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# The effect of environmental factors and root system on $CO_2$ efflux in different types of soil and land uses

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## Abstract

Carbon dioxide ($CO_2$) efflux from 0–5 cm topsoil layer in conventional tillage plots, in grassland and forest *Retisol* (in West Lithuania in a hilly terrain) and *Cambisol* (in Central Lithuania in a plane terrain) was investigated using a closed chamber method. The soil $CO_2$ efflux was measured six times per growing season from April to August in 2018. Soil temperature and the volumetric water content were recorded at 5 cm depth at the same time as soil $CO_2$ efflux measurements. Small soil monoliths were collected for the measurements of plant root parameters within 0–10 cm layer and were investigated later in the laboratory.

In *Cambisol*, the efflux values ranged from 0.20 to 2.67 μmol $CO_2$ $m^{-2}$ $s^{-1}$ under conventional tillage, from 1.10 to 3.41 μmol $CO_2$ $m^{-2}$ $s^{-1}$ in grassland and from 0.89 to 2.28 μmol $CO_2$ $m^{-2}$ $s^{-1}$ in forestland. In *Retisol*, the efflux values varied from 0.81 to 3.54 μmol $CO_2$ $m^{-2}$ $s^{-1}$ under conventional tillage, from 1.23 to 2.69 μmol $CO_2$ $m^{-2}$ $s^{-1}$ in grassland and from 0.88 to 2.06 μmol $CO_2$ $m^{-2}$ $s^{-1}$ in forestland. The soil temperature varied from 11.5°C to 33.6°C during the experimental period and averaged 22.8°C and 21.1°C at 5 cm depth in *Cambisol* and *Retisol*, respectively. The volumetric water content at 5 cm depth averaged 18.7% and 23.9% in *Cambisol* and *Retisol*, respectively. The volumetric water content in *Cambisol* was markedly lower than in *Retisol* during the whole experimental period. The maximum root volume within 0–10 cm depth was determined in grassland *Retisol*. Root volume under conventional tillage in *Cambisol* was 6.2-fold lower, in *Retisol* – 5.1-fold lower, in forest *Retisol* – 1.9-fold lower, in forest *Cambisol* – 1.4-fold lower and in grassland *Cambisol* – 1.1-fold lower compared to grassland *Retisol*. Average $CO_2$ efflux from *Retisol* was 12% lower than that from *Cambisol*. Soil $CO_2$ emission decreased in the following order: *Cambisol* – grassland > forestland > conventional tillage plots and *Retisol* – grassland > conventional tillage plots > forestland. Volumetric water content was found to increase soil $CO_2$ efflux; however, at the content higher than 20%, efflux decreased. A soil temperature of up to 25°C increased soil $CO_2$ emission. However, with a further increase in soil temperature, soil respiration decreased in both soil types investigated.

The decrease in root volume and root length density depended on the land use: grassland > forestland > conventional tillage plots.

Keywords: *Cambisol*, *Retisol*, root volume, soil temperature, volumetric water content.

## Introduction

Soil $CO_2$ efflux is associated with many factors, including soil temperature, soil moisture, soil porosity, root volume and, therefore, is still not entirely understood. The influence of environmental factors on $CO_2$ emission from the soil is of great importance from the agronomy, environment and climate change point of view.

Soil $CO_2$ emission from the soil is the result of respiration of plant roots, microbial activity and decay of organic matter, which depend on the temperature and water content of the soil (Pumpanen et al., 2015). $CO_2$ efflux from the soil depends on the soil temperature, water content, substrate input from plants, soil texture and root density (Zhou et al., 2016).

Soil respiration is a measure of all the carbon dioxide ($CO_2$) produced by underground processes, including heterotrophic and autotrophic respiration by roots and organisms of the soil. Soil respiration has become a recognized key component for assessing the potential of ecosystems within the framework of global budget C and for predicting its change in global changes (Noh et al., 2010). Quantifying soil $CO_2$ emission is a key process for understanding the dynamics of carbon in different ecosystems. However, soil $CO_2$ emission can change annually, as fluxes respond differently to changing environmental variables, such as nutrient availability, moisture content and soil temperature (Noh et al., 2010).

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In many studies, soil water content and soil temperature have been identified as the key factors in soil–atmosphere exchange of $CO_2$. The effect of soil temperature on the exchange of $CO_2$ between the soil and atmosphere is mainly direct, and an increase in soil temperature leads to an increase in emission unless other factors are limiting. The effect of water content is more complex (Luo et al., 2012).

Land use is considered as one of the important factors affecting soil $CO_2$ efflux (Li et al., 2013). Soil temperature and water content are some of the key factors controlling $CO_2$ efflux in the soil (Schaufler et al., 2010; Ni et al., 2012). The physical properties of the soil, especially porosity and water content, are also essential, because they affect the transport of soil gas (Salmawati et al., 2019).

Soil temperature and water content are the main environmental factors that determine the production and flow of soil $CO_2$. In dry conditions, $CO_2$ emission from the soil is lower because of the low activity of roots and microorganisms. An increase in soil water content usually increases biological activity of the soil. Higher water content in the soil usually causes an increase in soil respiration. But if the moisture content in the soil is very high, the total $CO_2$ flow decreases due to limited oxygen diffusion and subsequent suppression of $CO_2$ efflux (Tavares et al., 2016).

Soil temperature is the best indicator of the dynamics of $CO_2$ flow rate. Faimon and Lang (2018) found a strong positive correlation between soil $CO_2$ efflux and soil temperature during the dry period of the experiment. Negassa et al. (2015) and Dong et al. (2017) revealed similar relationships between soil temperature and $CO_2$ efflux. Schaufler et al. (2010) found a nonlinear increase of soil $CO_2$ emission with increasing soil temperature. Temperature and water content of the soil influence the production of soil $CO_2$ by affecting the activity of plant roots and microorganisms as well as the gas diffusion process through soil pores (Wei et al., 2014).

Groundwater level and soil water content are important control factors, but their impact on soil $CO_2$ efflux production is more complex. Dong et al. (2017) have estimated that soil $CO_2$ efflux slightly correlated with soil water content. Compared to soil saturation conditions, $CO_2$ production usually increases, when the soil dries up to the optimum moisture content and then decreases with further drying. It has also been reported that soil $CO_2$ efflux decreases with decreasing volumetric water content. Higher soil water content was associated with intensive soil $CO_2$ efflux in agricultural peatlands (Zeng, Gao, 2016). Soil temperature and water content are important parameters in regulating $CO_2$ emission from the soil in terrestrial ecosystems. In a high-latitude terrestrial ecosystem, it is essential to understand, if it is $CO_2$ uptake by plants or $CO_2$ release from the soil that controls carbon balance (Kim et al., 2013 b). According to Bortolotto et al. (2015), soil temperature is the variable, which best explains the changes in soil $CO_2$ efflux, while moisture is also an important factor for soil $CO_2$ emission.

The aim of this study was to establish the effect of soil temperature, soil water content and parameters of plant roots on soil $CO_2$ efflux in conventional tillage plots, grassland and forestland in *Cambisol* and *Retisol*.

## Materials and methods

*Experimental site description.* Soil types involved in this research are classified according to WRB (2015) as *Endocalcaric Endogleyic Cambisol* (Loamic, Drainic) in Akademija (55°23′38″ N, 23°51′35″ E), Kėdainiai district, Central Lithuanian lowland, and as *Dystric Retisol* (Loamic, Bathygleyic), in Bijotai (55°31′12″ N, 22°36′55″ E), Šilalė district, hummocky upland area of West Lithuania (Fig. 1).

***Figure 1.*** The experimental sites: A – Akademija, Kėdainiai distr., and B – Bijotai, Šilalė distr., Lithuania

Basic soil properties at 0–10 cm depth of *Cambisol* and *Retisol* under different land uses are provided in Table 1.

Three land uses in *Cambisol* were investigated: 1) conventional tillage (CT) plots grown with spring wheat (*Triticum aestivum* L.); 2) natural grassland with the dominant plant species: *Medicago sativa* L., *Galega orientalis* L., *Taraxacum officinale* L., *Lolium temulentum* L. and *Trifolium repens* L.; 3) natural forest with the dominant tree species: *Acer platanoides* L., *Tilia*

***Table 1.*** The textural composition and bulk density of soil at 0–10 cm depth of *Cambisol* and *Retisol* under different land uses

| Soil type | Land use | Soil fraction %<br>sand<br>2.0–0.063 mm | <br>silt<br>0.063–0.002 mm | <br>clay<br><0.002 mm | Texture | Bulk density Mg $m^{-3}$ |
|---|---|---|---|---|---|---|
| *Cambisol* | conventional tillage plots | 48.97 | 37.53 | 13.50 | loam | 1.58 |
| | grassland | 37.99 | 43.01 | 19.00 | loam | 1.18 |
| | forestland | 49.05 | 46.77 | 4.18 | sandy loam | 0.83 |
| *Retisol* | conventional tillage plots | 40.39 | 38.62 | 20.99 | loam | 1.58 |
| | grassland | 63.03 | 27.73 | 9.24 | sandy loam | 1.37 |
| | forestland | 49.52 | 41.13 | 9.35 | loam | 0.83 |

*cordata* L., *Fraxinus excelsior* L., including grass cover: *Aegopodium podagraria* L., *Pulmonaria obscura* L. and *Anemone nemorosa* L.

Three land uses in *Retisol* were investigated: 1) conventional tillage (CT) plots grown with winter wheat (*Triticum aestivum* L.); 2) natural grassland with the dominant plant species: *Dactylis glomerata* L., *Festuca ovina* L., *Leontodon autumnalis* L., *Taraxacum officinale* L. and *Trifolium repens* L.; 3) natural forest with the dominant tree species: *Acer platanoides* L., *Quercus robur* L., including grass cover: *Aegopodium podagraria* L., *Anemone nemorosa* L. and *Pulmonaria obscura* L.

*Measurement of soil carbon dioxide ($CO_2$) efflux.* The soil $CO_2$ efflux (µmol $m^{-2}$ $s^{-1}$) was measured using a closed chamber LI-8100A (LI-COR Inc., USA). Three soil collars were positioned randomly in each plot. Soil $CO_2$ efflux was measured 6 times per growing season from April to August in 2018 at the same time of the day, from 10 a.m. to 5 p.m.

*Investigations of the environmental factors.* Soil temperature (ST) (°C) and volumetric water content (VWC) (%) were investigated during soil $CO_2$ efflux measurement. The ST and VWC were measured at 5 cm depth with a portable sensor HH2 WET (Delta-T Devices Ltd., UK).

*Investigations of the root system.* Small monoliths 10 × 10 × 10 cm from the topsoil (0–10 cm depth) were taken from each land use treatment with three replications (Lapinskienė, 1993). Samples were collected at the flowering stage (BBCH 61–65) of plants. Samples were tightly packed into plastic bags and stored in a freezer at −20°C temperature until analysed. Before analysis, the soil samples with roots were carefully washed with running water using 500 and 250 µm sieves. Admixtures were removed from the washed roots. The roots were dyed with Neutral Red reagent and chopped into 2 cm long pieces. The analysis of root length density, root volume and diameter was done using the software *WinRhizo* (Bouma et al., 2000).

*Environmental conditions.* Lithuania's climate, which ranges between maritime and continental, is relatively mild. The mean annual air temperature is close to 6.5°C. The average annual precipitation in 2018 was 1000 mm in the western part and 700 mm in the central part of the country. In 2018, there were 199 days with precipitation in the western part of the country and 175 days in the central part.

*Statistical analysis.* The differences among the investigated parameters were compared using one-way analysis of variance (ANOVA) and Fisher's protected least significant difference (LSD) test. Standard deviation (SD) was calculated using the software *STAT-ENG*. All statistical analyses were performed using software package *SAS*, version 7.1 (SAS Inc., USA) at $P < 0.05$ and $P < 0.01$ levels of confidence. Correlation-regression analysis between different treatments was also performed.

## Results and discussion

The effect of land use on soil $CO_2$ efflux and ST was statistically significant at $P < 0.001$, while on VWC the effect was significant at $P < 0.0019$. The effect of soil type on VWC was statistically significant at $P < 0.0303$, while on soil $CO_2$ efflux and ST the effect was not significant at $P < 0.1587$ and $P < 0.1362$, respectively (Table 2).

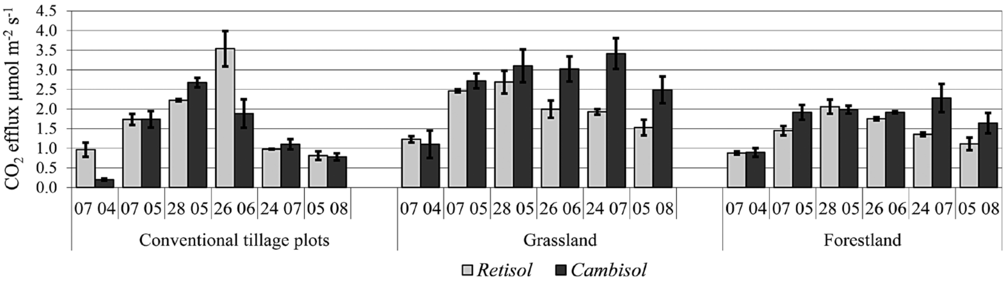
***Table 2.*** The results of ANOVA for soil $CO_2$ efflux, soil temperature (ST) and volumetric water content (VWC) in relation to different types of soil and land uses

| Source of variation | Degree of freedom | $CO_2$ efflux | | ST | | VWC | |
|---|---|---|---|---|---|---|---|
| | | *F* | *Pr > F* | *F* | *Pr > F* | *F* | *Pr > F* |
| Soil type | 1 | 2.02 | 0.1587 | 2.25 | 0.1362 | 4.82 | 0.0303 |
| Land use | 2 | 10.31 | 0.0001 | 14.99 | 0.0001 | 6.68 | 0.0019 |

***The dynamics of soil $CO_2$ efflux and environmental factors*** in the types of soil and land uses tested are presented in Figures 2–4.

Temporal variations in soil $CO_2$ efflux are shown in Figure 2. Putramentaitė et al. (2014) established that weather patterns (droughts and extreme events) had a significant influence on soil $CO_2$ emission.

After spring wheat sowing, soil $CO_2$ efflux increased gradually and reached the maximum during the period from early May to late June in *Cambisol* and during the period from early May to late July in *Retisol*, while gradually declined in August (Fig. 2). On June 26, the soil $CO_2$ efflux under CT in *Cambisol* dramatically increased compared with grassland and forest *Cambisol*. On July 24, the $CO_2$ efflux in grassland *Retisol* dramatically increased compared with conventional tillage plots and forest *Retisol*. The $CO_2$ efflux averaged across land uses in *Retisol* was 12% lower than in *Cambisol* (Table 3).



*Note.* Bars represent standard error; n = 3.

***Figure 2.*** The dynamics of the soil $CO_2$ efflux under different land uses in *Retisol* and *Cambisol* during the growing season (2018)

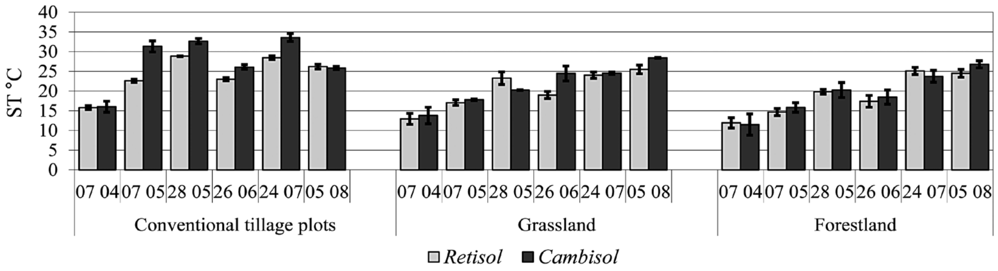
***Table 3.*** The soil $CO_2$ efflux (mean ± standard deviation), soil temperature (ST) and volumetric water content (VWC) in relation to different types of soil and land uses

| Factor | Soil type | Land use | $CO_2$ efflux ± SD µmol $m^{-2}$ $s^{-1}$ | ST ± SD °C | VWC ± SD % |
|---|---|---|---|---|---|
| Soil type | *Cambisol* | | 1.9 ± 0.13 a | 22.8 ± 0.9 a | 18.7 ± 1.5 b |
| | *Retisol* | | 1.7 ± 0.10 a | 21.1 ± 0.7 a | 23.9 ± 1.8 a |
| Land use | | conventional tillage plots | 1.55 ± 0.16 b | 25.9 ± 1.0 a | 15.5 ± 1.6 b |
| | | grassland | 2.3 ± 0.14 a | 20.9 ± 0.8 b | 24.1 ± 2.1 a |
| | | forestland | 1.6 ± 0.09 b | 19.2 ± 0.9 b | 24.4 ± 2.1 a |

*Note.* Factor data followed by the same letters are not significantly different at $P < 0.05$.

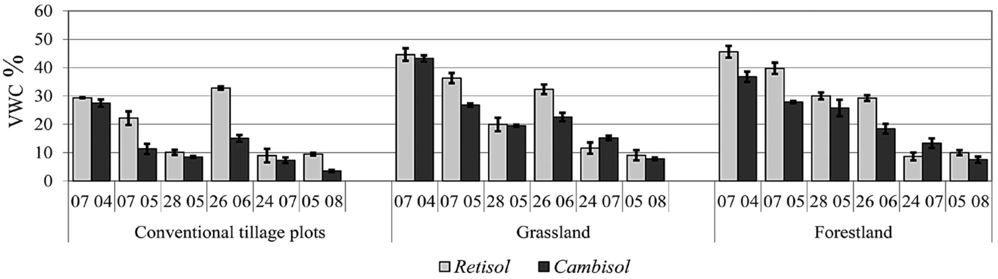
According to our data of 2017 (Kochiieru et al., 2018), the average $CO_2$ efflux in *Retisol* was 11% higher than in *Cambisol*. It is noteworthy that at the same measurement points the average soil $CO_2$ emission in 2018 was 23% higher than in 2017. The $CO_2$ efflux averaged across soil type: in grassland it was 1.4-fold higher than in forestland and 1.5-fold higher than in conventional tillage plots. The ST and VWC had significant effect on soil $CO_2$ efflux. The ST varied from 11.5°C to 33.6°C during the investigation period with averages of 22.8°C and 21.1°C at 5 cm depth in *Cambisol* and *Retisol*, respectively (Fig. 3 and Table 3). At the same measurement places these values were 20% higher in 2018 than in 2017.

The soil VWC at 5 cm depth averaged 18.7% and 23.9% in *Cambisol* and *Retisol*, respectively (Fig. 4 and Table 3). The VWC in *Retisol* was profoundly higher than in *Cambisol* during the whole experimental period. The VWC was 7% lower than in 2017 from the same land use and soil type (Kochiieru et al., 2018).



*Note.* Bars represent standard error; n = 3.

***Figure 3.*** The dynamics of soil temperature (ST) under different land uses in *Retisol* and *Cambisol* during the growing season (2018)



*Note.* Bars represent standard error; n = 3.

***Figure 4.*** The dynamics of soil volumetric water content (VWC) under different land uses in *Retisol* and *Cambisol* during the growing season (2018)

***The influence of land use on soil $CO_2$ efflux, ST and VWC*** was significant ($P < 0.05$) (Table 4). The decrease in $CO_2$ efflux, ST and VWC was related to soil type and land use.

$CO_2$ efflux at 5 cm depth averaged 1.40 (CT), 1.77 (forestland) and 2.64 (grassland) µmol $m^{-2}$ $s^{-1}$ in *Cambisol* and 1.43 (forestland), 1.71 (CT), 1.97 (grassland) µmol $m^{-2}$ $s^{-1}$ in *Retisol*. The $CO_2$ efflux in *Retisol* was

***Table 4.*** The influence of land use on soil $CO_2$ efflux (mean ± standard deviation), soil temperature (ST) and volumetric water content (VWC) at 5 cm depth averaged across dates of measurements

| Land use | $CO_2$ efflux ± SD µmol $m^{-2}$ $s^{-1}$ | | ST ± SD °C | | VWC ± SD % | |
|---|---|---|---|---|---|---|
| | *Cambisol* | *Retisol* | *Cambisol* | *Retisol* | *Cambisol* | *Retisol* |
| Conventional tillage plots | 1.40 ± 0.21 b | 1.71 ± 0.24 ab | 27.6 ± 1.5 a | 24.2 ± 1.1 a | 12.2 ± 1.9 b | 18.8 ± 2.4 a |
| Grassland | 2.64 ± 0.22 a | 1.97 ± 0.14 a | 21.6 ± 1.2 b | 20.3 ± 1.1 b | 22.5 ± 2.7 a | 25.6 ± 3.2 a |
| Forestland | 1.77 ± 0.13 b | 1.43 ± 0.10 b | 19.4 ± 1.4 b | 18.9 ± 1.2 b | 21.6 ± 2.4 a | 27.2 ± 3.4 a |
| *F* | 11.61 | 2.46 | 9.62 | 5.59 | 5.85 | 2.15 |
| *Pr > F* | 0.0001 | 0.0957 | 0.0003 | 0.0064 | 0.0051 | 0.1273 |

*Note.* Data followed by the same letters are not significantly different at $P < 0.05$; n = 18.

significantly lower than in *Cambisol* in grassland and forestland, except the CT treatment (Table 4). The $CO_2$ efflux under CT in *Cambisol* and in forest *Retisol* was 1.9-fold lower, under CT in *Retisol* and in forest *Cambisol* – 1.5-fold lower, in grassland *Retisol* – 1.3-fold lower than in grassland *Cambisol*. The ST at 5 cm depth averaged 19.4°C (forestland), 21.6°C (grassland) and 27.6°C (CT) in *Cambisol* and 18.9°C (forestland), 20.3°C (grassland) and 24.2°C (CT) in *Retisol*. The ST at 5 cm depth in forest *Retisol* was 1.5-fold lower, in grassland *Retisol* and in forest *Cambisol* – 1.4-fold lower, in grassland *Cambisol* – 1.3-fold lower, under CT in *Retisol* – 1.1-fold lower than under CT in *Cambisol*. The VWC at 5 cm depth averaged 12.2% (CT), 21.6% (forestland) and 22.5% (grassland) in *Cambisol* and 18.8% (CT), 25.6% (grassland) and 27.2% (forestland) in *Retisol*. The VWC under CT in *Cambisol* was 2.2-fold lower, under CT in *Retisol* – 1.5-fold lower, in forest *Cambisol* – 1.3-fold lower, in grassland *Cambisol* – 1.2-fold lower and in grassland *Retisol* – 1.1-fold lower than in forest *Retisol*.

***The relationships between soil $CO_2$ efflux, ST and VWC.*** The ST is one of the best indicators of the dynamics of soil $CO_2$ efflux. A strong positive correlation between the soil $CO_2$ efflux and the ST during the dry season of measurement was found by Faimon and Lang (2018). Similar results of the relationships between ST and soil $CO_2$ efflux were found by Negassa et al. (2015) and Dong et al. (2017), while Dossou-Yovo et al. (2016) and Pergrina (2016) did not find any correlation between these parameters.

The relationships between the ST, VWC and $CO_2$ efflux in different types of soil and land uses are presented in Table 5. A significant relationship between $CO_2$ efflux and ST through the whole experimental period was found in conventional tillage plots ($P < 0.01$), in grassland and in forest *Cambisol* ($P < 0.05$) (Table 5). No correlation between these variables was found in all land uses in *Retisol*. Similar results of relationships between $CO_2$ efflux and ST were found by Kochiieru et al. (2018) through the whole period of investigations under the same land uses in *Cambisol* and *Retisol*. A significant negative relationship between $CO_2$ efflux and VWC in grassland *Cambisol* ($P < 0.01$) and a positive correlation under CT in *Retisol* ($P < 0.05$) were found. Significant negative correlations ($P < 0.01$) between ST and VWC were observed in all land uses in *Cambisol* and *Retisol*.

***Table 5.*** The soil $CO_2$ efflux, soil temperature (ST) and volumetric water content (VWC) at 5 cm depth and their correlation matrix

| Land use | Parameters | Correlation matrix of types of soil | | | |
|---|---|---|---|---|---|
| | | *Cambisol* | | *Retisol* | |
| | | ST | VWC | ST | VWC |
| Conventional tillage plots | $CO_2$ efflux µmol $m^{-2}$ $s^{-1}$ | 0.65** | −0.40 | 0.07 | 0.49* |
| | ST °C | 1.00 | −0.77** | 1.00 | −0.78** |
| | VWC % | | 1.00 | | 1.00 |
| Grassland | $CO_2$ efflux µmol $m^{-2}$ $s^{-1}$ | 0.48* | −0.64** | 0.20 | −0.10 |
| | ST °C | 1.00 | −0.87** | 1.00 | −0.95** |
| | VWC % | | 1.00 | | 1.00 |
| Forestland | $CO_2$ efflux µmol $m^{-2}$ $s^{-1}$ | 0.51* | −0.41 | 0.18 | −0.01 |
| | ST °C | 1.00 | −0.75** | 1.00 | −0.90** |
| | VWC % | | 1.00 | | 1.00 |

*, ** – the least significant difference at $P < 0.05$ and $P < 0.01$, respectively; n = 18

During the whole growing season, the relationship between soil $CO_2$ efflux and ST at 5 cm depth can be described by a simple multiple regression model: $y = -0.02x^2 + 0.88x - 7.32$ ($R^2 = 0.58$, $P < 0.05$) (Fig. 5).

Soil $CO_2$ efflux displayed a typical polynomial relationship with VWC at the 5 cm depth: $y = -0.01x^2 + 0.20x + 0.17$ ($R^2 = 0.63$, $P < 0.05$) (Fig. 6). This indicates that the VWC and ST were the main factors limiting the rate of $CO_2$ efflux under different land uses for the experimental period (during the growing season of 2018) in moderate climatic conditions.

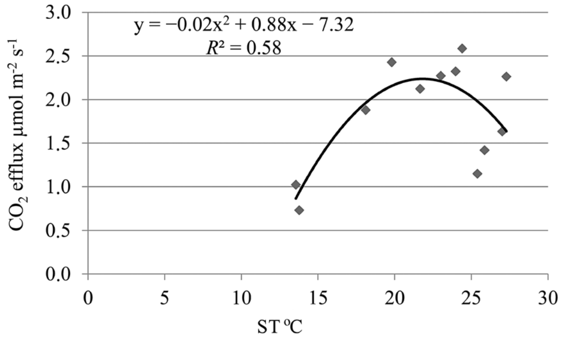


***Figure 5.*** The relationship between $CO_2$ efflux and soil temperature (ST) at 5 cm depth under different land uses and types of soil

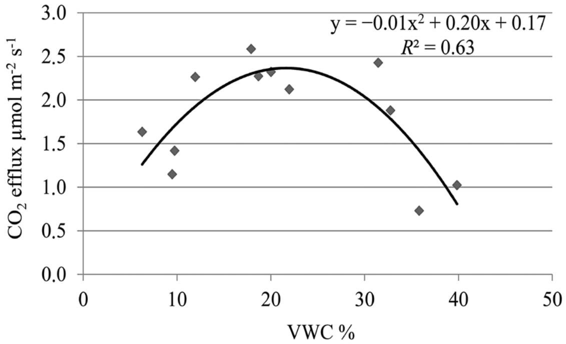


***Figure 6.*** The relationship between soil $CO_2$ efflux and volumetric water content (VWC) at 5 cm depth under different land uses and types of soil

The ST from 10°C to 25°C increased $CO_2$ efflux (Dhital et al., 2014; Finzi et al., 2014; Kim et al., 2013 a; Zeng, Gao, 2016), while the ST higher than 25°C decreased $CO_2$ efflux from the soil. Similar results (for ST from 17°C to 26°C) were obtained by Tavares et al. (2016) and Bogužas et al. (2018). A negative correlation between $CO_2$ efflux and VWC was detected at 5 cm depth under different land uses and types of soil (Fig. 6). Kallenbach et al. (2010) found a similar result, while Reth et al. (2005) did not find any relationship between these variables.

The activity of roots in the soil with lower VWC is usually low, and therefore $CO_2$ efflux was lower (Wang et al., 2014). With an increase in water content in the soil, the biological activity of the soil increase, and this causes an increase in soil respiration. However, prolonged rains increase the water content to an almost saturated state in the soil (Pla et al., 2017), the total soil $CO_2$ emission decrease due to limited oxygen diffusion in the soil (Deng et al., 2017). The VWC from 7% to 20% increased $CO_2$ efflux (Darenova et al., 2016), while the VWC higher than 20% decreased $CO_2$ efflux from the soil. Similar results were obtained by some other researchers (Pena-Quemba et al., 2016; Tavares et al., 2016).

***Influence of land use on root networks.*** The parameters of roots in the three land uses of two soil types at 0–10 cm depth are shown in Table 6.

***Table 6.*** The effect of different land uses and types of soil on the parameters of roots at 0–10 cm depth

| Land use | Mean root diameter ± SD, mm | | Root volume ± SD, $cm^3$ | | Root length density ± SD, km $m^{-3}$ | |
|---|---|---|---|---|---|---|
| | *Cambisol* | *Retisol* | *Cambisol* | *Retisol* | *Cambisol* | *Retisol* |
| Conventional tillage plots | 0.31 ± 0.01 b | 0.36 ± 0.01 a | 0.89 ± 0.11 b | 1.08 ± 0.16 b | 122.6 ± 22.1 a | 104.2 ± 13.8 b |
| Grassland | 0.36 ± 0.05 b | 0.56 ± 0.17 a | 4.85 ± 1.19 a | 5.54 ± 2.08 a | 917.5 ± 420.1 a | 1594.1 ± 586.2 a |
| Forestland | 0.57 ± 0.04 a | 0.43 ± 0.01 a | 4.04 ± 1.25 a | 2.93 ± 0.34 ab | 154.9 ± 34.4 a | 200.2 ± 28.8 b |
| *F* | 14.64 | 0.97 | 4.38 | 3.38 | 3.41 | 6.05 |
| *Pr > F* | 0.0049 | 0.4320 | 0.0671 | 0.1041 | 0.1026 | 0.0364 |

*Note.* Values followed by the same letters are not significantly different at $P < 0.05$; n = 3; SD – standard deviation.

The root volume at 0–10 cm depth under CT in *Cambisol* was 6.2-fold lower, under CT in *Retisol* – 5.1-fold lower, in forest *Retisol* – 1.9-fold lower, in forest *Cambisol* – 1.4-fold lower and in grassland *Cambisol* – 1.1-fold lower than in grassland *Retisol* (Table 6). The decrease in root volume and root length density depended on land use and soil depth (Ning et al., 2015). At 0–10 cm depth, grassland *Retisol* had the greatest root length density (1594.1 km $m^{-3}$) and the mean root diameter (0.56 mm), while conventional tillage plots in *Retisol* had the lowest root length density (104.2 km $m^{-3}$) and the mean root diameter (0.36 mm). The distribution of roots in grassland is different from that under arable farming (Luo et al., 2010).

***The correlation between root volume, root length density and mean root diameter.*** The correlation matrix between the investigated mean root diameter, root volume and root length density at 0–10 cm depth is presented in Table 7.

***Table 7.*** The correlation matrix among root characteristics at 0–10 cm depth under different land uses (averaged for soil types)

| Land use | Root characteristics | Range | | Correlation matrix | |
|---|---|---|---|---|---|
| | | from | to | root volume | root length density |
| Conventional tillage plots | mean root diameter mm | 0.29 | 0.38 | 0.35 | −0.54 |
| | root volume $cm^3$ | 0.70 | 1.32 | 1.00 | 0.59* |
| | root length density km $m^{-3}$ | 79.8 | 153.4 | | 1.00 |
| Grassland | mean root diameter mm | 0.22 | 0.78 | 0.80** | 0.93** |
| | root volume $cm^3$ | 1.60 | 8.66 | 1.00 | 0.92** |
| | root length density km $m^{-3}$ | 408.9 | 2243.7 | | 1.00 |
| Forestland | mean root diameter mm | 0.41 | 0.64 | 0.63* | −0.35 |
| | root volume $cm^3$ | 2.18 | 6.42 | 1.00 | 0.49 |
| | root length density km $m^{-3}$ | 87.9 | 252.4 | | 1.00 |

*, ** – the least significant difference at $P < 0.05$ and $P < 0.01$, respectively; n = 6

Significant correlations between root volume and mean root diameter were recorded in grassland ($P < 0.01$) and forestland ($P < 0.05$). No relationship between these variables was established in conventional tillage plots (Table 7). Significant correlations between root volume and root length density at 0–10 cm depth were observed in conventional tillage plots ($P < 0.05$) and in grassland ($P < 0.01$). No correlation between these variables was found in forestland at the same depth. The relationship between mean root diameter and root length density was observed in grassland ($P < 0.01$). No relationship between these variables was established in conventional tillage plots and forestland. A negative correlation between mean root diameter and root length density was established in forestland, because the samples had tree roots with a diameter of more than 10 mm.

***The relationship between soil $CO_2$ efflux and root volume.*** A significant linear trend ($R^2 = 0.58$, $P < 0.05$) reflecting the relationship between soil $CO_2$ efflux and root volume was revealed (Fig. 7).

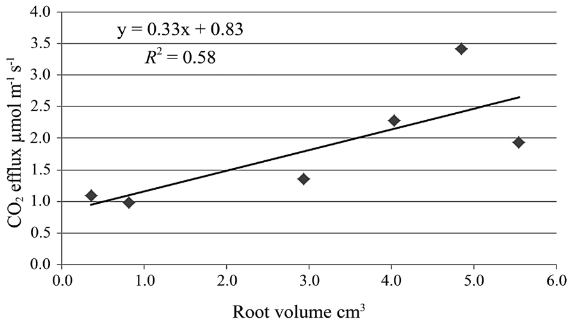


***Figure 7.*** The relationship between soil $CO_2$ efflux and root volume at 0–10 cm depth under different land uses and types of soil

The $CO_2$ emission was affected by root volume in both types of soil indicating that root activity plays one of the main roles in $CO_2$ production rate. Shibistova et al. (2002) established a similar relationship (y = 0.61 +

0.0703x; $R^2 = 0.64$, $P = 0.004$) between root density and soil $CO_2$ efflux rate in early spring.

## Conclusions

1. The average $CO_2$ efflux from *Cambisol* was 12% higher than from *Retisol*. Soil $CO_2$ emission in forestland and grassland *Cambisol* were 24% and 34% higher than in forestland and grassland *Retisol*, respectively. However, in conventional tillage plots, the $CO_2$ efflux in *Cambisol* was 22% lower than in *Retisol*. Under dry weather conditions and high temperatures, soil $CO_2$ emission from the soil increased by 23%.

2. A soil temperature (ST) of up to 25°C had a positive influence on the soil $CO_2$ efflux, but at ST above 25°C, the relationship was negative. The volumetric water content (VWC) of up to 20% increased soil $CO_2$ emission. With an increasing VWC, soil respiration decreased in both types of soil.

3. The root volume and root length density decreased in the following order: grassland > forestland > conventional tillage plots. The root volume had a positive influence on soil respiration.

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# Aplinkos veiksnių ir augalų šaknų sistemos įtaka $CO_2$ emisijai įvairios kilmės skirtingai naudojamuose dirvožemiuose

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## Santrauka

Anglies dioksido ($CO_2$) emisija iš dirvožemio viršutinio 0–5 cm sluoksnio buvo tirta uždaros kameros metodu taikant tradicinį žemės dirbimą, žolyne ir miško rudžemyje bei balkšvažemyje. $CO_2$ emisija nustatyta šešis kartus per vegetacijos sezoną, nuo 2018 m. balandžio iki rugpjūčio mėn. Dirvožemio temperatūra ir tūrinis vandens kiekis matuoti 5 cm gylyje tuo pačiu metu, kaip ir $CO_2$ emisija. Augalų šaknų tyrimui laboratorijoje atlikti monolitai paimti iš dirvožemio 0–10 cm sluoksnio.

Rudžemyje $CO_2$ emisija buvo nuo 0,20 iki 2,67 µmol $CO_2$ $m^{-2}$ $s^{-1}$ žemę dirbant tradiciškai, nuo 1,10 iki 3,41 µmol $CO_2$ $m^{-2}$ $s^{-1}$ žolyno ir nuo 0,89 iki 2,28 µmol $CO_2$ $m^{-2}$ $s^{-1}$ miško dirvožemyje. Balkšvažemyje $CO_2$ emisija svyravo 0,81–3,54 µmol $CO_2$ $m^{-2}$ $s^{-1}$ žemę dirbant tradiciškai, 1,23–2,69 µmol $CO_2$ $m^{-2}$ $s^{-1}$ žolyno ir 0,88–2,06 µmol $CO_2$ $m^{-2}$ $s^{-1}$ miško dirvožemyje. Matavimo laikotarpiu dirvožemio temperatūra svyravo nuo 11,5 iki 33,6 °C. Vidutinė temperatūra 5 cm gylyje rudžemyje buvo 22,8, balkšvažemyje – 21,1 °C. Rudžemyje ir balkšvažemyje tūrinis vandens kiekis 5 cm gylyje buvo vidutiniškai 18,7 ir 23,9 %. Visą matavimo laikotarpį dirvožemio tūrinis vandens kiekis buvo žymiai mažesnis rudžemyje nei balkšvažemyje. Didžiausias augalų šaknų tūris 0–10 cm sluoksnyje nustatytas balkšvažemyje augusio žolyno. Žemę dirbant tradiciškai rudžemyje šaknų tūris buvo 6,2 karto, balkšvažemyje – 5,1 karto, miško balkšvažemyje – 1,9 karto mažesnis; miško rudžemyje – 1,4 karto, žolyno rudžemyje – 1,1 karto mažesnis, palyginus su balkšvažemyje augusio žolyno šaknų tūriu. Dirvožemio $CO_2$ emisijos vidutinis kiekis balkšvažemyje buvo 12 % mažesnis nei rudžemyje. $CO_2$ emisija rudžemyje turėjo tendenciją mažėti šia linkme: žolynas > miško dirvožemis > tradicinio žemės dirbimo dirvožemis. Balkšvažemyje $CO_2$ emisija mažėjo tokia linkme: žolynas > tradicinio žemės dirbimo dirvožemis > miško dirvožemis. $CO_2$ emisiją didino tūrinis vandens kiekis, tačiau kai vandens kiekis dirvožemyje buvo didesnis nei 20 %, jis mažino emisiją. Išmetamo $CO_2$ kiekį didino dirvožemio temperatūra (iki 25 °C). Tačiau temperatūrai dar labiau padidėjus, ji sumažino abiejų tipų dirvožemių kvėpavimą.

Šaknų tūrio ir šaknų ilgio tankio sumažėjimas priklausė nuo žemės naudojimo pobūdžio: žolynas > miško dirvožemis > tradicinio žemės dirbimo dirvožemis.

Reikšminiai žodžiai: balkšvažemis, rudžemis, šaknų tūris, dirvožemio temperatūra, tūrinis vandens kiekis.