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Soil water capacity, pore-size distribution and CO_2 e-flux in different soils after long-term no-till management

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Abstract

Little is known about the effects of modern soil management practices, especially no-tillage, on soil physical state, soil pore size distribution and soil water capacity after a long-time of successive application on different soil types. The investigations were performed in 2014 at the Institute of Agriculture, Lithuanian Research Centre for Agriculture and Forestry in Central Lithuania's lowland on a sandy loam-textured *Endocalcari-Epihypogleyic Cambisol* (*CMg-p-w-can*) and at the Experimental Station of Aleksandras Stulginskis University on a silt loam-textured *Endohypogleyic-Eutric Planosol* (*PLe-gln-w*). The goals of this paper were a) to compare soil water capacity, soil pore-size distribution and CO_2 e-flux in *Cambisol* and *Planosol*, b) to evaluate the effect of long-term no-tillage application in combination with and without residue management on hydro-physical properties of soils with different genesis and c) to assess the suitability of such management practice for practical use.

Regarding different soils genesis, the lower bulk density and higher total porosity were registered within 0–20 cm depth in *Planosol* than in *Cambisol*, while *Cambisol* was better aerated than *Planosol* due to a greater space of macropores. A risk of waterlogging condition may occur in *Planosol* due to a greater share of meso- and microporosity within 5–35 cm soil depth, compared to *Cambisol*.

No-tillage application with crop residue returning was more suitable on *Cambisol* than on *Planosol*. This soil management system increased volumetric water content in the soil and CO_2 e-flux. No-tillage with residue removal on *Cambisol* conditioned soil CO_2 e-flux increase when volumetric soil water content ranged from 0.159 to 0.196 $m^3\ m^{-3}$. When soil water content increased up to 0.220–0.250 $m^3\ m^{-3}$, the e-flux peak was reached at which the further CO_2 e-flux sloped down. On *Planosol*, the soil CO_2 e-flux peak ranges were lower, i.e. approximately 0.170–0.200 $m^3\ m^{-3}$. Long-term residue returning onto soil surface on *Planosol* acted as a physical obstruction inside mesopores in 5–10 cm and within macropores in 5–10 and 15–20 cm layers and, finally, causing clogging them. Increase of soil surface volumetric water content in *Planosol* caused a decrease in soil CO_2 e-flux.

Key words: bulk density, field capacity, permanent wilting point, soil pore structure, water retention.

Introduction

European Environmental Agency and Environment Research Centre concern climate change projection, especially emphasizing the importance of research on water capacity on cultivated soils (Report EUR 25186 EN, 2012). The investigations on soil conservation and saving of soil moisture resources are one of the most important topics in modern agronomy. Unfortunately, such type of investigations are still lacking on soils of Boreal region. Lithuania belongs to the Boreal region which is the largest bio-geographical region of Europe. The young soils that formed after the glacial period are generally shallow over large areas of the Boreal region (http://www.eea.europa.eu/publications/report_2002_0524_154909/biogeographical-regions-in-europe).

Cambisols and *Planosols* are well represented in Lithuania. These soils are intensively used in agriculture. *Cambisols* and *Planosols* are soils with different characteristics, both in morphology and the chemistry of clay fraction (Abakumov et al., 2009). *Cambisol* has a weakly differentiated soil profile of eluvial-illuvial processes (Lietuvos dirvožemiai, 2001; Mažvila et al., 2006; 2008; Schöning, Kögel-Knabner, 2006). *Planosols* are soils with mostly light-coloured horizon that shows signs of periodic water stagnation, which abruptly overlies dense subsoil having significantly more clay than top-soil layer. One of the most important features of *Planosol* is that waterlogging condition often occurs due to a dense subsoil environment. Root development is also hindered due to low hydraulic conductivity of dense, compacted subsoil (Mažvila et al., 2006; IUSS Working Group…, 2014).

About 32% of European soils are highly susceptible to compaction, while 18% are moderately affected by compaction (Owens et al., 2004). Soil compaction causes several negative consequences, i.e. reduction of oxygen and water supply to plant roots, reduction in water infiltration and lower soil retention and finally, loss of soil fertility and land value depreciation (Van-Camp et al., 2004). Compaction also leads to a reduction in biological activity, porosity and permeability (Report EUR 23490 EN/1, 2008; Report EUR 25186 EN, 2012). The sensitivity of soils to compaction depends on soil properties such as texture and moisture, organic carbon content, and on several external factors such as climate and land use. One of the way to conserve soil water, increase organic matter content, fungal dominated communities at the crop-residue layer and macropores structure in the soil under no-till application (Kladivko et al., 1997; Montgomery, 2008). This technology is spreading in order to reduce costs, prevent soil erosion, protect soil fauna and increase productivity (Roger-Estrade et al., 2009). According to many investigations (Moran et al., 1994; Bronick, Lal, 2005; Strudley et al., 2008; Bogužas et al., 2010), no tillage application improves the soil structure, increases pores quantity in subsoil as compare with traditional tillage. Water absorption in the soil is up to five times higher under no-tillage than under conventional soil tillage. Ploughless tillage system is increasingly used in Lithuania. This management practices reduces the need for mechanical soil tillage, saves time and energy resources, but also influences soil physical environment. Numerous experimental have revealed about conservation tillage impact on physical properties of different soils (Bogužas et al., 2010; Feiza et al., 2011; Romaneckas et al., 2012). The results after four years of direct drilling on *Luvisol* in Eastern Lithuania revealed that total soil porosity did not exceed 0.46 m^3 m^{-3} in 5–10 cm layer. In 15–20 and 25–30 cm layers, total porosity was significantly lower and relative difference reached 11% and 30%, respectively (Feiza et al., 2014).

What new, modern soil management practices, especially no-tillage, could have an effect on soil physical state, water conservation ability after several years of successive application on different soil types is of great interest from both scientific and practical point of view.

Soil type can play an important role regarding no-tillage impact on soil physical environment. The goals of this paper were a) to compare soil water capacity, soil pore-size distribution and CO_2 e-flux in *Cambisol* and *Planosol*, b) to evaluate the effect of long-term no-tillage application in combination with and without residue management on the properties of soils differing in genesis and c) to assess the suitability of such management practice for practical use.

Material and methods

Site and soil description and experimental design. Experiments were conducted in 2014 on two soils differing in genesis and in two geographical sites. One of them was carried out at the Institute of Agriculture, Lithuanian Research Centre for Agriculture and Forestry on an *Endocalcari-Epihypogleyic Cambisol* (*CMg-p-w-can*) with sandy loam texture on the basis of a long-term (since 1999) experiment. Soil texture, hydraulic and agrochemical soil characteristics of 0–20 cm layer are presented in Table 1. A 5-course crop rotation including winter wheat (*Triticum aestivum* L.) → spring oilseed rape (*Brassica napus* L.) → spring wheat (*Triticum aestivum* L.) → spring barley (*Hordeum vulgare* L.) → pea (*Pisum sativum* L.) was implemented in the trial. Post-harvest residues (straw) of preceding crop were removed from the 1/2 of the field. On the other half of the field the residues were chopped and spread on the soil surface. No-tillage involved application of herbicide Glyphosate (4 l ha^{-1}) three weeks after preceding crop harvesting to control emerged weeds and volunteer plants. Direct drilling was done by a rotary seed drill. Since trial establishment the rates of mineral NPK fertilizers were calculated according to soil properties and expected yield of the crop grown. Fertilizers were broadcast on the soil surface and slightly incorporated by a rotary seed drill under no-tillage. The size of each plot was 20 × 3.3 m = 66 m^2.

The other field experiment was carried out at the Experimental Station of Aleksandras Stulginskis University on the basis of a long-term (since 1999) two-factorial field experiment on an *Endohypogleyic-Eutric Planosol* (*PLe-gln-w*) with silt loam texture. Soil texture, hydraulic and agrochemical soil characteristics of 0–20 cm layer are presented in Table 1. A short crop rotation was introduced: winter wheat (*Triticum aestivum* L.) → spring barley (*Hordeum vulgare* L.) → spring oilseed rape (*Brassica napus* L.). The straw of preceding crop was removed from one half of the experimental field or was chopped and spread during harvesting on the other half. No-tillage involved application of herbicide Glyphosate (4 l ha^{-1}) three weeks after preceding crop harvesting. Complex fertilizer was applied before sowing. The size of each plot was 17 × 6 m = 102 m^2.

Table 1. Soil site characteristics (0–20 cm)

Index	Mean value	
	Cambisol	*Planosol*
Sand %	53.7	33.7
Clay %	13.7	16.0
Silt %	32.6	50.3
Saturated hydraulic conductivity cm hr^{-1}	1.64	1.44
Saturation m^3 m^{-3}	0.44	0.46
Field capacity m^3 m^{-3}	0.22	0.26
Soil organic carbon (SOC) g kg^{-1}	15.1	16.6
Available P_{AL} mg kg^{-1}	158	116.0
Available K_{AL} mg kg^{-1}	137	111.0
pH_{KCl}	5.9	7.6

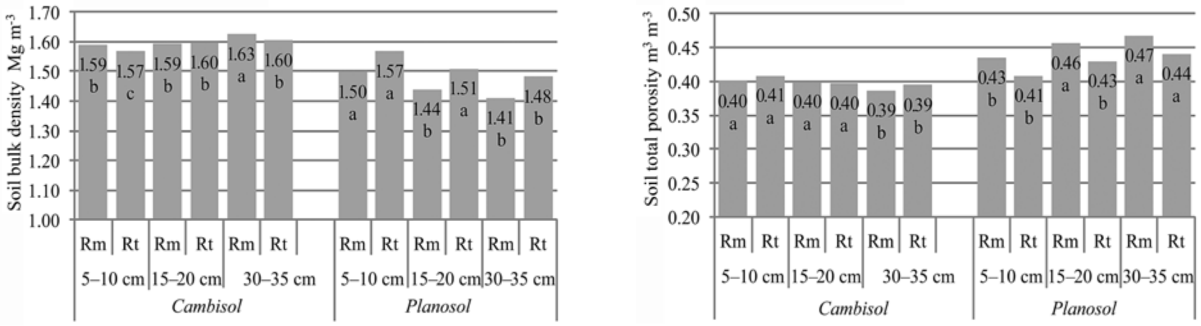
Soil sampling and analytical methods. Soil sampling was done in April 2014 in the stand of winter wheat. Undisturbed core samples were collected using stainless steel rings (100 cm^3 volume) from 5–10, 15–20 and 30–35 cm depths for soil water release characteristics (h Pa) determination in six replicates. Water release characteristics were determined at −4, −10, −30 and −100 hPa (in a sand-box) and at −300 hPa (in a sand-kaolin box). Loose soil samples were used for determination of water content at −15500 hPa tensions employing a high pressure membrane apparatus (Klute, 1986). The water content at −100 and −15500 hPa was regarded as the field capacity (prevailing in Europe) and the permanent wilting point, respectively. The amount of water between these two suctions was termed as plant available moisture content. Disturbed soil samples were collected for chemical analyses and soil site characteristics. They were collected from the 0–10 and 10–20 cm depth using an auger of 2 cm diameter. A composite soil sample for chemical analyses was prepared from six samples collected per each treatment from 0–10 and 10–20 cm depth. A closed chamber method was used to quantify soil surface CO_2 e-fluxes in crop stands. A portable infrared CO_2 analyser LiCor-6400 (ADC BioScientific Ltd, UK) attached to a data logger (IRGA method) was implemented. The measurements of CO_2 e-fluxes were done in four replications in each treatment. Soil surface volumetric water content was recorded at 7 cm soil depth by a portable soil sensor, type WET-2 with an HH2 Moisture Meter (Delta-T Devices Ltd, UK) near the chamber for net carbon dioxide exchange rate (NCER) measurement. Both soil CO_2 e-fluxes and soil volumetric water content measurements were done on 28 April, 16 May and 5 July.

Statistical analysis. Assumptions for ANOVA were checked and preliminary combined analyses of data from experiments representing two locations were performed as described by Petersen (1994). After that, the data were compared using Fisher's protected least significant difference (LSD) test at the probability levels $P < 0.05$ and $P < 0.01$. Correlation-regression analysis was also performed.

Results and discussion

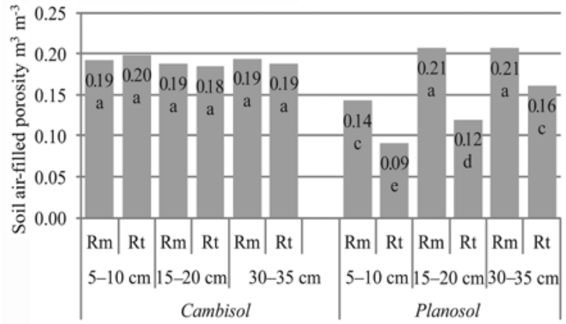
Interactions between location and treatments for investigated indices were significant, thus the data in this paper are presented for each location separately.

Basic soil physical properties. In *Cambisol*, soil depth had significant ($P < 0.01$) influence only on soil bulk density and total porosity (Fig. 1, Table 2). Bulk density consistently and significantly increased, total porosity significantly decreased with soil depth increasing. However, the influence of residue management method and its interaction with soil depth on bulk density, total porosity and air-filled porosity was insignificant.



Cambisol ($LSD_{05(A \times B)} = 0.028$)
Planosol ($LSD_{05(A \times B)} = 0.083$)

Cambisol ($LSD_{05(A \times B)} = 0.011$)
Planosol ($LSD_{05(A \times B)} = 0.031$)



Cambisol ($LSD_{05(A \times B)} = 0.021$)
Planosol ($LSD_{05(A \times B)} = 0.028$)

Notes. Rm – residues removed, Rt – residues returned; factor A – soil depth, factor B – residue management. Numbers followed by different letters are significantly different at $P \leq 0.05$ by the least square means test.

Figure 1. Soil bulk density, total and air-filled porosity under contrasting residue management

In *Planosol*, soil depth and residue management method had significant influence on bulk density ($P < 0.05$), total porosity ($P < 0.05$) and air-filled porosity ($P < 0.01$). Bulk density consistently and significantly decreased, total porosity and air-filled porosity significantly increased with soil depth increasing. Residue returning conditioned decrease of bulk density and increase of total porosity and air-filled porosity ($P < 0.01$). However, the interaction soil depth × residue was insignificant for all basic soil physical indices. As a result, better soil physical properties (lower bulk density, higher total porosity) were registered in *Planosol* than in *Cambisol*, while averaged air-filled porosity was higher in *Cambisol*. In *Planosol*, very high differences in air-filled porosity in residual backgrounds were revealed. Value of air-filled porosity in the background with returned residues was significantly ($P < 0.01$) lower than in the background without residues. This demonstrates that

Table 2. The level of significance for the impact of soil depth (factor A), residue management (factor B) and their interaction on soil bulk density, total and air-filled porosity and volumetric water content

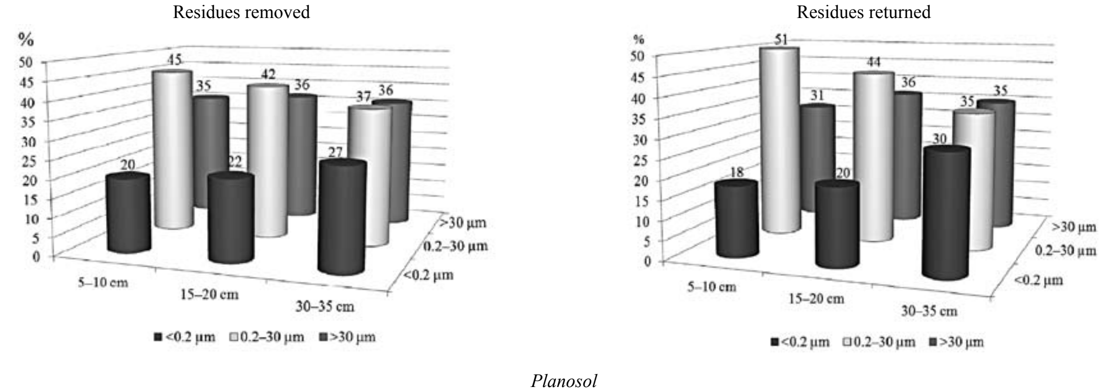
Indices	Soil type	Soil depth cm (factor A, data averaged across residue)			Residues (factor B, data averaged across depths)		Actions and interactions		
		5–10	15–20	30–35	Removed	Returned	A	B	A × B
Bulk density Mg m^{-3}	*Cambisol*	1.58 b	1.59 b	1.62 a	1.60 b	1.59 b	**	ns	ns
	Planosol	1.53 a	1.47 b	1.45 b	1.45 b	1.52 a	*	**	ns
Total porosity m^3 m^{-3}	*Cambisol*	0.40 a	0.40 a	0.39 b	0.40 b	0.40 b	**	ns	ns
	Planosol	0.42 b	0.44 a	0.45 a	0.45 a	0.43 b	*	**	ns
Air-filled porosity m^3 m^{-3}	*Cambisol*	0.20 b	0.19 b	0.19 b	0.19 b	0.19 b	ns	ns	ns
	Planosol	0.12 c	0.16 b	0.18 a	0.19 a	0.12 c	**	**	ns
Volumetric water content m^3 m^{-3}	*Cambisol*	0.21 b	0.21 b	0.20 b	0.20 b	0.21 b	ns	ns	ns
	Planosol	0.31 a	0.28 c	0.27 c	0.27 c	0.30 a	**	**	**

Note. Numbers followed by different letters within a set of a row are significantly different at $P \leq 0.05$ by the least square means test; * and ** – the least significant difference at $P < 0.05$ and $P < 0.01$, respectively; ns – not significant.

greater pore space was occupied by water. In *Cambisol*, the differences in air-filled porosity in backgrounds with residues or without them were insignificant.

Soil pore size distributiom. Soil pore structure differed between *Cambisol* and *Planosol* (Figs. 2–3, Table 3). In *Cambisol*, volume of macropores in 5–10, 15–20 and 30–35 cm layers was 165, 71 and 10 % higher, respectively, than in *Planosol*. Volume of mesopores in *Cambisol*, in 5–10 cm layer was 7% higher than in *Planosol*, while in 15–20 and 30–35 cm layers it was lower by 10% and 15%, respectively. Meanwhile, in *Cambisol*, in all soil layers volume of micropores was 60, 51 and 31 % lower, respectively, than in *Planosol*. In *Cambisol*, the space of micropores rose with deeper soil layer, the space of mesopores consistently decreased, while the space of macropores remained unchanged (Fig. 2). Impact of residue management on pore space distribution was trivial. In *Planosol*, the space of micropores declined with each deeper soil layer, the space of mesopores remained unchanged, while the space of macropores consistently increased (Fig. 2). Impact of residue management on pore space distribution in 15–20 and 30–35 cm layers was trivial, while in upper 5–10 cm layer residue returning significantly ($P < 0.01$) decreased macroporosity. Our data are in line with findings stating that under no-till soil bulk density is high and top-soil layer has a vertical orientation of macroporosity which encourage water movement within the soil (Soane et al., 2012).

Cambisol



Planosol

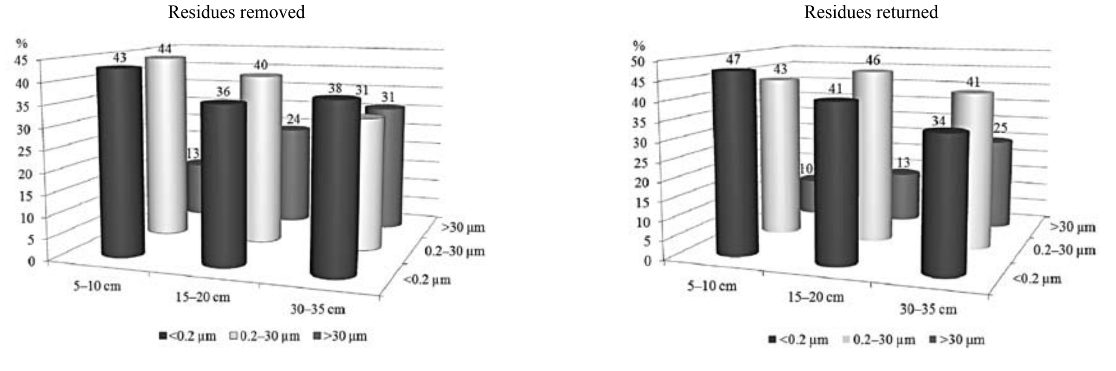


Figure 2. Soil pore space distribution (content of micropores, mesopores and macropores in % of total porosity) in *Cambisol* and *Planosol* under contrasting residue management at different soil depths in early spring in the stand of no-till winter wheat

In *Cambisol*, in 5–10 and 15–20 cm layers, the micropores (<0.2 µm) occupied on average 0.075 and 0.082 m^3 m^{-3} (or 20–22% of total porosity), respectively. In 30–35 cm layer their space significantly increased, compared to both upper layers (on average by 33% and 22%, respectively) (Fig. 3). The space of mesopores significantly decreased with each deeper soil layer. The highest changes were in 0.2–10 µm pore space, while soil depth had no influence on 10–30 µm pore space. Residue returning significantly increased mesoporosity only in 5–10 cm layer. The space of macropores (>30 µm) in all layers occupied 35–36% of total porosity. Space of 30–100 and 100–300 µm pores practically remained unchanged in all 5–35 cm soil layer. However, the space of >750 µm pores significantly increased with each deeper soil layer. Effect of residue returning asserted on soil macroporosity was observed only in 5–10 cm soil layer. Residue returning tended to decrease in 30–100 and 100–300 µm pore space and increase in 300–750 and >750 µm pore space.

In *Planosol*, the space of micropores (<0.2 µm) significantly decreased with each deeper soil layer. In 5–10, 15–20 and 30–35 cm layers, they occupied on average 0.188, 0,168 and 0.160 m^3 m^{-3} (or 34–47% of total porosity), respectively (Fig. 3).

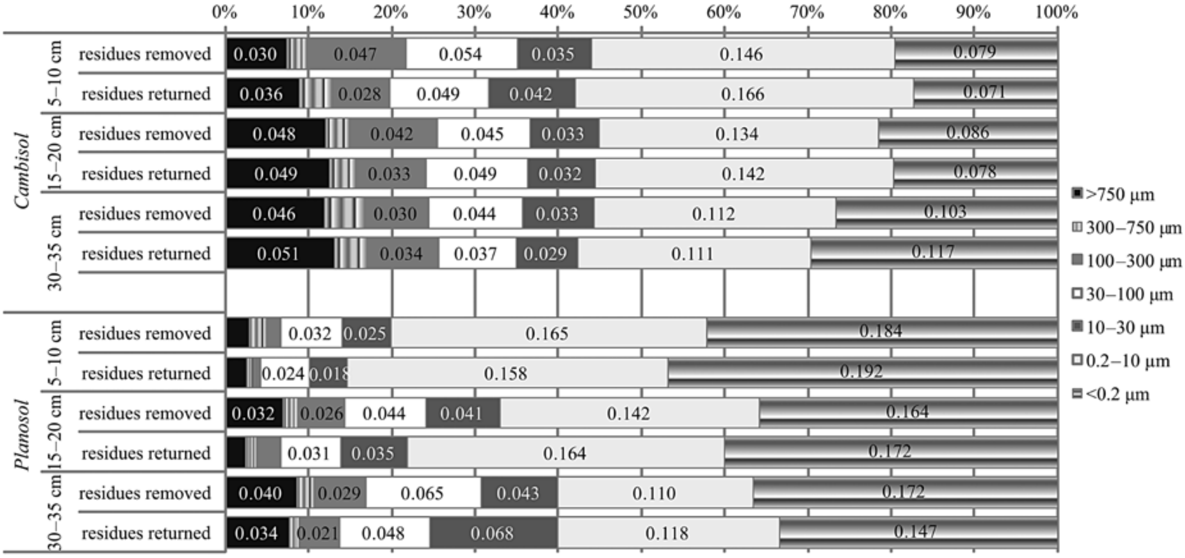


Figure 3. Soil pore structure (in m^3 m^{-3} of total porosity) in *Cambisol* and *Planosol* under contrasting residue management at different soil depths

Table 3. The level of significance for the impact of soil depth (factor A), residue management (factor B) and their interaction on soil pore size distribution in *Cambisol* and *Planosol* in early spring in the stand of no-till winter wheat

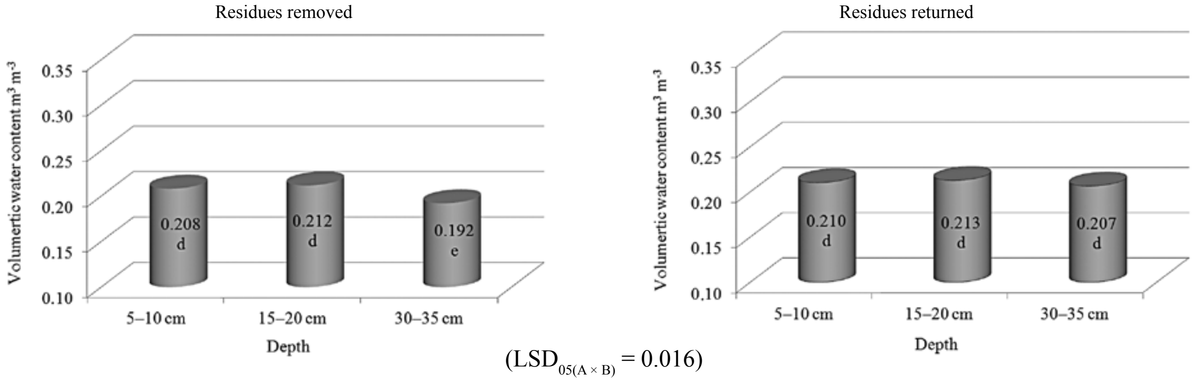
Soil pores µm	Soil type	Soil depth cm (factor A)			Residues (factor B)		Actions and interactions		
		5–10	15–20	30–35	Removed	Returned	A	B	A × B
Macropores (>30 µm)									
>750	*Cambisol*	0.033 c	0.049 a	0.049 a	0.041 b	0.046 b	**	ns	ns
	Planosol	0.011 d	0.021 c	0.037 a	0.028 b	0.018 c	**	**	*
300–750	*Cambisol*	0.013 b	0.012 b	0.017 a	0.013 b	0.015 b	*	ns	ns
	Planosol	0.006 b	0.007 b	0.007 b	0.009 a	0.005 b	ns	*	ns
100–300	*Cambisol*	0.038 a	0.038 a	0.032 b	0.040 a	0.032 c	*	**	**
	Planosol	0.005 d	0.019 a	0.025 a	0.021 b	0.012 d	**	**	ns
30–100	*Cambisol*	0.051 a	0.047 b	0.040 d	0.047 b	0.040 c	**	*	**
	Planosol	0.028 d	0.038 c	0.056 a	0.047 b	0.034 c	**	**	ns
∑ (macropores)	*Cambisol*	0.135 b	0.145 b	0.138 b	0.142 b	0.137 b	ns	ns	ns
	Planosol	0.051 e	0.085 c	0.126 a	0.105 b	0.070 d	**	**	ns
Mesopores (0.2–30 µm)									
10–30	*Cambisol*	0.039 a	0.033 c	0.031 d	0.034 c	0.035 c	**	ns	**
	Planosol	0.022 d	0.038 c	0.056 a	0.036 c	0.040 c	**	ns	**
0.2–10	*Cambisol*	0.156 a	0.138 b	0.111 d	0.131 c	0.140 b	**	*	ns
	Planosol	0.161 a	0.153 a	0.114 c	0.139 b	0.146 b	**	ns	ns
∑ (mesopores)	*Cambisol*	0.195 a	0.171 c	0.143 e	0.164 d	0.174 c	**	*	**
	Planosol	0.183 b	0.191 b	0.169 b	0.176 b	0.187 b	ns	ns	ns
Micropores (<0.2 µm)									
<0.2	*Cambisol*	0.075 c	0.082 c	0.110 a	0.089 b	0.089 b	**	ns	ns
	Planosol	0.188 a	0.168 b	0.159 c	0.173 b	0.170 b	**	ns	*

Note. Numbers followed by different letters within a set of a row are significantly different at $P \leq 0.05$ by the least square means test; * and ** – the least significant difference at $P < 0.05$ and $P < 0.01$, respectively; ns – not significant.

The space of mesopores in *Planosol* significantly decreased with each deeper soil layer. The highest changes were in 0.2–10 µm pore space. Their space decreased from 0.162 m^3 m^{-3} (in 5–10 cm layer) to 0.114 m^3 m^{-3} (in 30–35 cm layer). However, the space of 10–30 µm pores increased from 0.022 m^3 m^{-3} (in 5–10 cm layer) to 0.056 m^3 m^{-3} (in 30–35 cm layer). Residue returning tended to decrease in mesoporosity in 5–10 cm layer, while in 15–20 and 30–35 cm layers residues slightly enhanced the space of mesopores. The space of macropores (>30 µm) in 5–10, 15–20 and 30–35 cm layers occupied 10–13, 13–24 and 25–31 % of total porosity, respectively. Space of 30–100 and 100–300 µm pores practically was similar in 5–10 and l5–20 cm soil layers, while in 30–35 cm layer it significantly increased, compared to both upper layers. The space of >750 µm pores consistently increased with each deeper soil layer. Effect of residue returning on space of different pores was insignificant. However, residue returning significantly decreased total macroporosity in all soil layers.

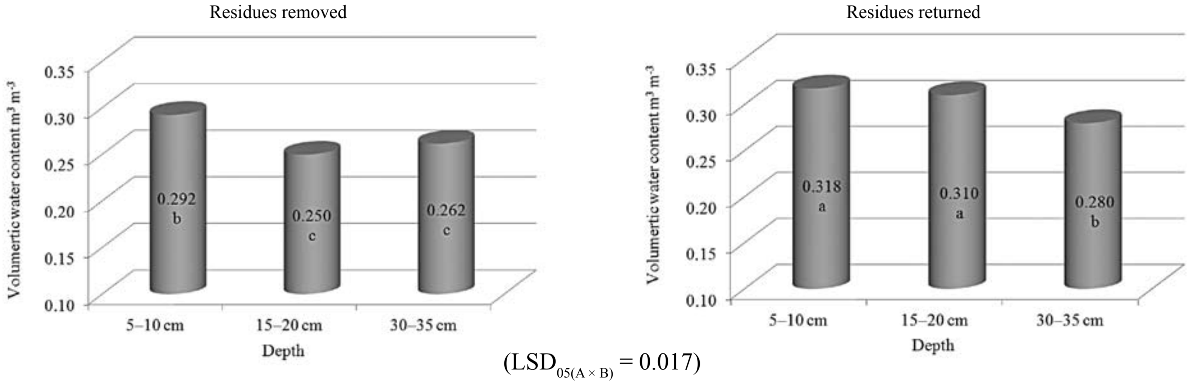
Soil pore space distribution determined soil volumetric water content in the field (Fig. 4, Table 2). Volumetric water content in 5–35 cm layer of *Cambisol*, irrespective of residue management, was 27% lower than in *Planosol*. In *Cambisol,* residues had no influence on volumetric water content in each soil layer investigated. Moreover, soil volumetric water content did not significantly differ in all layers. Meanwhile, in *Planosol* without residues, the highest volumetric water content was in 5–10 cm layer, while in 15–20 and 30–35 cm layers volumetric water content was lower by 14% and 10%, respectively. In *Planosol,* residue returning conditioned increase of volumetric water content within 5–10 and 15–20 cm layers, compared to residue removing. In background with residues, volumetric water content in 5–10 and 15–20 cm layers was very similar, but in 30–35 cm layer it was 10–12% lower than in both upper layers.

Cambisol



(LSD$_{05(A \times B)}$ = 0.016)

Planosol



(LSD$_{05(A \times B)}$ = 0.017)

Note. Numbers followed by different letters within treatments of individual soil are significantly different at $P < 0.05$ by the least square means test; factor A – soil depth, factor B – residue management.

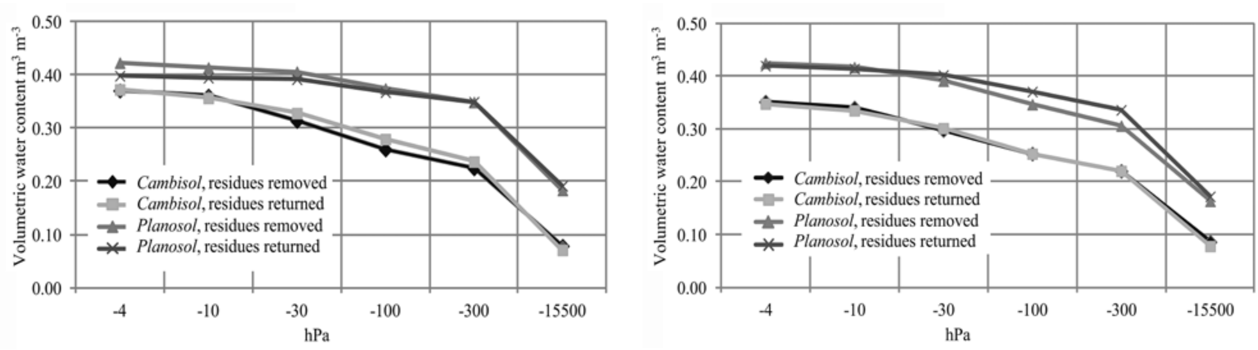
Figure 4. Soil volumetric water content in *Cambisol* and *Planosol* at an early spring in the stand of no-till winter wheat

These data suggest that *Cambisol* and *Planosol* have opposite soil water retention capacity. It is expected that different water retention capacity could differently influence soil vital processes and soil CO_2 e-fluxes.

Soil water capacity. In the overall 5–35 cm layer, soil water retention capacity of macropores, mesopores and micropores in *Cambisol* was lower than in *Planosol* by 18, 28 and 48 %, respectively (Fig. 5, Table 4).

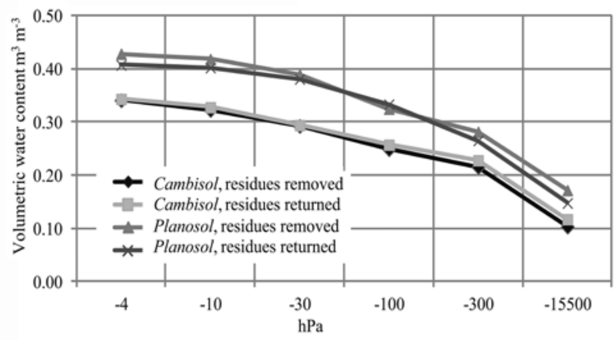
In *Cambisol*, after suction, macropores (>30 µm) retained 0.304–0.354 m^3 m^{-3}, mesopores (10–30 µm) – 0.224–0.258 m^3 m^{-3}, and micropores (<0.2 µm) – 0.089 m^3 m^{-3} of volumetric water. Residue returning slightly increased volumetric water content retention only in mesopores. The deeper soil layer was investigated, a significantly higher ($P < 0.01$) water retention in macropores and mesopores was determined. The deeper the soil layer was investigated, the significantly lower ($P < 0.01$) water retention in micropores was determined.

In *Planosol*, after suction, macropores retained 0.393–0.417 m^3 m^{-3}, mesopores – 0.314–0.353 m^3 m^{-3}, and micropores – 0.172 m^3 m^{-3} of volumetric water. Residue returning tended to increase volumetric water content retention in mesopores, while in macropores water retention significantly decreased. The deeper soil layer



5–10 cm
Cambisol ($LSD_{05(A \times B)}$ = 0.012)
Planosol ($LSD_{05(A \times B)}$ = 0.020)

15–20 cm
Cambisol ($LSD_{05(A \times B)}$ = 0.007)
Planosol ($LSD_{05(A \times B)}$ = 0.020)



30–35 cm
Cambisol ($LSD_{05(A \times B)}$ = 0.023)
Planosol ($LSD_{05(A \times B)}$ = 0.042)

factor A – soil depth, factor B – residue management

Figure 5. Soil water retention capacity in *Cambisol* and *Planosol* under contrasting residue management at different soil depths

Table 4. The level of significance for the impact of soil depth (factor A), residue management (factor B), water retention (factor C) and their interactions on soil water capacity in *Cambisol* and *Planosol* in early spring in the stand of no-till winter wheat

Soil depth (factor A)	Residues (factor B)	Water retention (factor C)		*Cambisol*				*Planosol*			
		suction hPa	pores µm	water content m³ m⁻³	actions A	actions B	actions C	water content m³ m⁻³	actions A	actions B	actions C
5–10 cm				0.271 a				0.353 a			
15–20 cm				0.257 c	**			0.347 b	**		
30–35 cm				0.257 c				0.329 c			
	removed			0.260 c		**		0.345 b		ns	
	returned			0.264 a				0.341 b			
		−4	>750	0.354 a				0.417 a			
		−10	300	0.340 b				0.410 a			
		−30	100	0.304 c			**	0.393 b			**
		−100	30	0.258 d				0.353 c			
		−300	10	0.224 e				0.314 d			
		−15500	<0.2	0.089 f				0.172 e			
Interactions											
A × B				**				**			
A × C				**				**			
B × C				*				**			
A × B × C				ns				ns			

Note. Numbers followed by different letters within a set of a column are significantly different at $P \leq 0.05$ by the least square means test; * and ** – the least significant difference at $P < 0.05$ and $P < 0.01$, respectively; ns – not significant.

was investigated, a significantly higher ($P < 0.01$) water retention in macropores was determined. The deeper the soil layer was investigated, the significantly lower ($P < 0.01$) water retention in mesopores and micropores was determined. So, mesopores in both *Cambisol* and *Planosol* revealed a solely high contribution to soil water retention.

The data obtained on soil water retention capacity leads to the conclusion that *Cambisol* is more aerated than *Planosol* due to a greater volume of macropores within the soil profile down to 35 cm depth. This means that surface water can easily move down toward soil profile. This is an important feature of the soil, because the excess water could drain down into deeper soil layers during heavy rain events, which often occur in summer as a consequence of climate change. The soil space occupied by macropores and mesopores was higher in *Planosol*. Unfortunately, a high risk of waterlogging condition occurrence should be taken into account in *Planosol* due to a greater microporosity as compared to *Cambisol.*

Influence of field capacity and permanent wilting point on top soil water content. The influences of residue management practice and soil depth ($P < 0.01$) and their interaction ($P < 0.01$) were significant for the water retention capacity at hPa −100 tension. This point of soil water release characteristics is known as field capacity. This indicator, averaged across residue management practices and soil depth, was higher in *Planosol* than in *Cambisol* (Table 4). This means that under no-till conditions *Planosol* has a greater capability to collect water. In *Planosol*, field capacity slightly but significantly decreased with each deeper soil layer. In *Cambisol*, in 15–20 and 30–35 cm layers field capacity was identical, in 5–10 cm layer it was 6% higher. In both *Cambisol* and *Planosol* long-term residues returning under no-till caused slightly but significantly higher field capacity than in the fields where residues had been removed for many years.

The influences of soil depth and residue management were significant ($P < 0.01$) for the water retention capacity at hPa −15500 tension. This point of soil water release characteristics is known as permanent wilting point. Moreover, permanent wilting point is fixed and depends on soil origin. Permanent wilting point in *Planosol* was 89% higher than in *Cambisol*.

We consider that hydro-physical properties of different soil layers significantly determine soil surface volumetric water content. Field capacity and permanent wilting point significantly influenced changes of soil surface (0–10 cm) volumetric water content. However, consistent pattern in *Cambisol* and *Planosol* differed (Fig. 6). Furthermore, the ratio between field capacity and permanent wilting point additionally revealed differences between hydro-physical properties of *Cambisol* and *Planosol*.

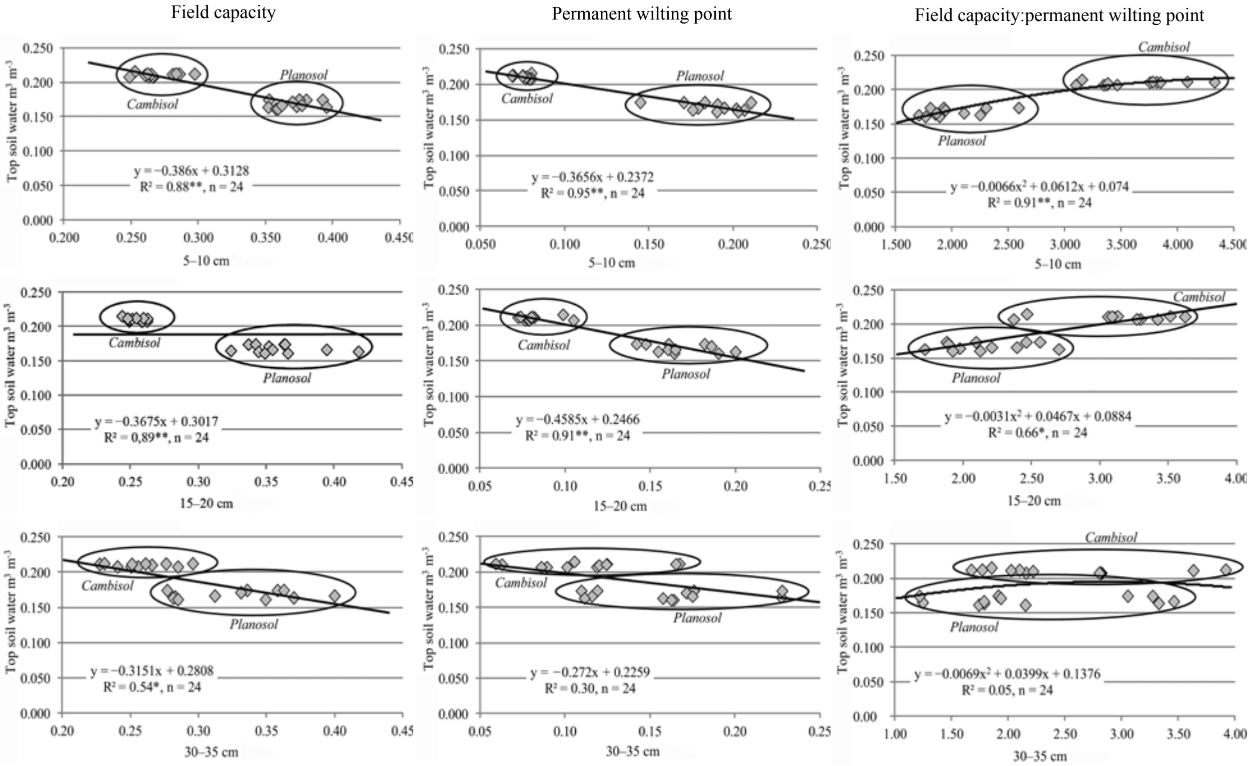
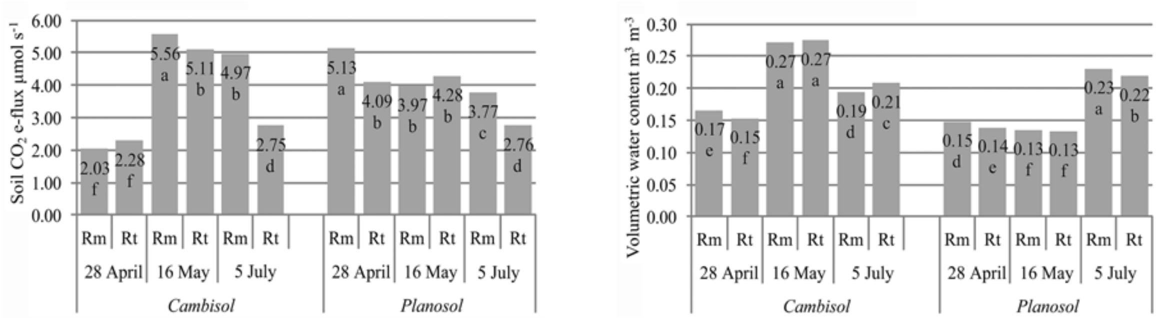


Figure 6. Response of soil surface (0–10 cm) volumetric water content to field capacity, permanent wilting point and ratio between these indices at different soil depths in *Cambisol* and *Planosol*

Irrespective of high field capacity in *Planosol*, the permanent wilting point of this soil type also was high. Consequently, the ratio between field capacity and permanent wilting point was low. Moreover, this ratio tended to increase from 2.00 in 5–10 cm layer to 2.16 and 2.24 in 15–20 and 30–35 cm layers, respectively. In *Cambisol*, the field capacity and permanent wilting point ratio was higher than in *Planosol* on average by 44%. In contrast to *Planosol*, this ratio tended to decrease from 3.62 in 5–10 cm layer to 3.12 and 2.48 in 15–20 and 30–35 cm layers, respectively. Zettl et al. (2011) also found that higher water storage at field capacity values in boreal area of Canada is associated with increased textural heterogeneity.

The higher field capacity and permanent wilting point ratio was determined, the higher soil surface volumetric water content dominated during plant vegetation period. The strongest correlation between volumetric water content and field capacity, volumetric water content and permanent wilting point and between volumetric water content and field capacity and permanent wilting point ratio was determined in 5–10 cm soil layer. Very strong correlation between these indices also remained in 15–20 cm layer. However, influence of hydro-physical conditions of 30–35 cm layer on soil surface volumetric water content was weak.

Soil CO$_2$ e-flux. It is known that agricultural practices play a significant role in production and consumption of greenhouse gas, specifically, CO$_2$ (Rastogi et al., 2002; Smith et al., 2008). Soil water content is consider as the most influential environmental factor controlling soil surface CO$_2$ fluxes (Lopes de Gerenyu et al., 2005; Feiziene et al., 2012). Soil net carbon exchange rates peaked at intermediate soil moisture and decreased under increasingly dry conditions (drought induced), but also decreased when soils became water saturated (van Straaten et al., 2009). In the case of soil water surplus, the total soil CO$_2$ e-flux is reduced, because of limited diffusion of oxygen and subsequent suppression of CO$_2$ emissions. Whereas soil surface volumetric water content significantly responded to soil water release characteristics, we suppose that volumetric water content changes can play significant role in CO$_2$ e-flux.



Cambisol (LSD$_{05(A \times B)}$ = 0.471)
Planosol (LSD$_{(A \times B)}$ = 0.919)

Cambisol (LSD$_{05(A \times B)}$ = 0.377)
Planosol (LSD$_{05(A \times B)}$ = 0.478)

Rm – residues removed, Rt – residues returned; factor A – date of measurements, factor B – residue mangement

Figure 7. Soil surface (0–10 cm) CO$_2$ e-flux and volumetric water content in *Cambisol* and *Planosol*

Soil CO$_2$ e-flux significantly responded to measurement date and residue management practices and their interaction ($P < 0.01$). In both *Cambisol* and *Planosol*, soil surface volumetric water content also significantly ($P < 0.01$) responded to measurement date and residue management practices. Interaction of these factors was significant at $P < 0.05$ (Fig. 7, Table 5).

Table 5. Variance analysis of soil CO$_2$ e-flux and volumetric water content in *Cambisol* and *Planosol* in 0–10 cm layer

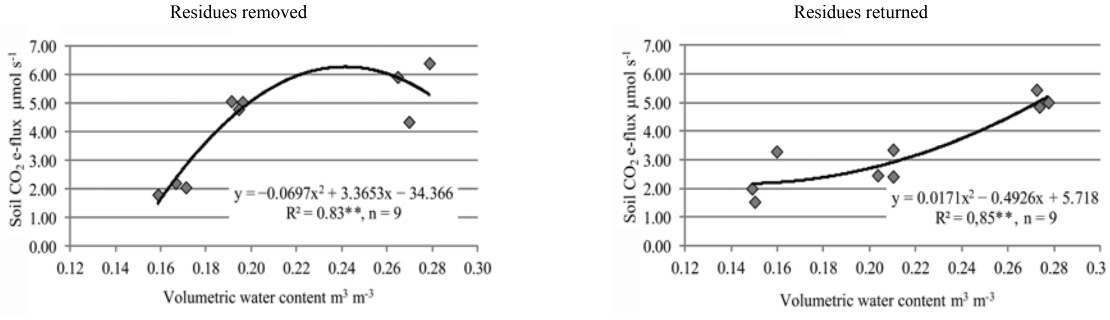
Indices	Soil type	Date of measurements (factor A)			Residues (factor B)		Actions and interactions		
		2014			removed	returned	A	B	A × B
		28 April	16 May	5 July					
CO$_2$ e-flux µmol s^{-1}	*Cambisol*	2.155 e	5.331 a	3.859 c	4.185 a	3.378 c	**	**	**
	Planosol	4.609 a	4.127 b	3.263 c	4.291 a	3.708 b	**	*	ns
Volumetric water content m^3 m^{-3}	*Cambisol*	0.159 c	0.273 a	0.201 b	0.210 b	0.212 b	**	ns	**
	Planosol	0.144 c	0.134 d	0.225 a	0.171 a	0.164 c	**	**	*

Note. Numbers followed by different letters within a set of a row are significantly different at $P \leq 0.05$ by the least square means test; * and ** – the least significant difference at $P < 0.05$ and $P < 0.01$, respectively; ns – not significant.

Mean soil CO$_2$ e-flux did not differ between *Cambisol* and *Planosol* during winter wheat vegetation period in spite of the fact that mean volumetric water content in *Cambisol* was 26% higher than in *Planosol* (Table 5). Surely, weather conditions (rainfall, air temperature) had influence on soil surface volumetric water content. However, the pattern of soil surface dynamic volumetric water content changes fully reflected the soil release characteristics. Consequently, we found that on *Cambisol*, in background without residues, soil CO$_2$ e-flux increase than volumetric water content ranged from 0.159 to 0.196 m^3 m^{-3} (Fig. 8). Correlation analysis exhibited that soil volumetric water content approximate range from 0.220 to 0.250 m^3 m^{-3} can be characterized as a peak after which CO$_2$ e-flux slopes down. On *Planosol*, the soil CO$_2$ e-flux peak ranges were lower, i.e. approximately 0.170–0.200 m^3 m^{-3}. We support the proposition of van Straaten et al. (2009) that soil CO$_2$ e-flux reduced because of limited diffusion of oxygen. Really, water retention in all soil layers in *Planosol* was higher than in *Cambisol* and this pattern influenced soil surface volumetric water content also (Table 4). This demonstrates that the higher volumetric water content was determined, the lower oxygen content took part in diffusion processes.

On *Cambisol*, in background with returned residues, soil CO$_2$ e-flux consistently increased when volumetric water content ranged from 0.149 to 0.278 m^3 m^{-3}. It means that long-term residue returning practice changed soil pore-space distribution, first of all in 5–10 cm layer, i.e. increased mesoporosity (also field capacity) and slightly decreased macroporosity, while microporosity remained unchanged. Consequently, changes in soil pore-space distribution caused changes in

Cambisol



Planosol

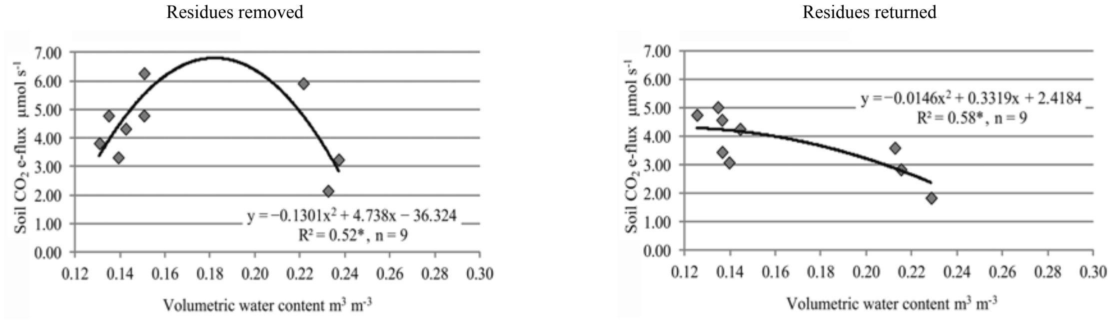


Figure 8. Response of soil CO_2 e-flux to volumetric water content during plant vegetation period

water release characteristics. Decrease in water retention in macropores was compensated for by increase in water retention in mesopores. Thus enlarged sum of mesopores and macropores acted like drainage pores and prevented soil surface from prolonged water surplus. In turn, that ensured favourable conditions for heterotrophic and autotrophic respiration. On *Planosol*, long-term residue returning practice tended to increase microporosity within 5–10 and 15–20 cm layers. Unfortunately, long-term residues returned onto soil surface acted as a physical obstruction inside mesopores in 5–10 cm and within macropores in 5–10 and 15–20 cm layers and, finally, causing clogging of them. It means that water retention capacity in mesopores and macropores decreased. Such soil pores drainage system could not prevent soil surface from prolonged water surplus. Consequently, the soil CO_2 e-flux consistently decreased than soil surface volumetric water content ranged from 0.125 to 0.229 m^3 m^{-3}.

Conclusions

1. The soil genesis is an important factor which determines options for soil management activities. Lower bulk density and higher total porosity were registered in *Planosol* than in *Cambisol*. However, the plough layer (0–20 cm) of *Cambisol* had a greater pore space of macropores than *Planosol*. Due to this soil property, the surface water can more easily move from topsoil down to deeper layers. A risk of waterlogging condition may occur in *Planosol* due to a greater share of meso- and microporosity within 5–35 cm soil depth, compared to *Cambisol*.

2. Long-term no-tillage with residue (straw) removing on *Cambisol* determined an increase in CO_2 e-flux when soil water content ranged from 0.159 to 0.196 m^3 m^{-3}. Soil volumetric water content range approximately from 0.220 to 0.250 m^3 m^{-3} can be characterized as a peak after which CO_2 e-flux sloped down. On *Planosol*, the soil CO_2 e-flux peak ranges were lower, i.e. approximately 0.170–0.200 m^3 m^{-3}.

3. Enlarged total volume of mesopores and macropores on *Cambisol* under long-term no-tillage with residue (straw) returning was responsible for CO_2 e-flux increase. On *Planosol*, long-term residue returning onto soil surface acted as a physical obstruction inside mesopores in 5–10 cm and within macropores in 5–10 and 15–20 cm layers and, finally, caused clogging of them. Increase of soil surface volumetric water content caused soil CO_2 e-flux decrease.

4. No-tillage application with crop residue returning was more suitable on *Cambisol* than on *Planosol*. Topsoil water excess was a limiting factor for CO_2 exchange. CO_2 e-flux peak range was lower in *Planosol* than in *Cambisol*.

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Dirvožemio vandentalpa ir CO_2 emisija skirtinguose dirvožemiuose, ilgą laiką taikant tiesioginę sėją

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Santrauka

Nedaug žinoma apie modernių žemdirbystės sistemų, ypač tiesioginės sėjos, ilgalaikio taikymo įtaką skirtingo tipo dirvožemių fizikinei būklei, porų dydžiui ir jų pasiskirstymui bei vandentalpai. Tyrimai atlikti 2014 m. Lietuvos agrarinių ir miškų mokslų centro Žemdirbystės institute, Vidurio Lietuvos žemumoje, smėlingame priemolyje (giliau karbonatingame sekliai glėjiškame rudžemyje, RDg8-k2) ir Aleksandro Stulginskio universitete, dulkiškiame priemolyje (giliau glėjiškame pasotinateme palvažemyje, PLb-g4). Tyrimų tikslas: a) palyginti dirvožemio vandentalpą, porų dydžius bei jų pasiskirstymą ir CO_2 emisiją rudžemyje bei palvažemyje, b) įvertinti ilgalaikių tiesioginės sėjos ir šiaudų tvarkymo sistemų įtaką skirtingų grupių dirvožemių hidrofizikinėms savybėms, 3) įvertinti praktinę tokios žemės dirbimo sistemos taikymo įtaką dirvožemių fizikinės būklės pokyčiams.
Skirtingos genezės dirvožemiuose atlikti tyrimai parodė, jog mažesnis tankis ir didesnis bendrasis poringumas buvo nustatyti palvažemio viršutiniame 0–20 cm sluoksnyje, palyginus su rudžemiu, tačiau rudžemis pasižymėjo geresne aeracija dėl didesnio makroporų tūrio. Dėl žymiai didesnio mezo- ir mikroporų tūrio dirvožemio 5–35 cm sluoksnyje palvažemis vertintinas kaip linkęs labiau užmirkti nei rudžemis. Tiesioginė sėja fone su šiaudais buvo tinkamesnė žemės dirbimo sistema taikyti rudžemyje nei palvažemyje. Ši žemdirbystės sistema padidino drėgmės kiekį dirvožemyje ir jo kvėpavimo intensyvumą. Tiesioginę sėją taikant rudžemyje fone be šiaudų, CO_2 emisija didėjo, kai vandens kiekis kito nuo 0,159 iki 0,196 $m^3\ m^{-3}$. Kai vandens kiekis padidėjo iki 0,220–0,250 $m^3\ m^{-3}$, dirvožemio kvėpavimas po pasiekto didžiausio CO_2 emisijos kiekio pradėjo mažėti. Palvažemyje didžiausias CO_2 srautų kiekis buvo pasiektas dirvožemio drėgmei esant mažesnei, t. y. maždaug 0,170–0,200 $m^3\ m^{-3}$. Palvažemyje ilgalaikis tiesioginės sėjos taikymas ir liekanų skleidimas dirvos paviršiuje lėmė dirvožemio 5–10 cm sluoksnyje esančių mezoporų ir 5–10 bei 15–20 cm sluoksniuose esančių makroporų užsikimšimą. Palvažemyje vandens kiekio didėjimas dirvožemio viršutiniame sluoksnyje mažino CO_2 emisiją.

Reikšminiai žodžiai: lauko drėgmė, porų struktūra, tankis, vandentalpa, vytimo drėgmė.