Original Paper

Effect of tillage systems on the quality of different soil types

Nora Polláková[1]*, Elżbieta Wójcik-Gront[2], Jerzy Jonczak[3], Martin Juriga[1]
[1]*Slovak University of Agriculture, FAFR, Institute of Agronomic Sciences, Slovakia*
[2]*Warsaw University of Life Sciences, Institute of Agriculture, Department of Biometry, Poland*
[3]*Warsaw University of Life Sciences, Department of Soil Environment Sciences, Poland*

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The tillage technology used can influence the soil quality positively or negatively. The aim of this work was to compare the impact of reduced (RT) and conventional (CT) tillage technologies on selected physical and chemical properties of Mollic Fluvisol, Chernozem, and Haplic Luvisol. Differences in the properties of soils treated with RT and CT were investigated at fifteen sites to a depth of 40 cm. The results showed that in Mollic Fluvisol, which naturally has higher soil organic matter (SOM) content, changing the tillage system from CT to RT caused minimal negative changes in soil properties, including a significant increase in bulk density (ρ_d), a decrease in available water capacity (Θ_p) and hot water soluble carbon (C_{HWL}); in contrast, the change in tillage system was positively reflected in a statistically significant increase in total organic carbon (C_{ox}) and degree of humification. For Chernozem and Haplic Luvisol, which naturally have medium to low SOM content, changing tillage from CT to RT resulted in a significant decrease in C_{HWL} content and degree of humification. All physical parameters assessed were significantly deteriorated (there was an increase in ρ_d and wilting point, a significant decrease in air-filled porosity and Θ_p. There was no significant improvement in any of the soil properties studied. It can be concluded that the CT system is more suitable for Chernozem and Haplic Luvisol tillage than the RT system. In Mollic Fluvisol, the RT system is more or less equally suitable for tillage as the CT system.

Keywords: available water capacity, air-filled porosity, bulk density, soil organic matter, tillage technology

1 Introduction

The development of knowledge about the requirements of agricultural crops for the soil-climatic environment, nutrition and plant protection has shown that conventional tillage described as any tillage activity that utilizes mouldboard ploughing followed by seedbed preparation can be replaced by other technologies. One of the alternatives is the use of minimization tillage technologies (reduced, plough-less), that allow efficient land management (Kotorová et al., 2018). However, it is necessary to be aware of the risks associated with the use of these technologies in different soil and climatic conditions and crops.

Conventional tillage is the most intensive tillage method that primarily incorporates crop residues, weeds, manure, compost, fertiliser, lime, and other soil conditioners into the soil (Strudley et al., 2008). However, the long-term use of conventional technology tends to negatively affect soil properties, particularly the loss of organic matter due to its accelerated mineralization caused by increased O_2 availability (Sithole et al., 2019), the formation of soil pans below the ploughing depth (Bertolino et al., 2010) accompanied by increased soil bulk density, reducing porosity, mainly macroporosity and thus decreasing air, water, and nutrient availability to organisms, increasing macroaggregate destruction (Jha et al., 2012), and erosion (Vach et al., 2018), resulting in less stable crop yields.

The results of numerous scientific works have shown that reducing the depth and intensity of tillage can lead to an increase in the content of soil organic matter (Šoltýsová and Danilovič, 2011; Jakab et al., 2023), decrease in soil pH and significant increase in hydrolytic acidity (Polláková et al., 2020), an improvement in the state of structural aggregates (Fernandes et al., 2023) and an increase in the biological activity of the soil (Chen et al., 2019). Reduced

***Corresponding Author:** Nora Polláková, Slovak University of Agriculture, FAFR, Institute of Agronomic Sciences, Tr. Andreja Hlinku 2, 949 76 Nitra, Slovakia
nora.pollakova@uniag.sk https://orcid.org/0000-0003-1992-5129

tillage has also contributed to better water management by increasing saturated hydraulic conductivity by 24.6% and available water capacity by 10.2% (Li et al., 2019). In conjunction with reduced tillage, mulching of plant residues remaining on the soil surface helps limit unproductive water evaporation, reduce water, and wind erosion (Kovaříček et al., 2008), limit leaching of mobile nitrogen forms, etc.

Neglecting the interrelations between the cultivation technology and its impact on soil properties can cause a considerable threat to soil quality. Thus, the aim of this work was to compare the impact of reduced (RT) and conventional (CT) tillage technologies on selected physical and chemical properties of Mollic Fluvisol, Chernozem, and Haplic Luvisol. Differences in the properties of soils treated using conventional and reduced tillage technologies were investigated at fifteen experimental sites. Soil samples were collected with respect to the same soil subtype on adjacent plots, one of which was treated conventionally and the second with reduced technology. Soil sampling and analyses were performed to a depth of 40 cm for each of the 10 cm layers.

2 Material and methods

2.1 *Sites of soil sampling*

Soil properties were examined for three soil types: Mollic Fluvisol, Chernozem, and Haplic Luvisol (WRB, 2006). Mollic Fluvisol was formed on the carbonate alluvial sediment of the Váh River, Chernozem on carbonate loess, and Haplic Luvisol on decarbonated loess. In all soil types studied, the topsoil (0–30 cm) was the anthric horizon. In Mollic Fluvisol and Chernozem the residual mollic horizon was below the anthric horizon, while in Haplic Luvisol the argic horizon was below the anthric horizon.

Two of studied agricultural enterprises, Selice and Dolná Streda, are situated in the Danube lowland near the Váh River at an altitude of 113–130 meters. The average annual temperature was 9.7 °C and average precipitation was 566.3 mm in the period 1951–2000. The remaining enterprises are situated in the Danube hills at an altitude of 160–280 m above sea level. The average annual temperature in Močenok and Dolná Malanta was 9.9 °C and the average total annual precipitation was 547.6 mm; in Prašice, Dolné Dubové and Krakovany 9.3 °C and 579.1 mm in the period 1951–2000 (Špánik et al., 2012).

The study was carried out in seven agricultural enterprises where some fields have been cultivated with reduced technologies for a long term (6–22 years). For research were selected fifteen sampling sites, which consisted of two plots in close proximity (neighbouring), one of which had been managed for a long time with reduced tillage (RT) and the second with conventional technology (CT). Plots CT and RT of each pair had to have the same soil subtype and texture.

Large-scale tillage in the study sites was done for centuries until 1960, when the land (after collectivisation in the 1950s and 1960s) began to be farmed intensively. Conventional tillage technology has become commonly used, therefore the CT was taken as the control variant in this study. Beginning 1993, reduced tillage systems have been progressively introduced in Slovakia.

2.2 *Cultivation and fertilization practices*

The crops grown on fields are very similar at all locations studied, as farmers only grow profitable ones that change regularly. Therefore, we were able to compare soil properties on plots that are cultivated by more than one farm. Crops grown on each fields: *Triticum aestivum* L., *Triticum durum* L., *Hordeum vulgare* L., *Zea mays* L., *Brassica napus* L. var. *napus*, *Helianthus annuus* L. In addition to the crops listed above, *Medicago sativa* L. is grown in Malanta and Selice; *Pisum sativum* L. in Malanta and Prašice; *Beta vulgaris* L. in Selice and Dolné Dubové; and *Glycine max* L. in Krakovany.

The crop rotation in individual agricultural enterprises as s well as crop grown during soil sampling are shown in the Table 1. The farms that keep livestock (Dolné Dubové, Dolná Malanta, Krakovany and Prašice), supply regularly the farmyard manure (FYM) at average dosage 40 $t.ha^{-1}$ every four years. Fertilizer (NPK) application rate was calculated by the balance method (Kováčik and Ryant, 2019) widely used in the Slovak Republic.

Technologies used in the studied localities: Conventional tillage (CT) includes mouldboard ploughing to a depth of 25–30 cm and subsequent cultivation in order to prepare the seedbed. Soil processed by reduced tillage (RT) to a depth of 10–12 cm was not turned over. Chiselling to a depth of 40 cm (without overturning) was used depending on the current physical condition of the soil.

2.3 *Soil sampling and analyses*

All agricultural enterprises from which the soil samples were taken cooperate with the Slovak University of Agriculture. An evaluation of the soil properties as affected by the different tillage practices was carried out on medium-textured soils, at 15 sites, which included three soil types – Mollic Fluvisol, Chernozem, and Haplic Luvisol (WRB, 2006). Each soil type was represented on five different sites (Table 1).

Soil samples were collected in April and May 2015 and 2016 as follows: Two 2,400 m^2 plots (120 × 20 m) were

Table 1 Location of sampling sites, crops in rotation and crops grown during sampling, soil type, and texture

Locality	Technology	Years of RT	Crops	Soil type	Texture	Crop in RT and CT during sampling
Močenok	RT CT	15	1–6 1–6	Chernozem 1 Chernozem 2 Chernozem 3 Mollic Fluvisol 1	ssi ssi ssi spi	5^{RT}, 1^{CT} 3^{RT}, 6^{CT} 1^{RT}, 1^{CT} 1^{RT}, 1^{CT}
Krakovany	RT CT	6	1–6, 10 1–6, 10	Chernozem 4 Mollic Fluvisol 2	ssi si	9^{RT}, 6^{CT} 4^{RT}, 4^{CT}
D. Streda	RT CT	9	1–6 1–6	Mollic Fluvisol 3 Mollic Fluvisol 4	si si	2^{RT}, 2^{CT} 1^{RT}, 5^{CT}
Selice	RT CT	22	1–7, 9 1–7, 9	Mollic Fluvisol 5	si	$-^{RT}$, $-^{CT}$
D. Dubové	RT CT	10	1–6, 9 1–7, 9	Chernozem 5 Luvisol 1 Luvisol 2	ssi ssi ssi	1^{RT}, 1^{CT} 1^{RT}, 1^{CT} 10^{RT}, 10^{CT}
Prašice	RT CT	15	1–6, 8 1–6, 8	Luvisol 3 Luvisol 4	ssi ssi	5^{RT}, 1^{CT} 1^{RT}, 2^{CT}
D. Malanta	RT CT	21	1–8 1–8	Luvisol 5	si	4^{RT}, 4^{CT}

RT – reduced tillage, CT – conventional tillage, spi – sandy-clay-loam, ssi – silty-clay-loam, si – clay-loam, 1 – *Triticum aestivum*, 2 – *T. durum*, 3 – *Hordeum vulgare*, 4 – *Zea mays*, 5 – *Brassica napus* var. *napus*, 6 – *Helianthus annuus*, 7 – *Medicago sativa*, 8 – *Pisum sativum*, 9 – *Beta vulgaris*, 10 – *Glycine max*

established at all fifteen sites for soil sampling, one at the land cultivated by reduced tillage and one on the adjacent land managed by conventional tillage (i.e., 15 plots at RT and 15 plots at CT). On each plot, six soil pits were excavated in the 20 × 20 m networks, and each layer was sampled from 10 cm to 40 cm deep. Thus, a total of 740 soil sub-samples were taken for chemical analyses. For the analyses of physical parameters, undisturbed soil samples were taken using a cylindrical core. Two samples were taken per each 10 cm layer, i.e. 8 cylindrical cores per one soil pit, 1,440 cores total. Sampling at one site was done for one day, i.e. from six soil pits on reduced tillage and from six pits on the neighbouring plot with conventional tillage.

In the laboratory, subsamples for chemical analyses were air dried, then composite samples were compiled for each layer studied. Thus, we obtained four composite soil samples from depths 0–10; 10–20; 20–30; 30–40 cm from 24 subsamples taken from six pits per plot of RT. Similarly, four composite samples were obtained from 24 subsamples of the plot with CT. Each composite soil sample was ground and sieved through a 0.25 mm diameter mesh.

Total organic carbon (C_{ox}) was analysed by Tyurin method (Hrivňáková et al., 2011), the content of labile carbon (C_L) by method of Loginow et al. (1987), non-labile carbon (C_{NL}) was calculated as the difference of total and labile carbon, lability of organic carbon (L) was calculated as the subdivision of labile carbon and non-labile carbon, hot water soluble carbon (C_{HWL}) was determined by method of Körchens and Schulz (1999); fractional composition of humus by the truncated fractionation of Kononova and Belchikova, total nitrogen content (N_t) by Kjeldahl method (Hrivňáková et al., 2011).

Physical (bulk density – ρ_d) and hydrophysical soil properties (air-filled porosity – V_A, available water capacity – Θ_P, and wilting point – Θ_V) were determined in the samples according to standard methods (Hrivňáková et al., 2011). Textural composition was determined using the pipette method (Hrivňáková et al., 2011). Soil texture values were previously published in Halmo et al. (2017).

In the statistical analysis, the two-way analysis of variance was used to determine statistically significant differences of the studied variables between the cultivation methods (conventional tillage and reduced tillage) and the soil type (Mollic Fluvisol, Chernozem, and Haplic Luvisol). Homogeneous groups were distinguished by Tukey's test for $\alpha = 0.05$. Principal Component Analysis was used to determine the relationship between soil data for three soil types (Mollic Fluvisol, Chernozem, and Haplic Luvisol), four soil depth (0–10 cm, 10–20 cm, 20–30 cm and 30–40 cm) and tillage technology (conventional tillage and reduced tillage). The relationships between all the variables were also tested using the Pearson correlation test for $\alpha = 0.05$. The Pearson correlation test was also used for the same variables in two different tillage types CT and RT. All statistical analyses were performed with Statistica TM v. 13.1.

3 Results and discussion

3.1 *Chemical properties of organic matter in the studied soils*

Soil organic matter content is regulated by the balance between biotic inputs and losses and abiotic conditions. Under the conditions of agricultural production in Slovakia, with low humus stocks in soils, organic matter inputs are not sufficient to cover the need for organic matter. The main source of organic matter remains manure, slurry, composts and straw (Zaujec et al., 2009). The main indicator of soil organic matter content is the total organic carbon content. Scientific works of many authors (Lützow et al., 2002; Šimanský 2016; Šimanský 2017; Jakab et al., 2023) show that the tillage system significantly influences the soil organic matter (SOM) content.

We evaluated the differences in soil properties at each site between reduced and conventional tillage for each 10 cm layer up to a depth of 40 cm. In the soil profiles studied, there is a clear decrease in organic carbon content with increasing depth, which is related to the main biomass of the root system, soil organisms, root exudates, and incorporated plant residues in the topsoil layer (Table 2). When comparing soils treated with reduced tillage (RT) and conventional tillage (CT), significant differences in both the content and distribution of organic matter in the profiles are observed between the tillage methods studied. A higher C_{ox} content in the surface (0–10 cm) layer is observed in the reduced tilled soils compared to the conventionally tilled soils. A sharp decrease in C_{ox} content in the system RT occurred already in the layer of 10–20 cm, while in the conventionally tilled soil it decreased in the layer of 30–40 cm. This is closely related to the depth of tillage and incorporation of post-harvest residues and organic fertilizers into the soil, which is up to 10–12 cm deep in RT, while conventional tillage is up to 30 cm deep. In the conventionally tilled soils, C_{ox} content was more or less balanced in the 0–30 cm layer. Similar results were also obtained by Bayer et al. (2002), Du et al. (2017), while in contrast, Saha and Ghosh (2013) reported higher C_{ox} contents in the whole studied profile (0–30 cm) of soils with reduced tillage.

Along with the decrease in total organic carbon with increasing depth, there was also a decrease in hot water-soluble carbon (C_{HWL}). We hypothesised that C_{HWL} is much more abundant in the surface layer of 0–10 (20) cm

Table 2 Total (C_{ox}) and hot water-soluble organic carbon (C_{HWL}), C : N ratio, and degree of humification (% C_{HA} of C_{ox}) in soil tilled conventionally (CT) and reduced (RT) in Mollic Fluvisol, Chernozem, and Haplic Luvisol

Depth	C_{ox} (g.kg^{-1})		C_{HWL} (g.kg^{-1})		C_{ox} : N_t		C_{HA} (% of C_{ox})	
	CT	RT	CT	RT	CT	RT	CT	RT
Chernozem								
0–10	16.08 ±2.63a	18.11 ±3.96a	0.57 ±0.15a	0.56 ±0.16a	10.20 ±0.71a	10.24 ±0.67a	27.53 ±3.01a	24.99 ±3.76a
10–20	15.63 ±2.92a	14.10 ±3.31a	0.38 ±0.16a	0.45 ±0.15a	10.58 ±1.04a	10.40 ±0.75a	27.24 ±3.16a	26.09 ±4.46a
20–30	14.85 ±3.23a	12.83 ±3.74a	0.54 ±0.13a	0.43 ±0.13b	10.49 ±0.85a	9.98 ±0.60a	28.26 ±3.81a	26.66 ±4.18a
30–40	9.92 ±2.59a	9.35 ±3.32a	0.40 ±0.11a	0.34 ±0.14a	9.48 ±1.45a	9.21 ±1.47a	28.21 ±4.50a	26.54 ±7.20a
(0–40)	14.12 ±3.73a	13.60 ±4.72a	0.48 ±0.16a	0.45 ±0.16a	10.19 ±1.11a	9.96 ±1.02a	27.81 ±3.60a	26.07 ±4.99b
Haplic Luvisol								
0–10	11.16 ±1.44a	12.61 ±2.54a	0.45 ±0.11a	0.49 ±0.16a	9.91 ±0.60a	10.14 ±0.63a	23.44 ±2.68a	21.28 ±2.47b
10–20	11.07 ±0.46a	11.04 ±1.49a	0.43 ±0.05a	0.40 ±0.07a	10.24 ±1.04a	10.71 ±1.05a	23.90 ±3.96a	21.16 ±2.36b
20–30	10.33 ±0.90a	8.14 ±1.46b	0.39 ±0.06a	0.31 ±0.10b	10.50 ±0.87a	10.00 ±1.23a	23.71 ±4.27a	20.34 ±4.30b
30–40	6.72 ±0.98a	5.83 ±1.73a	0.29 ±0.06a	0.23 ±0.05b	8.54 ±1.20a	9.22 ±1.53a	28.21 ±5.40a	20.62 ±5.42b
(0–40)	9.82 ±2.08a	9.41 ±3.20a	0.39 ±0.10a	0.36 ±0.14a	9.80 ±1.20a	10.02 ±1.25a	24.81 ±4.54a	20.85 ±3.78b
Mollic Fluvisol								
0–10	22.31 ±1.90a	25.08 ±4.68b	0.74 ±0.20a	0.70 ±0.20a	10.83 ±0.75a	11.39 ±0.67b	21.06 ±2.21a	22.60 ±4.10a
10–20	23.03 ±2.58a	20.96 ±4.29a	0.71 ±0.18a	0.57 ±0.17b	10.41 ±1.09a	10.97 ±0.86a	20.78 ±4.13a	24.08 ±6.31a
20–30	21.03 ±3.34a	18.34 ±5.02a	0.58 ±0.21a	0.47 ±0.08a	10.24 ±1.19a	10.45 ±1.12a	21.48 ±5.82a	23.16 ±4.71a
30–40	15.81 ±2.60a	15.72 ±5.24a	0.41 ±0.14a	0.41 ±0.10a	10.09 ±1.51a	9.91 ±1.51a	21.30 ±4.67a	22.87 ±4.61a
(0–40)	20.54 ±3.85a	20.02 ±5.85a	0.61 ±0.22a	0.54 ±0.18b	10.39 ±1.17a	10.68 ±1.20a	21.16 ±4.30a	23.18 ±4.90b

Different letters (a–b) indicate that the soil properties in the layers are significantly different at $P < 0.05$ according to Tukey's test

Table 3 The Pearson correlation coefficients between the same variables measured in conventional and reduced tillage for $\alpha = 0.05$

C_{ox} (g.kg^{-1})	N_t (g.kg^{-1})	$C_{ox} : N_t$	C_L (g.kg^{-1})	C_{NL} (g.kg^{-1})	C_{hws} (g.kg^{-1})
0.86***	0.86***	-0.29	0.63**	0.87***	0.66*
L	C_{HA} (% of C_{ox})	ρ_d (t.m^{-3})	V_A (%)	Θ_V (%)	Θ_P (%)
-0.49	-0.37	0.50	-0.28	0.59*	-0.33

of soil with reduced tillage compared to CT. However, the obtained results did not confirm this hypothesis. On the contrary, a higher content of C_{HWL} was observed in all soil types in the conventional system compared to the reduced system, which was even statistically proven in Chernozem (20–30 cm layer), in Haplic Luvisol (20–40 cm layer) and in Mollic Fluvisol (10–20 and 0–40 cm layer) (Table 2). Hazarika et al. (2009) also found significantly lower C_{HWL} contents in RT soils at 15 and 25 cm depth (222 and 118 μgC.kg^{-1}) than in CT tilled soils (307 and 220 μgC.kg^{-1}); however, in contrast to our study, they found significantly higher C_{HWL} contents in RT in the 0–5 cm surface layer.

Total nitrogen (N_t), a component of soil organic matter, especially humus, also showed the same trend as C_{ox}. In general, as the degree of humification increases, the proportion of nitrogen in humus also increases, which is often evaluated as the C : N ratio (Baties, 1996). The results show that the $C_{ox} : N_t$ ratio decreased steadily with increasing depth, indicating a higher degree of decomposition, mineralization, humification, and/or stabilization of soil organic matter with depth. There were no significant differences in $C_{ox} : N_t$ ratios between RT – and CT – tilled soils, except for Mollic Fluvisol, which had a significantly higher $C_{ox} : N_t$ ratio in the 0–10 cm layer in RT soil. The narrower $C_{ox} : N_t$ ratio and higher humification with increasing soil depth was confirmed by the higher humic acid carbon (C_{HA}) proportion of C_{ox}, which is commonly referred to as the degree of humification (Zaujec et al., 2009). In contrast to the other profiles, we observed a trend toward a slight decrease in the degree of humification with depth in the RT tillage system of Haplic Luvisol (Table 2). In the profiles of Haplic Luvisol and Chernozem, we found a significantly lower degree of humification in the reduced system than in the conventional system (Table 2). In contrast, we found a significantly higher percentage C_{HA} of C_{ox} in the 0–40 cm thick layer in Mollic Fluvisol, i.e., changing tillage from CT to RT increased the degree of humification in Mollic Fluvisol, while it decreased in Chernozem and Haplic Luvisol. Greater humification of organic matter promotes its stabilization and the sequestration of carbon in the soil.

The results in Table 3 show a correlation between CT and RT for all variables. Most of them, especially those evaluating the quantity and quality of soil organic carbon,

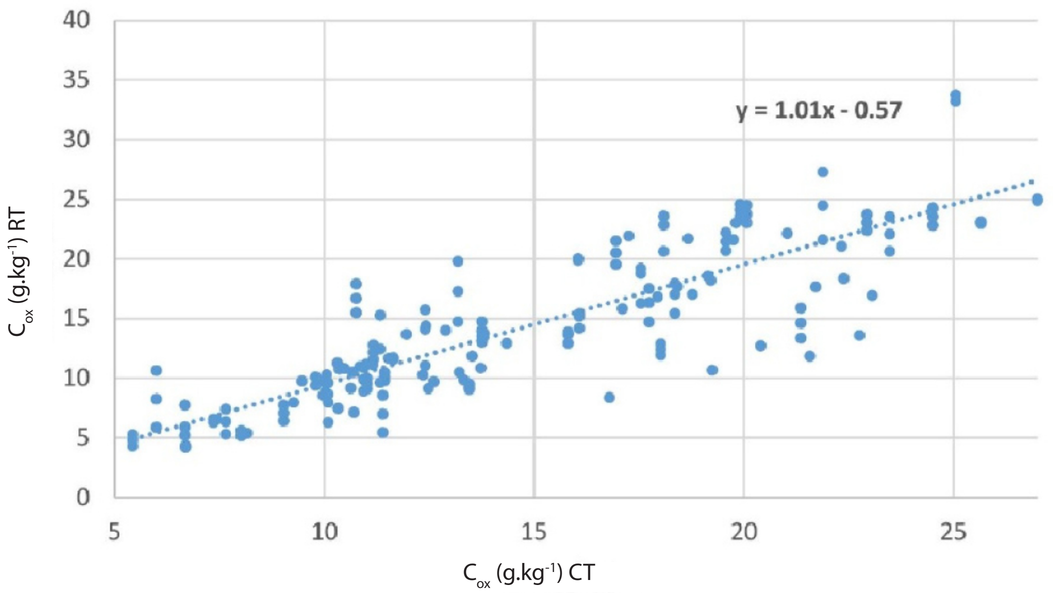

Figure 1 Linear regression analysis for total soil organic carbon (C_{ox}) under conventional and reduced tillage system (CT and RT)

are significant. A graphical representation of the linear regression analysis for C_{ox} content under conventional and reduced tillage system is shown in Figure 1.

3.2 *Physical parameters of the studied soils*

Tillage often leads to soil compaction. The main indicators of compaction are high bulk density and low soil porosity. Of the agrotechnical interventions, loosening, tillage, compaction by machinery passes, organic fertilization and liming have the greatest impact on soil volume change. These interventions change bulk density by 15–45% (Zaujec et al., 2009).

When comparing the bulk density in the profiles between the tillage methods evaluated, significant differences between CT and RT are evident (Table 4). We found that Chernozem, which was tilled long term with RT, had a significantly higher bulk density (ρ_d) in the 10–30 cm layer and significantly lower available water capacity (Θ_P) in the 0–40 cm layer (especially in the 10–30 cm layer) compared to CT. According to Fulajtár (2006), a value of V_A below 10% is considered critical for healthy plant growth and life of organisms. In the tillage system RT, the limits of V_A were exceeded in the layer 10–40 cm for all soil types, while in the system CT, the critical values were exceeded from 20 and 30 cm for Haplic Luvisol and Chernozem, and from 10 cm for Mollic Fluvisol. Chernozem, which was managed with RT, was shown to have a significantly higher values of wilting point (Θ_V) in the 0–40 cm layer (especially in the 10–20 cm layer) than in CT. The above physical parameters suggest that the CT system is more suitable for tillage Chernozem than the RT system. In agreement with our results, Šimanský et al. (2016) also found a significantly lower ρ_d value in the 0–30 cm layer in soils tilled with the CT system compared to soils tilled with the RT system. They found that in Chernozem, which was cultivated with the RT system, severe compaction occurred already at a depth of 10 cm, while in CT at a depth of 30 cm.

In terms of soil-forming substrate and natural genesis, a compacted layer in the profile is not expected to form in Chernozems unaffected by anthropogenic activity. On the other hand, Luvisols formed in the process of illimerization (displacement of clay by rainwater from the upper parts of the soil profile and its concentration in the Bt-luvic, clay-enriched horizon) have a natural predisposition to form a compacted layer (Bt horizon).

Table 4 Bulk density (ρ_d), air-filled porosity (V_A), wilting point (Θ_V) and available water capacity (Θ_P), in soil tilled conventionally (CT) and reduced (RT) in Mollic Fluvisol, Chernozem, and Haplic Luvisol

Depth	ρ_d		V_A		Θ_V		Θ_P	
	(t.m^{-3})		(%)					
	CT	RT	CT	RT	CT	RT	CT	RT
Chernozem								
0–10	1.31 ±0.11a	1.26 ±0.15a	13.13 ±7.14a	13.40 ±5.19a	13.37 ±1.43a	13.48 ±1.73a	20.15 ±4.54a	20.94 ±2.33a
10–20	1.37 ±0.12a	1.54 ±0.07b	11.46 ±5.45a	4.50 ±3.26b	14.69 ±1.34a	15.64 ±0.86b	18.73 ±2.98a	18.62 ±2.41a
20–30	1.39 ±0.10a	1.51 ±0.05b	11.23 ±6.40a	6.64 ±2.20b	14.61 ±1.53a	15.43 ±1.41a	18.59 ±3.41a	18.43 ±2.10a
30–40	1.44 ±0.06a	1.45 ±0.11a	7.10 ±3.09a	7.23 ±3.59a	15.56 ±1.61a	16.44 ±2.27a	20.20 ±3.53a	18.66 ±3.25a
(0–40)	1.38 ±0.11a	1.44 ±0.15b	10.73 ±6.04a	7.94 ±4.94b	14.56 ±1.65a	15.25 ±1.95b	19.42 ±3.67a	19.16 ±2.72a
Haplic Luvisol								
0–10	1.33 ±0.10a	1.30 ±0.11a	14.90 ±6.22a	16.63 ±5.02a	13.08 ±1.14a	14.27 ±2.37a	16.84 ±2.97a	15.79 ±2.42a
10–20	1.48 ±0.11a	1.60 ±0.09b	10.24 ±4.68a	5.40 ±2.34b	14.76 ±1.91a	16.86 ±1.83b	17.00 ±1.83a	15.58 ±2.28b
20–30	1.57 ±0.11a	1.61 ±0.07a	6.39 ±4.08a	5.42 ±2.03a	15.66 ±2.07a	17.54 ±2.38b	16.77 ±2.85a	14.49 ±2.66b
30–40	1.54 ±0.07a	1.57 ±0.05a	6.61 ±2.40a	6.00 ±1.77a	17.52 ±1.63a	18.21 ±2.20a	15.64 ±1.96a	14.69 ±2.25a
(0–40)	1.48 ±0.13a	1.52 ±0.15a	9.54 ±5.66a	8.37 ±5.68a	15.26 ±2.34a	16.72 ±2.63b	16.56 ±2.47a	15.14 ±2.42b
Mollic Fluvisol								
0–10	1.36 ±0.20a	1.27 ±0.17a	10.93 ±7.26a	12.75 ±6.59a	15.73 ±2.85a	14.88 ±2.30a	18.27 ±3.69a	19.95 ±2.91a
10–20	1.42 ±0.13a	1.47 ±0.17a	6.40 ±4.43a	5.31 ±4.58a	16.98 ±3.06a	18.07 ±2.88a	19.74 ±2.80a	17.62 ±3.47b
20–30	1.44 ±0.14a	1.54 ±0.07b	6.19 ±4.56a	3.99 ±2.53a	16.95 ±3.23a	18.56 ±4.19a	19.34 ±3.01a	16.44 ±3.44b
30–40	1.48 ±0.09a	1.49 ±0.06a	5.61 ±2.48a	5.52 ±4.39a	16.67 ±3.55a	16.87 ±4.30a	18.94 ±2.05a	17.92 ±3.28a
(0–40)	1.42 ±0.15a	1.44 ±0.16a	7.28 ±5.33a	6.89 ±5.79a	16.58 ±3.16a	17.09 ±3.74a	19.07 ±2.94a	17.98 ±3.46b

Different letters (a–b) indicate that the soil properties in the layers are significantly different at $P < 0.05$ according to Tukey's test

Thus, in addition to anthropogenic compaction by over-traffic, the Bt horizon formed in the soil-forming process may also contribute to the compaction of Luvisols. Comparing the soil properties found in Chernozem and Haplic Luvisol (Table 4), in particular the 10–40 cm layer, the natural contribution of illimerization to the increase of ρ_d in Haplic Luvisol is evident.

Similar to Chernozem, also Haplic Luvisol long-term tilled by RT system had worse physical parameters in the 10–40 cm layer than CT. Haplic Luvisol tilled by RT, had higher ρ_d values (even significant in the 10–20 cm layer), and lower V_A values (significant in the 10–20 cm layer). However, Haplic Luvisol cultivated RT had statistically significantly worse hydrophysical properties, such as higher Θ_V values and available water capacity (Θ_P) in the 0–40 cm layer (especially in the 10–30 cm layer). Thus, plants grown on Haplic Luvisol long-term tilled by RT wither already at higher soil moisture values, and their soil properties allow for lower available water capacity. From the above physical, especially hydrophysical parameters, it can be concluded that the CT system is more suitable than RT for treating Haplic Luvisol.

In the Mollic Fluvisol, the RT tillage system had minimal effect on changing soil properties. The RT soil had a significantly higher ρ_d only in the layer of 20–30 cm; the available water capacity was significantly lower in the 0–40 cm layer (especially the 10–30 cm layer). From the above parameters, it can be concluded that the change of tillage system did not considerably change the physical properties of the soil and that the RT system is more or less as suitable for tillage Mollic Fluvisol as the CT system.

3.3 Correlations between physical properties, organic carbon and nitrogen

The relationships between selected physical properties and organic carbon fractions and nitrogen in soils tilled by conventional and reduced systems are shown in Table 5. The results confirm the known relationship that organic nitrogen, carbon and especially its labile forms contribute to the decline of ρ_d in soil. Since organic matter promotes the formation of structural aggregates (Tindsal and Oades, 1982; Šimanský and Bajčan, 2014) and the associated increased porosity (especially macroporosity), we also predicted a positive correlation between V_A and the carbon fractions. Although the correlation was positive, it was not significant. Higher correlation values were achieved by labile forms of organic carbon (C_{hws} and C_L), but only the correlation between V_A and organic carbon lability (L) was significant. Thus, the value V_A was probably influenced more by the soil architecture itself than by the organic matter content. A very similar trend, but a negative relationship was found between Θ_V and the fractions of organic carbon and nitrogen. We had also predicted a stronger effect of organic matter on the decrease in Θ_V values, but the effect was weak. However, the highly significant correlation between Θ_P and the fractions of organic carbon and nitrogen confirmed the known fact that soils with higher organic matter content bind water better, but also release it to plants (Tindsal and Oades, 1982; Polláková et al., 2017). Since Mollic Fluvisol, which was tilled by RT system, had a lower carbon content in the 10–40 cm layer, the values of Θ_P were significantly lower just in the RT soil compared to CT (Table 4).

To evaluate the relationship between the variables measured for the assessed soils and soil characteristics, the PCA analysis was used. Two principal components (PC1 and PC2) explained more than 74% of the variability in the data used in the analysis. PCA results were performed for the combination of three soil types (Mollic Fluvisol, Chernozem, and Haplic Luvisol), four soil depths (0–10 cm, 10–20 cm, 20–30 cm and 30–40 cm) and tillage type (CT and RT) with the measured variables (soil physical parameters, soil organic matter SOM and humus substances) (Figure 2). PCA allowed us to determine the relationship between the variables and the multivariate differences between site characteristics (soil type, tillage, and layer). Since the largest differences between trials occurred on the horizontal axis (PC1), the largest variation

Table 5 The Pearson correlation coefficients between physical properties and organic carbon and nitrogen in soil tilled conventionally and reduced in Mollic Fluvisol, Chernozem, and Haplic Luvisol

Parameter	ρ_d (t.m^{-3})	V_A (%)	Θ_V (%)	Θ_P (%)
C_{ox} (g.kg^{-1})	-0.52*	0.15	-0.07	0.61**
N_t (g.kg^{-1})	-0.52*	0.12	-0.05	0.64**
C_{ox} : N_t	-0.30	0.18	-0.19	0.28
C_{hws} (g.kg^{-1})	-0.63**	0.36	-0.29	0.59**
C_L (g.kg^{-1})	-0.66**	0.38	-0.33	0.61**
C_{NL} (g.kg^{-1})	-0.50*	0.12	-0.04	0.60**
L	-0.12	0.48*	-0.55*	-0.23

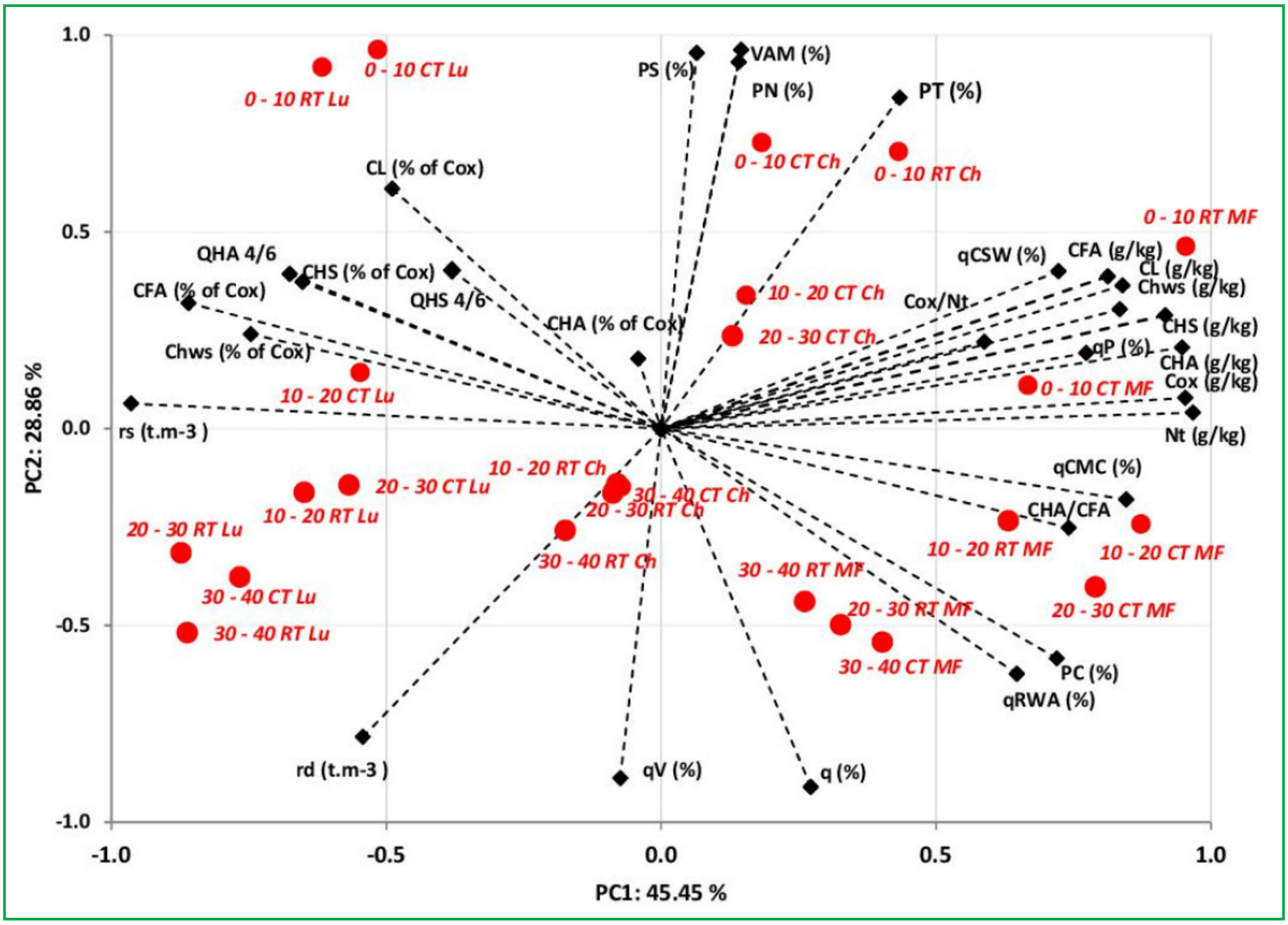

Figure 2 A biplot of the first two components of a PCA model of combination of three soil types MF – Mollic Fluvisol, Ch – Chernozem, and Lu – Haplic Luvisol), four soil depth (0–10 cm, 10–20 cm, 20–30 cm and 30–40 cm) levels and tillage type (CT and RT) and measured variables (physical soil parameters, soil organic matter SOM and humus substances

was due to soil type and not tillage. The same soil type was grouped separately: Haplic Luvisol, on the left of the figure, Chernozem in the middle, and Mollic Fluvisol in the right part of the figure.

4 Conclusions

In the Mollic Fluvisol soil type, which naturally has a higher SOM content, changing the tillage system from CT to RT caused minimal negative changes in soil properties. In the RT soil, there was a significant increase in bulk density in the 20–30 cm layer, a decrease in available water capacity in the 0–40 cm layer (especially in the 10–30 cm layer), and also a decrease in hot water soluble carbon in the 0–40 cm layer (especially in the 10–20 cm layer); in contrast, the change from CT to RT was positively reflected in a statistically significant increase in C_{ox} in the 0–10 cm layer and also in an increased degree of humification (0–40 cm layer).

For the Chernozem and Haplic Luvisol soil types, which naturally have medium to low SOM content, changing the tillage system from CT to RT resulted in several negative changes in soil properties. In terms of soil chemistry, the RT soil showed a significant decrease in hot water-soluble carbon (C_{HWL}) content and degree of humification (in Haplic Luvisol even in the whole profile studied). All assessed physical parameters were significantly deteriorated (there was an increase in bulk density (ρ_d) and wilting point (Θ_V), a significant decrease in air-filled porosity (V_A) and, in Haplic Luvisol, also in available water capacity (Θ_P). No significant improvement was observed in any of the soil properties. It can be concluded that the CT system is more suitable for Chernozem and Haplic Luvisol tillage than the RT system. In Mollic Fluvisol, on the other hand, the RT system is more or less equally suitable for tillage as the CT system.

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