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The effect of soil macroporosity, temperature and water content on CO_2 efflux in the soils of different genesis and land management

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Abstract

This paper analyses the effects of soil macropores, temperature and water content on soil carbon dioxide (CO_2) efflux behaviour, which could help understand the mechanism of CO_2 efflux as influenced by soil type and land use methods. The temporal dynamic changes of CO_2 efflux from the soil surface using a closed chamber method (LI-COR LI-8100A Automated Soil CO_2 Flux System) were measured. Soil CO_2 efflux was investigated at a topsoil depth of 0–5 cm in (1) arable land under conventional tillage on *Cambisol* (*CM*), (2) grassland on *Cambisol*, (3) park on *Cambisol*, (4) arable land under conventional tillage on *Retisol* (*RT*), (5) grassland on *Retisol* and (6) forest on *Retisol*. CO_2 emission was measured six times per growing season from May to September in 2017. Soil macropore network was researched by implementing an X-ray computed tomography and carried out at the laboratory of the Institute of Agrophysics, Polish Academy of Sciences in Lublin, Poland.

Macropores resulting from soil pedogenesis and land use methods played an important role on soil water, temperature and gas transport. The type of soil vegetation cover and amount of soil macropores significantly influenced soil respiration rate. The efflux values were recorded ranging from 0.71 to 3.43 μmol CO_2 m^{-2} s^{-1} (*Cambisol*) and from 0.70 to 3.05 μmol CO_2 m^{-2} s^{-1} (*Retisol*) in the grassland, from 0.43 to 2.57 μmol CO_2 m^{-2} s^{-1} (*Cambisol*) in the park, from 0.44 to 2.52 μmol CO_2 m^{-2} s^{-1} (*Retisol*) in the forest, from 0.52 to 2.68 μmol CO_2 m^{-2} s^{-1} (*Retisol*) and from 0.09 to1.57 μmol CO_2 m^{-2} s^{-1} (*Cambisol*) in the conventional tillage. Computational tomography data revealed that the content of macropores amounted to 10.75% in the grassland site, 1.97% in the park and 1.21% in the conventional tillage within the soil depth of 3–8 cm of the *Cambisol* and 6.45% in the forest, 4.94% in the conventional tillage and 3.86% in the grassland at the same soil depth of the *Retisol.* Soil temperature, water content and macroporosity were the main factors exerting the influence on soil gas origination rate. The relationship between soil CO_2 efflux and volumetric water content at a 5 cm depth can be described by a linear regression model $y = 0.0943x - 0.7651$, $R^2 = 0.53$ (valid for volumetric water content from 22.5 to 27.0 vol.% on *Retisol* and from 16.8 to 24.4 vol.% on *Cambisol*). Also, linear regression model $y = 0.1167x - 0.8214$, $R^2 = 0.65$ showed the relationship between soil CO_2 efflux and soil macroporosity at the 3–8 cm depth. Soil CO_2 efflux displayed a typical polynomial relationship with soil temperature at the 5 cm depth; however, the relationship was very weak.

Both soil type and land use methods had a noticeable influence on macroporosity, surface area and macropore range of soil pore-size distribution. The amount of macropores in macropore geometry was an important factor when dealing with CO_2 flow. Topsoil CO_2 efflux under contrasting vegetation cover and management conditions on *Cambisol* and *Retisol* was directly related to soil macroporosity and volumetric water content.

Key words: *Cambisol*, *Retisol*, volumetric water content, X-ray computed tomography.

Introduction

Soil carbon dioxide (CO_2) efflux is a physical process driven primarily by the CO_2 concentration diffusion gradient between the upper soil layers and the atmosphere near the soil surface. Soil CO_2 production is heavily influenced by environmental factors, including soil temperature, soil moisture, macropores.

The importance of macropores as preferential pathways of water, air and chemicals in the soil has been

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widely recognized (Lin et al., 2005; Jarvis, 2007; Hu et al., 2016). Reconstruction, visualization and quantification of 3-D macropore networks are essential for correlation macropore characteristics to their physical functions and for prediction of their dynamics under diverse land uses. Different types of macropores have distinct geometrics and therefore function differently (Luo et al., 2008). Soil type and land use method are among the main factors influencing macropore characteristics (Gantzer, Anderson, 2002; Mooney, Morris, 2008; Udawatta et al., 2008; Zhou et al., 2008; Luo et al., 2010). X-ray computed tomography has been used in recent years as a new method to quantify soil pores, especially macropore development, at a much higher resolution than the previous methods, such as dye tracing, spectral image analysis and thin section (Taina et al., 2008; Munkholm et al., 2012). Soil pore characteristics are important for a large range of essential soil functions such as colloid, water and gas transport, habitat for soil organisms as well as soil mechanical properties such as soil friability (Munkholm et al., 2012).

Greenhouse gas (GHG) emissions from agricultural soils are a substantial contributor to climate change (Smith et al., 2008), there for development of agricultural practices that mitigate GHG emissions from agricultural soils is very important (Mangalassery et al., 2013). Tillage regime has been regarded as one of the important factors affecting efflux from the soils (Li et al., 2013). Tillage management can affect factors controlling soil respiration, soil temperature, soil water content (Liu et al., 2006) and macroporosity. Soil moisture and temperature are among the most important factors controlling soil CO_2 emissions (Lopes de Gerenyu et al., 2005; Schaufler et al., 2010; Ni et al., 2012). Under dry conditions, the soil CO_2 efflux is lower because root and micro-organism activity is typically low. Increasing the soil water content normally increases the bio-activity in the soil. Higher soil water content usually causes soil respiration increase. But if soil water content is very high, the total soil CO_2 efflux is reduced, because of limited diffusion of oxygen and subsequent suppression of CO_2 emission. Soil temperature is the best predictor of the dynamics of the soil CO_2 flux rate. The high positive correlation between CO_2 efflux and soil temperatures was found in natural and agricultural ecosystems of the Russian taiga zone (Kudeyarov, Kurganova, 1998). Schaufler et al. (2010) revealed a non-linear increase of CO_2 efflux with temperature increasing. Tillage regime has been regarded as one of the important factors affecting CO_2 emissions from soils (Li et al., 2013). Soil temperature and soil moisture influence both the production of CO_2 by affecting microorganism and root activity, and the diffusion of gases through the soil pores (Wei et al., 2014).

The goal of this paper is to present the findings on soil carbon dioxide (CO_2) efflux originated from soils of different genesis and under contrasting land use methods. The attention was focused on the evaluation of soil temperature, volumetric water content and the network of the macroporosity effects on soil CO_2 efflux regime.

Materials and methods

Soils and sampling. Two soil types were studied: *Endocalcari Endogleyic Cambisol* (*CM-gln.can-lo.dr*) (*loamic*, *drainic*) situated at Institute of Agriculture (55°23′38″ N, 23°51′35″ E), Lithuanian Research Centre for Agriculture and Forestry in Dotnuva, and *Bathygleyic Dystric Retisol* (*RT-dy.gld-lo*) (*loamic*) near Bijotai (55°31′12″ N, 22°36′55″ E), Šilalė distr. The soils are classified according to WRB (2014). Both soil types are representative and commonly found in the Central (*Cambisol*) and in the Western (*Retisol*) parts of Lithuania.

Three land use methods on *Cambisol*: 1) conventional tillage – stubble cultivation (10–12 cm) after crop harvesting; in 2–3 weeks deep (23–25 cm) ploughing; before sowing, shallow cultivation (4–5 cm) 1–2 times; plant residues (straw) chopped and spread in the field; straw mineralization activated by adding nitrogen fertiliser; the crop was beans; 2) grassland – area where the vegetation is dominated by grasses: *Medicago sativa*, *Galega orientalis*, *Taraxacum officinale*, *Lolium temulentum* and *Trifolium repens*; 3) park area – the dominant vegetation is trees: *Acer platanoides*, *Tilia cordata*, *Fraxinus excelsior*, and grasses: *Aegopodium podagraria*, *Pulmonaria obscura*, *Anemone nemorosa*.

Three land use methods on *Retisol*: 1) conventional tillage – stubble cultivation (10–12 cm) after crop harvesting; in 2–3 weeks deep (23–25 cm) ploughing; before sowing, shallow cultivation (4–5 cm) 1–2 times; plant residues (straw) chopped and spread in the field; straw mineralization activated by adding nitrogen fertiliser; the crop was winter wheat; 2) grassland – area where the vegetation is dominated by grasses: *Leontodon autumnalis*, *Festuca ovina*, *Dactylis glomerata*, *Taraxacum officinale* and *Trifolium repens*; 3) forest – the dominant vegetation is trees *Quercus robur* and *Acer platanoides*, and grasses *Aegopodium podagraria*, *Pulmonaria obscura* and *Anemone nemorosa*. Thus, there were six treatments investigated in this study: *Cambisol*-grassland, *Cambisol*-conventional tillage, *Cambisol*-park, *Retisol*-grassland, *Retisol*-conventional tillage and *Retisol*-forest.

For soil macropore network determination, one intact soil column for scanning with a computed tomography, 50 mm in diameter and 50 mm in length was sampled from each treatment at the 3–8 cm soil depth on April 20, 2017 on *Cambisol* and on May 12, 2017 on *Retisol*. Samples were taken to carefully push polyvinyl chloride pipe vertically and gradually into the soil. The soil inside the cylinders was secured with two plastic caps for natural soil water content preservation. Undisturbed soil cores were stored in a refrigerator at a constant 3–4°C temperature.

Carbon dioxide (CO_2) efflux measurements and characterization. In this research we investigated the temporal dynamic changes of CO_2 efflux (μmol m^{-2} s^{-1}) from the soil surface using a closed chamber method – LI-COR LI-8100A Automated Soil CO_2 Flux System (LI-COR Inc., USA). Soil CO_2 efflux was determined from the topsoil in: 1) arable land under conventional tillage on *Cambisol*, 2) grassland on *Cambisol*, 3) park on *Cambisol*, 4) arable land under conventional tillage on *Retisol*, 5) grassland on *Retisol* and 6) forest on *Retisol*. Each CO_2 efflux measurement was done in three replications. Measurement of CO_2 efflux was carried out six times per growing season from May to September, 2017, at the same time of the day (from 10 a.m. to 5 p.m.) and at the fixed locations in the site. Soil temperature (T-soil) and volumetric water content (VWC) were measured at the 5 cm depth using a portable HH2 WET sensor. It was determined at the same time and same site with CO_2 efflux measurements.

X-ray computed tomography. X-ray computational tomography (XRT) analysis of soil samples (50 mm in diameter and 50 mm in length) was performed in the Institute of Agrophysics, Polish Academy of Sciences, laboratory of X-ray Computed Tomography (Lamorski, 2017) in October 2017 using a device GE Nanotom 180S (GE Sensing & Inspection Technologies GmbH, Germany). Each XRT measurement was done in a single copy. The scan resolution, i.e. voxel size was 0.0215 mm. The parameters of the XRT acquisition were as follows: X-ray source voltage 150 kV, X-ray source current 40 µA and 0.2 mm Cu filter was used to avoid beam hardening effect. During the XRT scan, the samples were rotated in 360° and 1200 2D radiograms were recorded. The recorded radiograms were averages of 12 2D images taken at the same angular position to minimize the detector noise. The next step was three-dimensional (3D) soil sample image reconstruction based on the recorded two-dimensional (2D) radiograms. Reconstruction was done using software *DatosX 2.0* (GE Sensing & Inspection Technologies GmbH). As a result, 16 bit grey-level 3D images were generated. Image analysis was performed using VG Studio Max 2.0 (Volume Graphics GmbH, Germany), Fiji (National Institutes of Health, USA) and software *Avizo 9* (Field Electron and Ion Company, USA). The first step was the region of interest selection and extraction of the soil core image from the whole 3D scanned volume. Next step included the median filtering with kernel size 3px to minimize the noise before thresholding the images. Thresholding was done using IsoData algorithm (Ridler, Calvard, 1978) with thorough inspection of the thresholded images. After that the labelling of the detected pores was performed. The group of voxels connected by at least one voxel face was treated as an individual pore. As a result of the labelling, the volumes, surface and equivalent diameter of individual macropores were determined.

Description of meteorological conditions. Climatic peculiarities are determined by both continental and oceanic factors. The mean annual air temperature in Lithuania is close to 6°C, and mean annual amount of precipitation varies from 620 to 700 mm and more. Precipitation in 2017 amounted to 736.1 mm in the central part and to 1276.1 mm in the western part of Lithuania. In 2017, there were 117 days with precipitation in Dotnuva and 200 days in Bijotai.

Statistical analysis. The statistical software package *SAS 7.1* (SAS Inc., USA) was used for all data analysis. The data was compared using Fisher's least significant difference (LSD) test at the probability levels $P < 0.05$ and $P < 0.01$. Simple linear regressions were carried out to examine the relationship between different parameters. Correlation-regression analysis was also implemented.

Results and discussion

The effect of land use methods on soil CO_2 efflux, temperature and water content. All processes taking part in the soil are closely interrelated. Changes in weather patterns caused by the climate change, including droughts and extreme events, have a significant influence on greenhouse gas emission (Putramentaite et al., 2014). According to literature, the soil CO_2 efflux peaked at intermediate soil moisture and decreased under dry conditions and under water-saturation conditions (van Straaten et al., 2009).

This trend was observed in our investigations under different land use methods of *Retisol* and under conventional tillage and park of *Cambisol*. In grassland of *Cambisol* this relationship was not registered because soil temperature affected the efflux of CO_2 (Figs 1–3). Temporal variations of soil CO_2 effluxes are summarized in Figure 1. Generally, the effluxes increased gradually after sowing, reached the maximum between the end of July to mid-August on *Cambisol*, between the beginning of June to mid-July on *Retisol*, and then declined gradually until mid-September (Fig. 1).

Soil temperature varied from 9.8°C to 26.3°C during the experiment period, with averages of 17.4°C and 16.9°C at 5 cm depth on *Cambisol* and *Retisol*, respectively (Fig. 2).

Soil volumetric water content at 5 cm depth averaged 20.4% and 25.2% on *Cambisol* and *Retisol*, respectively (Fig. 3). Volumetric water content on *Retisol* was profoundly higher than that on *Cambisol* during the whole experimental period.

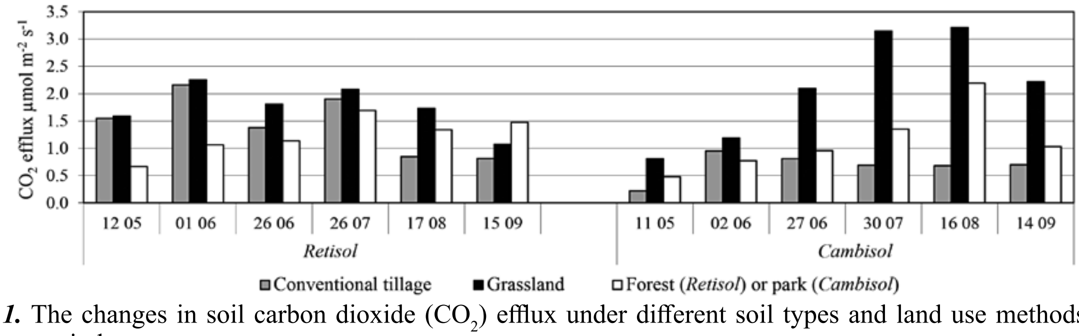

Figure 1. The changes in soil carbon dioxide (CO_2) efflux under different soil types and land use methods during vegetation period

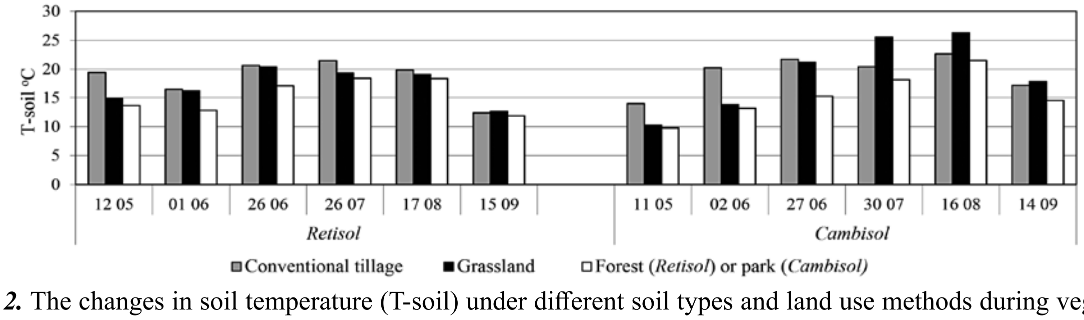

Figure 2. The changes in soil temperature (T-soil) under different soil types and land use methods during vegetation period

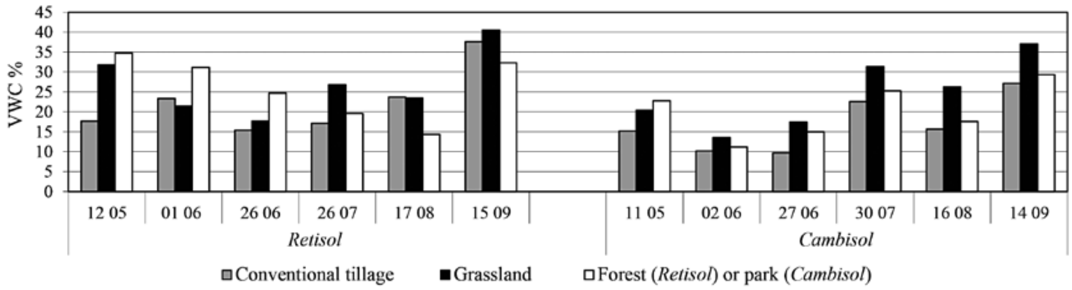

Figure 3. The changes in soil volumetric water content (VWC) under different soil types and land use methods during vegetation period

The influence of land use methods was significant ($P < 0.01$) for CO_2 efflux, soil temperature and volumetric water content (Table 1).

Correlation between CO_2 efflux, soil temperature (T-soil) and volumetric water content (VWC). The correlation matrix between the investigated indices and CO_2 efflux is presented in Table 2. Significant correlation between CO_2 efflux and soil temperature through the whole period of observations was recorded under all land use methods of *Cambisol*. Such relationship was not established in the soil management systems of *Retisol*. Significant correlations between soil CO_2 efflux and volumetric water content were observed in grassland treatment in *Cambisol* and *Retisol*, and in forest in *Retisol* only. Significant correlations ($P < 0.01$) in treatments of *Retisol* were observed between volumetric water content and soil temperature and ($P < 0.05$) in grassland of *Cambisol*.

Table 1. The effects of land use methods on soil carbon dioxide (CO_2) efflux, soil temperature (T-soil) and volumetric water content (VWC) at the 5 cm depth averaged across dates of measurement

Land use method	CO_2 efflux μmol m^{-2} s^{-1}		T-soil °C		VWC %	
	Cambisol	*Retisol*	*Cambisol*	*Retisol*	*Cambisol*	*Retisol*
Conventional tillage	0.68 c	1.44 ab	19.3 a	18.4 a	16.8 c	22.5 b
Grassland	2.11 a	1.75 a	19.2 a	17.1 b	24.4 a	27.0 a
Forest	–	1.23 b	–	15.4 c	–	26.2 ab
Park	1.13 b	–	15.4 c	–	20.2 b	–
			Contrasts			
Conventional tillage *vs* grassland	−1.44**	−0.31 ns	0.1 ns	1.3*	−7.6**	−4.5*
Grassland *vs* forest	–	0.52**	–	1.7**	–	0.8 ns
Grassland *vs* park	0.98**	–	3.8**	–	4.2**	–
Forest *vs* conventional tillage	–	−0.21 ns	–	−3.0**	–	3.7 ns
Park *vs* conventional tillage	0.46*	–	−3.9**	–	3.4**	–

Note. CO_2 efflux, T-soil and VWC data followed by the same letters are not significantly different at $P < 0.05$; *, ** – the least significant difference at $P < 0.05$ and $P < 0.01$, respectively, ns – not significant.

Table 2. Correlation matrix of soil carbon dioxide (CO_2) efflux, soil temperature (T-soil) and volumetric water content (VWC) at the 5 cm depth under different soil types and land use methods

Soil type	Land use method	Indices	Range		Correlation matrix	
			from	to	T-soil	VWC
Cambisol	conventional tillage	CO_2 efflux μmol m^{-2} s^{-1}	0.09	1.57	0.56*	−0.18
		T-soil °C	13.6	24.0	1.00	−0.32
		VWC %	8.5	28.9		1.00
	grassland	CO_2 efflux μmol m^{-2} s^{-1}	0.71	3.43	0.94**	0.58*
		T-soil °C	9.3	26.7	1.00	0.42*
		VWC %	12.9	37.8		1.00
	park	CO_2 efflux μmol m^{-2} s^{-1}	0.43	2.57	0.81**	0.06
		T-soil °C	8.6	24.2	1.00	−0.10
		VWC %	6.4	32.6		1.00
Retisol	conventional tillage	CO_2 efflux μmol m^{-2} s^{-1}	0.52	2.68	0.26	−0.44
		T-soil °C	12.2	21.7	1.00	−0.90**
		VWC %	14.4	38.5		1.00
	grassland	CO_2 efflux μmol m^{-2} s^{-1}	0.7	3.05	0.37	−0.61**
		T-soil °C	12.4	22.2	1.00	−0.76**
		VWC %	14.8	42.9		1.00
	forest	CO_2 efflux μmol m^{-2} s^{-1}	0.44	2.52	0.14	−0.52*
		T-soil °C	9.4	19.8	1.00	−0.66**
		VWC %	13.0	36.1		1.00

*, ** – the least significant difference at $P < 0.05$ and $P < 0.01$, respectively

The relationships between soil CO_2 efflux and soil temperature and volumetric water content (VWC). During the whole growing season, correlation analyses showed poor interrelation between soil CO_2 efflux and soil temperature at 5 cm depth ($P > 0.05$). The relationship between CO_2 efflux and volumetric water content was positive ($R^2 = 0.53$, $P < 0.05$) (Fig. 4). This indicated that the volumetric water content was one of the main factors limiting the rate of CO_2 efflux from the different

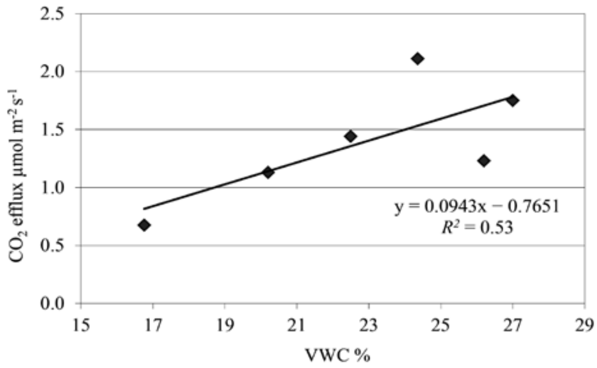

Figure 4. The relationship between soil carbon dioxide (CO_2) efflux and volumetric water content (VWC) at the 5 cm depth under different soil types and land use methods

soils of different land use methods for this period. This finding is in line with the data found in literature (Lopes de Gerenyu et al., 2005; Wei et al., 2014).

Visualization of macropore networks. A three-dimensional (3D) visualization of macropores in the six soil columns are shown in Figures 5 and 6.

The macropores formed by roots were highly continuous and round in shape. The smaller and more randomly and less continuously distributed macropores were likely inter-aggregate macropores, such as those formed by freezing and thawing or wetting and drying (Luo et al., 2010). The macropores for the conventional tillage (C-CT) and the park (C-P) were less abundant as compared to those in the grassland (C-G), while were less tortuous and somewhat smoother (Fig. 5). Many continuous and tubular pores, formed by decayed plant roots of perennial grasses, were also observed in both the grassland: C-G (Fig. 5) and R-G (Fig. 6).

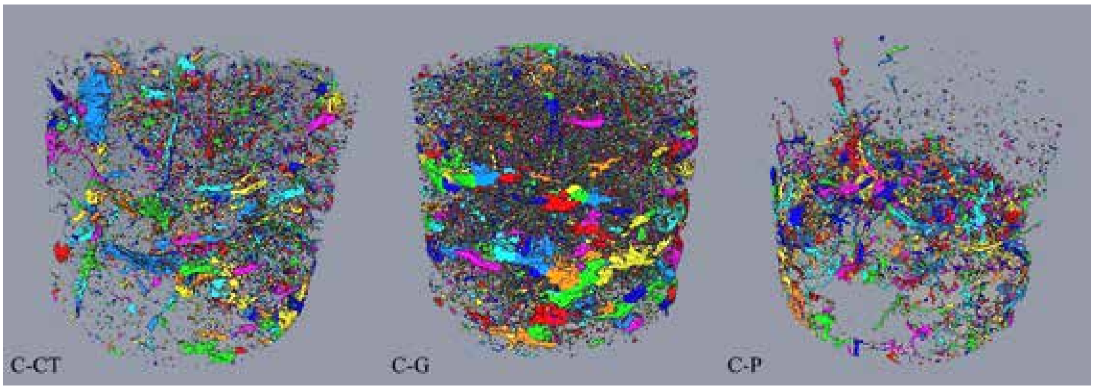

Figure 5. Three-dimensional (3D) visualization of soil macropore networks for the soil columns (44.81 mm in diameter and about 38.2 mm in vertical length after cutting) in *Cambisol* (C) of conventional tillage (C-CT), grassland (C-G) and park (C-P) at the 3–8 cm depth

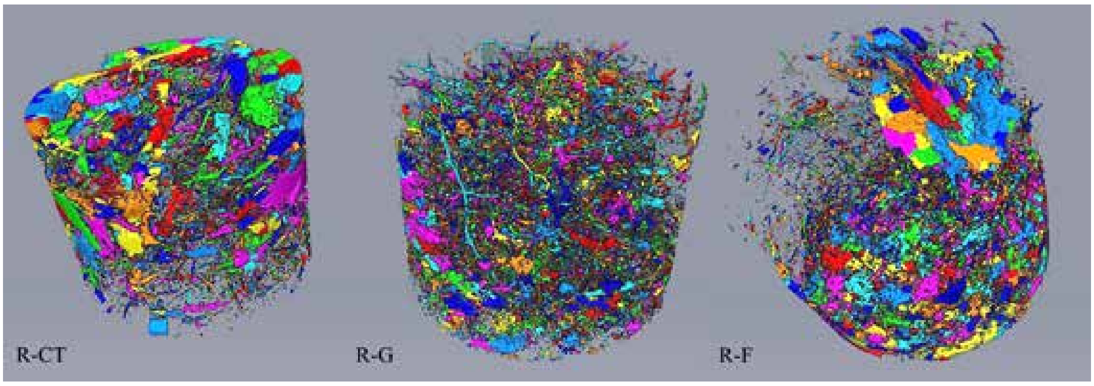

Figure 6. Three-dimensional (3D) visualization of soil macropore networks for the soil columns (44.81 mm in diameter and about 38.2 mm in vertical length after cutting) in *Retisol* (R) of conventional tillage (R-CT), grassland (R-G) and forest (R-F) at the 3–8 cm depth

Macropore characteristics differed among the different soil type and land use methods treatments. The volume of different size of macropores is provided in Figure 7.

Macroposity, surface area and macropore range of soil pore-size distribution. The macropore characteristics of all soil type and land use methods are listed in Table 3. The macroporosity for the grassland of *Cambisol* was the highest – 0.065 m^3 m^{-3}. It was six times higher compared to the two other land use methods, i.e. 0.007 m^3 m^{-3} for the conventional tillage of *Cambisol*, and 0.012 m^3 m^{-3} for the park of *Cambisol* and over twice higher compared to grassland (0.023m^3 m^{-3}, R-G,) conventional tillage (0.029 m^3 m^{-3}, R-CT) and forest (0.039 m^3 m^{-3}, R-F). The total surface area and macropore network density varied among the different soil type and land use methods in a way similar to that of macroporosity.

The grassland of *Cambisol* had the greatest total surface area for the entire column (69321.1 mm^2) and macroporosity (0.065 m^3 m^{-3}), while the conventional tillage of *Cambisol* had the lowest – 8150.5 mm^2 for total surface area and 0.007 m^3 m^{-3} for macroporosity.

Correlation between different macropore characteristics. Brewer (1964) has classified macropores according to the size into coarse (>5000 μm), medium

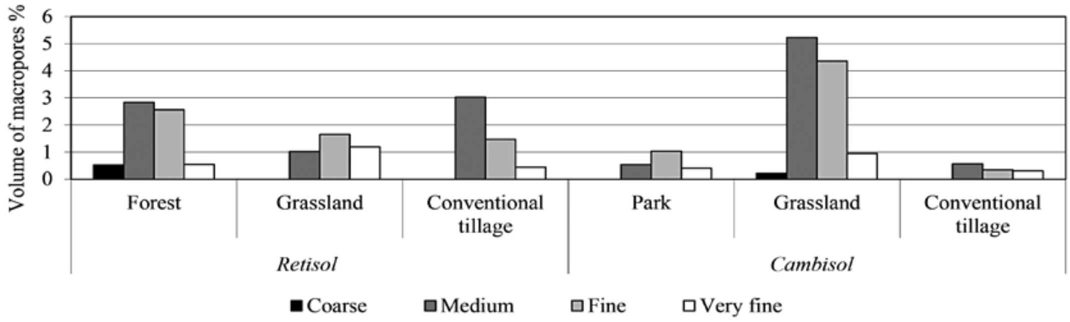

Figure 7. The volume of different size of macropores under different land use methods and soil types

Table 3. Macropore characteristics under different soil types and land use methods

Soil type	Land use method	Macroporosity m^3 m^{-3}	Total surface area mm^2	Mean pore size mm
Cambisol	conventional tillage	0.007	8150.5	0.21
	grassland	0.065	69321.1	0.28
	park	0.012	18135.5	0.26
Retisol	conventional tillage	0.029	25934.2	0.27
	grassland	0.023	32484.9	0.22
	forest	0.039	37830.5	0.26

(2000–5000 µm), fine (1000–2000 µm) and very fine (75–1000 µm). Macropore range of soil pore-size distribution under different land use methods and soil types is presented in Figure 7.

The correlation matrix between the different soil types and macropore sizes investigated is presented in Table 4. Significant correlations ($P < 0.01$) were observed between medium and fine and between fine and very fine pores ($P < 0.05$) for all the soil samples under different land use methods and soil types.

The correlation analysis revealed that the volume of macropores, surface area and macropore size were highly correlated (Table 5). Similar results were obtained by Luo et al. (2010).

Table 4. Correlation matrix of macropore range of soil pore-size distribution at the 3–8 cm depth for all the soil samples under different land use methods and soil types

Macropore size	Range %		Correlation matrix		
	from	to	medium	fine	very fine
Coarse	0.00	0.52	0.51	0.59	0.05
Medium	0.53	5.23	1.00	0.91**	0.31
Fine	0.34	4.36		1.00	0.55*
Very fine	0.40	1.19			1.00

*, ** – the least significant difference at $P < 0.05$ and $P < 0.01$, respectively

Table 5. Correlation matrix among different macropore characteristics at the 3–8 cm depth under different soil types and land use methods

Soil type	Land use method	Properties	Range		Correlation matrix	
			from	to	volume of macropores	pore size (diameter)
Cambisol	conventional tillage	surface area mm^2	0.019	137.94	0.89**	0.80**
		volume of macropores mm^3	0.0003	40.24	1.00	0.62*
		pore size (diameter) mm	0.076	4.25		1.00
	grassland	surface area mm^2	0.024	389.92	0.91**	0.82**
		volume of macropores mm^3	0.0003	67.53	1.00	0.70*
		pore size (diameter) mm	0.075	5.05		1.00
	park	surface area mm^2	0.017	276.09	0.98**	0.75*
		volume of macropores mm^3	0.0002	17.48	1.00	0.74**
		pore size (diameter) mm	0.076	3.22		1.00
Retisol	conventional tillage	surface area mm^2	0.017	196.48	0.94**	0.84*
		volume of macropores mm^3	0.0003	52.41	1.00	0.72*
		pore size (diameter) mm	0.075	4.64		1.00
	grassland	surface area mm^2	0.018	96.44	0.91**	0.82*
		volume of macropores mm^3	0.0002	22.60	1.00	0.66*
		pore size (diameter) mm	0.076	3.51		1.00
	forest	surface area mm^2	0.021	1156.87	0.92**	0.70*
		volume of macropores mm^3	0.0002	312.56	1.00	0.46
		pore size (diameter) mm	0.076	8.42		1.00

*, ** – the least significant difference at $P < 0.05$ and $P < 0.01$, respectively

The relationship between soil CO_2 efflux and volume of macropores. A significant linear trend (R^2 = 0.65, $P < 0.05$) reflecting the relationship between CO_2 efflux and volume of macropores was revealed (Fig. 8).

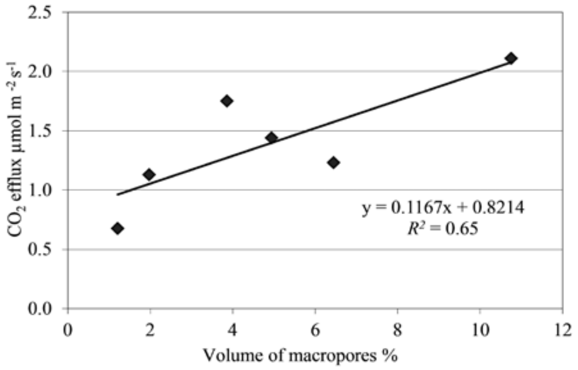

Figure 8. The relationship between soil carbon dioxide (CO_2) efflux and volume of macropores at the 3–8 cm depth under different soil types and land use methods

Soil CO_2 effluxes were affected by soil porosity in both soil types indicating that the soil pore network plays a major role in CO_2 produced by soil respiration. These findings are in agreement with the results published by Mangalassery et al. (2013).

Conclusion

The purpose of the study was to quantify the effect of soil macroporosity, soil temperature and soil water content on carbon dioxide (CO_2) efflux in *Cambisol* and *Retisol*, and land use methods: conventional tillage, grassland and park or forest. Average soil surface CO_2 efflux in *Retisol* was 11% higher than in *Cambisol*. Both soil types and land use methods had noticeable influences on the network of the macroporosity, surface area and macropore range of soil pore-size distribution. Volumetric water content ($y = 0.0943x - 0.7651$, $R^2 = 0.53$) and macroporosity ($y = 0.1167x - 0.8214$, $R^2 = 0.65$) were dominant factors enhancing CO_2 under different soil types and land use methods. During the whole growing season, the correlation analyses showed poor relationship between soil CO_2 efflux and soil temperature at the 5 cm depth. Topsoil CO_2 efflux under contrasting vegetation cover and management conditions on *Cambisol* and *Retisol* was directly related to soil macroporosity and volumetric water content.

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Dirvos makroporingumo, temperatūros ir vandens kiekio įtaka CO_2 emisijai įvairios kilmės skirtingai naudojamuose dirvožemiuose

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Santrauka

Straipsnyje analizuojama dirvožemio makroporų, temperatūros ir vandens kiekio įtaka anglies dioksido (CO_2) emisijai, priklausomai nuo dirvožemio tipo ir žemėnaudos. Momentinė CO_2 emisija nustatyta uždaro gaubto metodu. CO_2 emisija iš dirvožemio viršutinio 0–5 cm sluoksnio tirta (1) tradiciškai dirbtame lauke rudžemyje (RD), (2) daugiametėje pievoje rudžemyje, (3) parke rudžemyje, (4) tradiciškai dirbtame lauke balkšvažemyje (JI), (5) daugiametėje pievoje balkšvažemyje ir (6) miške balkšvažemyje. Ji matuota šešis kartus per augalų vegetaciją, 2017 m. gegužės–rugsėjo mėnesiais. Dirvožemio porų tinklo struktūra tirta kompiuterinės tomografijos aparatu. Tyrimai atlikti Lenkijos mokslų akademijos Agrofizikos institute Liubline.

Dirvožemio makroporingumą lėmė jo genezė ir žemėnauda, o makroporų kiekis turėjo įtakos vandens kiekiui, temperatūrai ir dujų judėjimui dirvožemyje. Dirvožemio emisija buvo nuo 0,71 iki 3,43 μmol CO_2 m^{-2} s^{-1} pievoje rudžemyje, nuo 0,43 iki 2,57 μmol CO_2 m^{-2} s^{-1} parke rudžemyje ir nuo 0,44 iki 2,52 μmol CO_2 m^{-2} s^{-1} miške balkšvažemyje. Žemę dirbant tradiciniu būdu, CO_2 emisija balkšvažemyje kito nuo 0,52 iki 2,68, rudžemyje – nuo 0,09 iki 1,57 μmol CO_2 m^{-2} s^{-1}. Kompiuterinė tomografija parodė, jog makroporų kiekis rudžemio 3–8 cm sluoksnyje pievoje siekė iki 10,75 %, parke – iki 1,97 %, ariamoje dirvoje – iki 1,21 % ir iki 6,45 % miške, iki 4,94 % žemę dirbant tradiciškai bei iki 3,86 % daugiametėje pievoje balkšvažemio 3–8 cm sluoksnyje. Svarbiausi veiksniai, turėję įtakos dujų išsiskyrimui, buvo dirvos temperatūra, drėgmė ir makroporų kiekis. Dirvožemio 5 cm gylyje ryšys tarp CO_2 emisijos ir tūrinio drėgmės kiekio nusakytas tiesinę priklausomybę aprašančia lygtimi $y = 0{,}0943x - 0{,}7651$, $R^2 = 0{,}53$ (galioja dirvožemio drėgmei esant 22,5–27,0 tūrio % ribose balkšvažemyje ir 16,8–24,4 tūrio % ribose rudžemyje). Be to, tiesinė priklausomybė pagal lygtį $y = 0{,}167x - 0{,}8214$, $R^2 = 0{,}65$ dirvožemio 3–8 cm sluoksnyje nustatyta tarp CO_2 emisijos ir makroporingumo. Dirvožemio 5 cm gylyje CO_2 emisijos ir temperatūros ryšys aprašytas polinomine (daugianare) priklausomybe, tačiau jis buvo labai silpnas.

Ir dirvožemio tipas, ir žemėnauda turėjo reikšmingą įtaką bendram makroporingumui, jo paviršiaus plotui ir makroporų grupei priskiriamų porų pasiskirstymui dirvožemyje. Makroporų kiekis ir jų pasiskirstymas buvo svarbus veiksnys, lėmęs CO_2 emisiją. Esant skirtingai žemėnaudai dirvos paviršiaus CO_2 emisija rudžemyje ir balkšvažemyje tiesiogiai priklausė nuo dirvožemio makroporingumo ir drėgmės kiekio.

Reikšminiai žodžiai: balkšvažemis, kompiuterinė tomografija, rudžemis, tūrinis vandens kiekis.