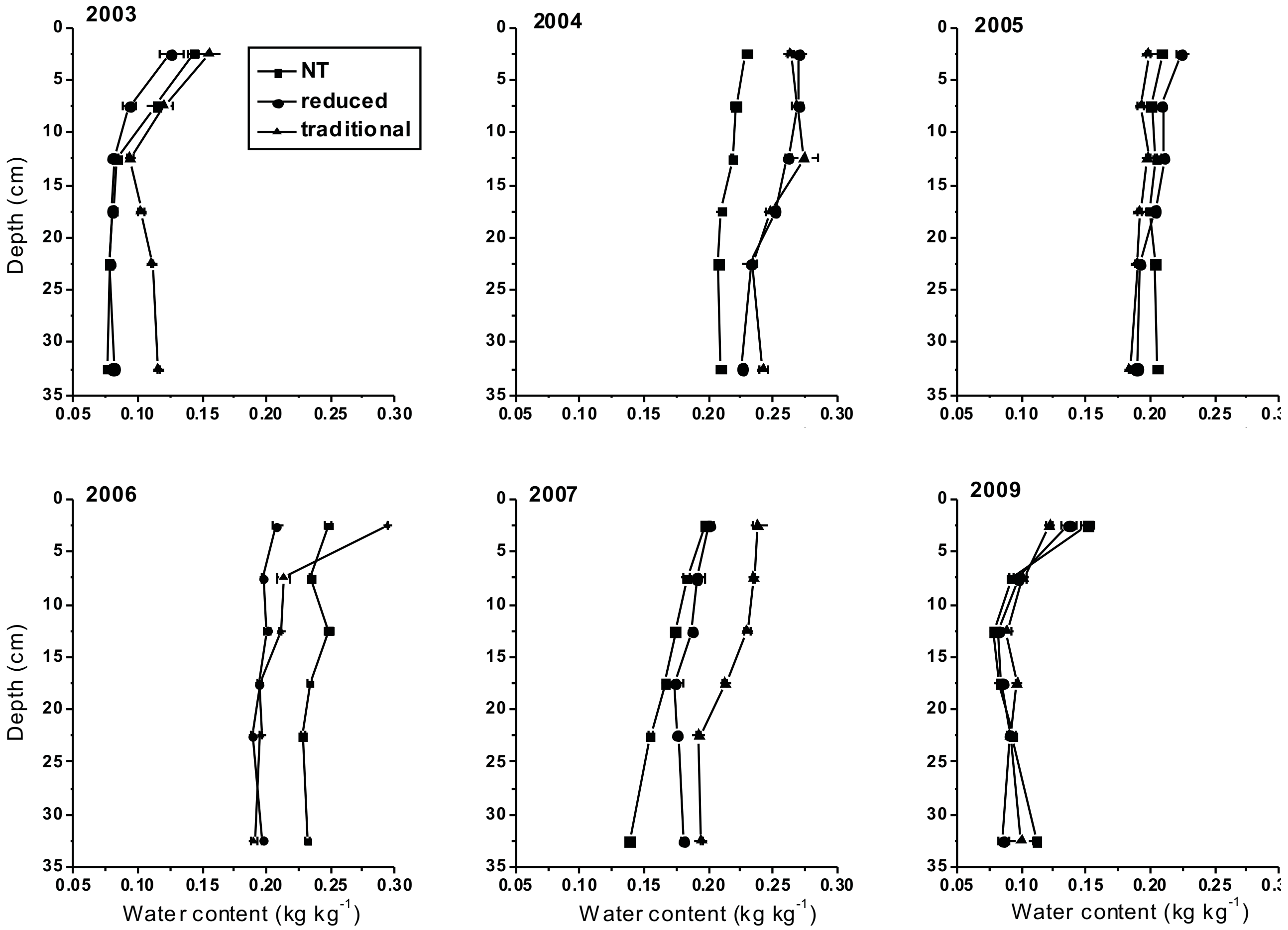

Fig. 6. Effects tillage systems on soil water content (error bars show ±s.e.).

Soils with high contents of readily-dispersible clay in the presence of water may experience collapse of their structures. The importance played by water in weakening the bonds between particles that constitute the structure with the consequent loss of the inter-aggregate pores and soil homogenization has been discussed by Czyż *et al.* (2002). Problems associated with clay dispersion include: anaerobic soil that is unsuitable for plant root growth, hard-setting on drying, and reduced infiltration of water with associated risk of run-off, flooding and erosion (Dexter and Czyż, 2000). The importance of primary binding agents in stabilizing soil structure has been emphasized by Kay (1990). Readily-dispersible clay (RDC) is also related to soil strength. A soil with a high content of readily-dispersible clay will be weaker when wet and stronger when dry than a soil with a low content of readily-dispersible clay. Reduced tillage decreased the quantity of readily-dispersible clay (RDC) and therefore increased soil stability, especially in the top layer 5-10 cm in both soils in comparison with traditional tillage (Czyż and Dexter, 2008; Dexter and Czyż, 2000; Gațe *et al.*, 2004).

Several studies on soil quality have been focused on the role and importance of organic matter due to its great impact on physical, chemical and biological properties (Reeves, 1997). It has been shown that organic matter reduces soil bulk density (Blanco-Canqui *et al.*, 2009) and improves tilth in the surface horizons (Bruce *et al.*, 1995). Usually, organic matter makes soil easier to work and more friable (Watts and Dexter, 1998), and it stabilizes and holds soil particles together into aggregates (Tisdall, 1996). By improving pore size distribution and decreasing bulk density, it improves the soil ability to store and transmit air and water (Bruce *et al.*, 1995; Kay, 1998).

CONCLUSIONS

1. In the top layer of the soil (0-15 cm) NT resulted in the highest mean values of soil bulk density at the 7.5 cm depth in comparison with the layers at 2.5 and 12.5 cm.
2. In the 0-15 cm layer after NT the highest mean values of soil bulk density occurred in comparison with TT and RT, excluding the wet year 2006.
3. There were no significant trends in soil water content at the times of sampling.
4. The non-inversion systems (RT and NT) decreased the content of readily-dispersible clay (RDC) and therefore increased soil stability, especially in the top layer (5-10cm) in comparison with inversion tillage (TT).

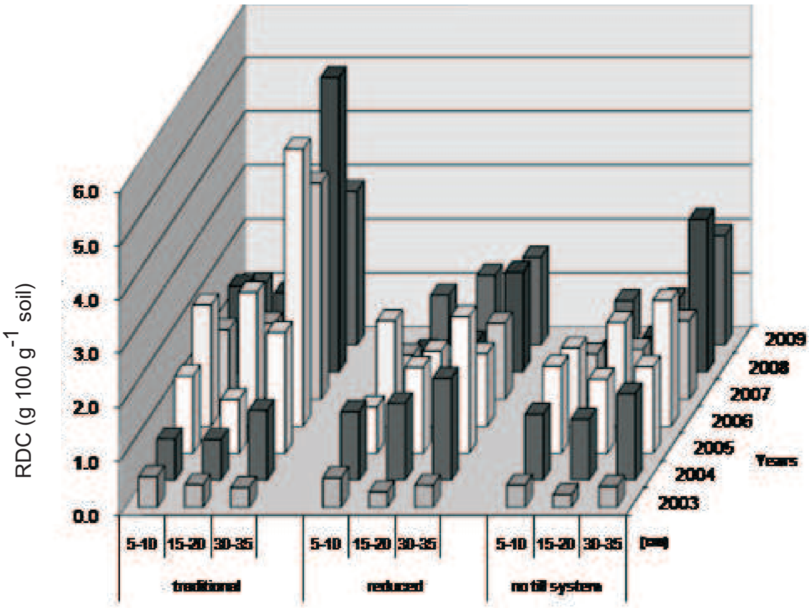

Fig. 7. Effects tillage systems on soil stability in water measured as the content of readily-dispersible clay, RDC (g 100 g^{-1} soil).

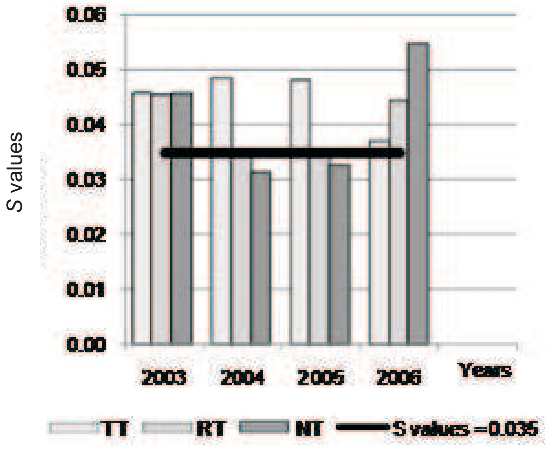

Fig. 8. Effects tillage systems on soil physical quality values, *S*, at 5-10 cm depth in the first four years of use of different tillage systems.

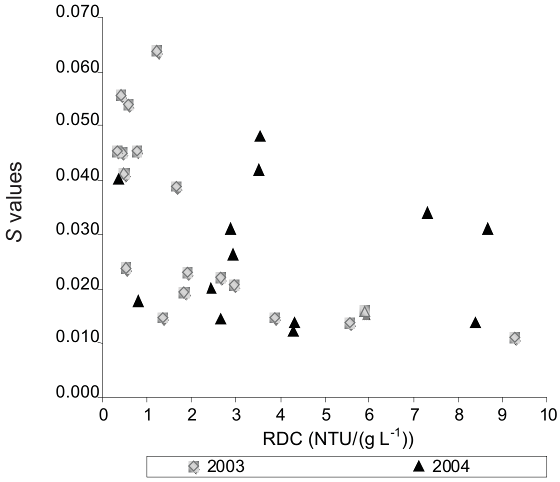

Fig. 9. Relationship between the index of physical quality, *S* and the content of readily-dispersible clay (in NTU/(g l^{-1})) (Gațe *et al.*, 2004).

5. In the 0-15 cm layer during first three years, the non-inversion systems (RT and NT) decreased the soil physical quality as quantified by *S*. From the fourth year, the soil physical quality (as measured by *S*) in these non-inversion systems began to increase.

6. These results show that, after conversion from a non-inversion system (TT) to a non-inversion system (RT or NT), the soil physical quality deteriorates for the first 3 years before starting to improve. This illustrates the importance of long-term experiments in the study of the effects of tillage systems on soil physical properties.

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