https://doi.org/10.17221/183/2018-PSE

Consumption of atmospheric methane by soil in a lowland broadleaf mixed forest

Jiří DUŠEK*, Manuel ACOSTA, Stanislav STELLNER, Ladislav ŠIGUT, Marian PAVELKA

Global Change Research Institute of the Czech Academy of Sciences, Brno, Czech Republic
**Corresponding author: dusek.j@czechglobe.cz*

ABSTRACT

Dušek J., Acosta M., Stellner S., Šigut L., Pavelka M. (2018): Consumption of atmospheric methane by soil in a lowland broadleaf mixed forest. Plant Soil Environ., 64: 400–406.

Soils of forest ecosystems can release or consume methane (CH_4) depending on their specific hydrological regime. Our study reported the consumption of CH_4 by soil in a lowland broadleaf mixed temperate forest in the Czech Republic (Central Europe). The motivation of our study was to determine the importance of CH_4 fluxes in context of carbon dioxide (CO_2) fluxes of a broadleaf mixed forest. CH_4 and CO_2 emissions from the soil were measured during the 2016 vegetation season on a long transect applying the chamber technique. The average daily consumption of atmospheric CH_4 by the forest soil ranged from 0.83 to 1.15 mg CH_4-C/m^2/day. This consumption of CH_4 during summer and autumn periods was not significantly affected by soil temperature and soil moisture. However, during spring period the consumption of CH_4 was positively significantly affected by soil temperature and moisture. Estimated amount of carbon (CH_4-C) consumed by the forest soil makes up a very small part of carbon (CO_2-C) participated in the ecosystem carbon cycle.

Keywords: floodplain; greenhouse gases; climate change; *Quercus*; *Fraxinus*

Methane (CH_4) is an important form of carbon (C) in the global C cycle and together with carbon dioxide (CO_2), nitrous oxide and water vapour belongs to greenhouse gases affecting global climate change (WMO 2016). The average concentration of atmospheric CH_4 was 1.845 ppm in 2015 and the average growth rate is about 6 ppb/year in the period 2007 to 2015 (WMO 2016). Methane emissions around the globe are product of different origin; processes like biogenic (microbial methanogenesis), thermogenic (slow transformation of organic matter into fossil fuels) or pyrogenic (biomass burning) (Schlesinger 2012). The biogenic processes represent a major source of CH_4 emissions. These include natural sources (natural wetlands, ruminants, fresh waters, termites) and anthropogenic sources of CH_4 (landfills, rice paddies, ruminants, natural gas, coal and oil). Aerobic terrestrial soils are the sink of CH_4 about 34 ± 4.3 Tg/year (Murguia-Flores et al. 2017). Mechanisms of CH_4 exchange between the atmosphere and soils are different and it depends on whether it is CH_4 emissions (positive efflux) or consumption (negative efflux). Methane can be released from soils to the atmosphere by molecular diffusion, ebullition, and plant-mediated transport. All of these mechanisms significantly affect the spatial and temporal variability of CH_4 emissions (Shvaleva et al. 2011, Kang et al. 2017). The consumption of CH_4 by methanotrophic bacteria (Striegl 1993) is affected mainly by soil physical properties that determine dynamics of gas transfer through the

Supported by the Ministry of Education, Youth and Sports of Czech Republic within the National Sustainability Program I (NPU I), LO1415 and LD15040, and by the Project CzeCOS/ICOS No. LM2015061.

https://doi.org/10.17221/183/2018-PSE

soil by molecular diffusion along gas partial pressure gradients. The potential of atmospheric CH_4 to diffuse into the soil is commonly exceeded by the ability of soil to consume CH_4 (Maier et al. 2017). The ability of soil to release/consume CH_4 is geographically widespread in terms of land use and type of ecosystem. Soils in temperate forests can consume 20–45 Tg CH_4 per year (Pitz and Megonigal 2017). Consumption of CH_4 can be also affected by different environmental factors (e.g. soil temperature, moisture) and by direct human interventions like fertilization (Tian et al. 2015).

The motivation of our study was to improve the knowledge about CH_4 exchange between broadleaf mixed forests soil and the atmosphere. It was expected that potential emission of CH_4 will be very low due to low water level resulted in mostly aerobic conditions in upper parts of soil profile. Individual aims of the conducted study are following: (i) to quantify soil CH_4 exchange between soil and the atmosphere; (ii) to determine the influence of environmental parameters such as soil temperature and soil moisture on CH_4 fluxes; and (iii) to determine the importance of CH_4 fluxes in context of CO_2 fluxes on the ecosystem level.

MATERIAL AND METHODS

Site description. The study was carried out at a lowland broadleaf mixed temperate forest (110-year old and 27 m high) at the altitude of 154 m a.s.l., close to the confluence of Morava and Dyje rivers (48°40.09'N, 16°56.78'E). The predominating soil types of the study site were Eutric Humic Fluvisol, Haplic Fluvisol and Eutric Fluvisol (according the FAO 2014 Classification) with the minimal soil depth about 60 cm. Soil porosity of surface soil layers up to 10 cm depth was about 66% and the porosity of lower soil layers in depth 10 cm to 30 cm was between of 39% to 45%. The alluvial plain was exposed by hydrological extremes such as floods and drought. The last larger flood was recorded in 2013 when water was above soil surface only in the lowest parts of the studied site. The area of our measurements, however, was not directly affected by this flood. Soil water table during measurements was in a depth below 2 m. The long-term average annual precipitation was 550 mm and the annual mean temperature was 9.3°C. Trees composition typical for the site was the hardwood forest English oak (*Quercus robur* L.), narrow-leaved ash (*Fraxinus angustifolia* Vahl), hornbeam (*Carpinus betulus* L.) and linden (*Tilia cordata* Mill.). The herbal layer of the forest was characterized by *Allium ursinum* L., *Anemone ranunculoides* L., *Lathyrus vernus* (L.) Bernh., *Galium odoratum* (L.) Scop., *Carex sylvatica* Huds. and *Acer campestre* L.

CH_4 and CO_2 measurements. CH_4 and CO_2 exchange from the soil was measured 3 times during the 2016 growing season. The exact dates of measurements were selected in order to characterize the year seasons, with typical meteorological conditions for the current season: spring (10th May), summer (20th, 21st July) and autumn (15th November). The measurements were carried out in a 150 m long transect at 30 positions in 5 mintervals. At each individual measured place a PVC collar with 20 cm inner diameter was permanently installed into the soil at about 5 cm depth for the whole growing season. CH_4 and CO_2 flux measurements itself were carried out using a non-steady state closed chamber system (Acosta et al. 2013). The cylindrical chamber with dimensions of 18 cm in inner diameter and volume of 3.167 L was used. Changing concentrations of gases inside the closed chamber were measured by a fast CH_4 analyser (GGA-30p, Los Gatos Research Inc., USA). The analyser gave corrected data to water vapour in 1 Hz frequency. Calculated CH_4 fluxes from individual measurements corresponded with typical fluxes of periods (spring = March, April, May; summer = June, July, August and autumn = September, October, November) of the growing season.

Data processing of chamber measurements. The data were processed using the R software environment for statistical computing (R Core Team 2017). Calculation of gas fluxes is based on the linear increase of gas concentration inside the chamber until closure time (5 min), taking into account the chamber volume (3.1667 L) and surface area covered (0.0281 m^2). Final flux includes corrections to the current air temperature and ambient air pressure by the physics ideal gas law. Distribution of primary data differed significantly from normal ($P < 0.01$), differences among the fluxes of CH_4 measured in individual periods of the growing season 2016 were tested using the non-parametric Kruskal-Wallis test (a distribution-free test for general alternatives) (Hollander et al. 2014).

https://doi.org/10.17221/183/2018-PSE

Table 1. Summary of meteorological and soil parameters of the 2016 growing period at the studied site

Period	Average air temperature at 2 m height (°C)	Amount of precipitation (mm)	Average soil temperature (°C)		Average soil moisture (%)		Global radiation	Soil heat flux
			5 cm	50 cm	5 cm	50 cm	(MJ/m^2/period)	
Spring	10.1	128.8	9.0	8.2	44.0	42.2	1364	+18.15
Summer	18.5	201.2	17.2	15.5	31.2	41.0	1950	+29.51
Autumn	9.6	93.2	10.6	14.4	25.9	32.3	760	–26.02

Multiple comparisons between individual seasons were tested using the kruskalmc procedure of the Pgirmess R-package (Siegel and Castellan 1988). The tightness of the relationship of CH_4 fluxes (consumption) with soil temperature, moisture and interaction between them were tested using nonparametric Spearman's correlation coefficient (Hollander et al. 2014).

Ancillary measurements of environmental conditions. During all CH_4 measurements micrometeorological parameters were measured automatically in 30-min resolution. Soil temperature (Pt100, Sensit, Czech Republic) and soil moisture (CS616, Campbell Scientific, USA) were measured in vertical profile at different depths (0, 5, 10, 20, 50 cm) at four representative positions of the studied forest. Soil heat flux was measured by four plate sensors (HFP01, Hukseflux Thermal Sensors B.V., the Netherlands) placed in soil in 5 cm depth. Global solar radiation was measured by a CMP21 Pyranometer (Kipp & Zonen, the Netherlands), air temperature/humidity at 2 m height (EMS33, EMS Brno, Brno, Czech Republic) and precipitation (386C rain gauge, MetOne, USA). Moreover, fluxes of CO_2 between the forest ecosystem and the atmosphere were measured by the Eddy covariance technique consisting of the ultrasonic anemometer Gill HS-50 (Gill Instruments, UK) and the enclosed-path infrared gas analyser LI-7200 (Li-Cor, USA) placed on a mast 44 m above ground level. The post-processing of high frequency data (20 Hz) was performed by the EddyPro® software (Li-Cor, USA) according to Aubinet et al. (2012).

RESULTS AND DISCUSSION

Environmental conditions. The conditions within the periods of spring, summer and autumn of the growing period varied characteristically according to the site location in the temperate zone (Table 1, Figure 1). At the beginning of the growing period in

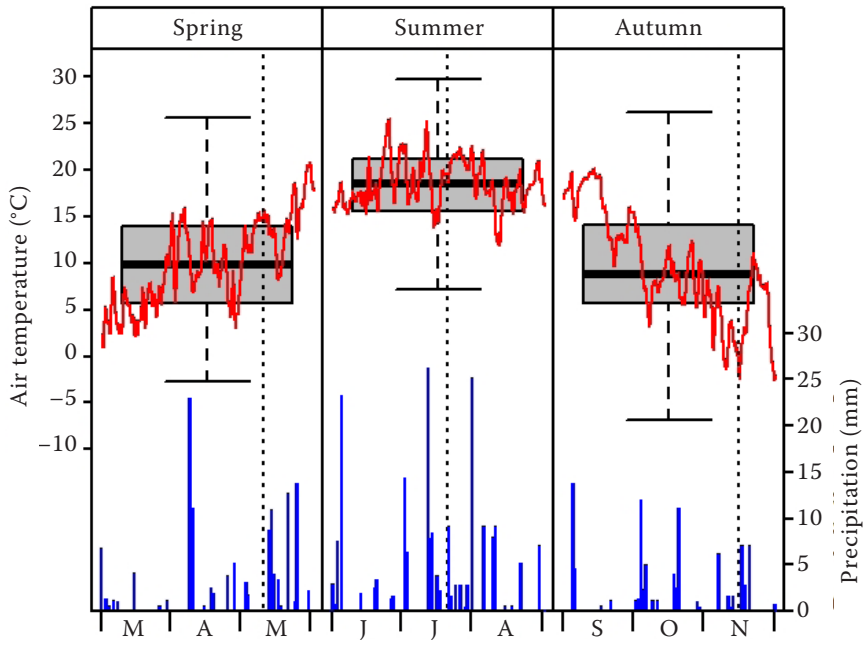

Figure 1. Meteorological conditions of the 2016 growing period. Mean daily air temperatures (red lines and boxes), boxes of upper and lower quartile represent 50% of the measured data, median (thick black lines inside boxes), whiskers of box show upper and lower extreme (1.5 × interquartile range). Blue bars represent daily sums of precipitation. Vertical dotted lines indicate date of in situ measurements

https://doi.org/10.17221/183/2018-PSE

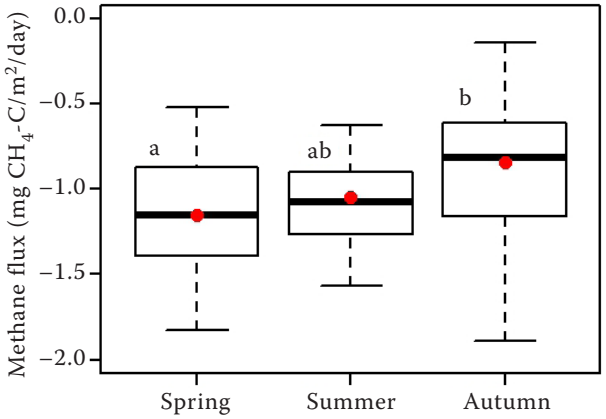

Figure 2. Consumption of CH_4 measured in forest during the 2016 growing period. Mean (red dots), median (thick black lines inside boxes), upper and lower quartile (boxes with 50% measured data) and whiskers of box show upper and lower extreme (1.5 × interquartile range). Statistically significant differences are marked with letters

spring, air temperature gradually increased to maximum in the summer period and then quite steeply decreased in the autumn period. Temperatures inside the soil profile changed and varied in different soil depths in response to the amount of incoming energy by solar radiation. During spring and summer positive balance of soil heat flux (heat storage) was observed, whereas negative balance (heat release) occurred only in the autumn period. Soil moisture was also changed between periods. Similar soil moisture in upper and lower part of the soil profile was in spring periods. Different soil moisture in upper and lower part of soil profile was found in summer and autumn periods.

Methane consumption during different periods of growing season. Mostly consumption of CH_4 was recorded with the exception of five measurements with very small release of CH_4 (emissions). Emissions were low with an average of 0.35 mg and 0.49 mg CH_4-C/m^2/day in summer and autumn, respectively. These emissions were obtained in different places of the measured transect. Averages and medians of CH_4 fluxes for individual periods were very similar (Figure 2). Averaged consumption per individual investigated period was –1.15 mg CH_4-C/m^2/day in spring, –1.04 mg CH_4-C/m^2/day in summer and –0.83 mg CH_4-C/m^2/day in autumn. Our measurements of CH_4 consumption were in the range reported in other studies (Castro et al. 1995, Murguia-Flores et al. 2017). In our study, the variability of CH_4 consumption was different for individual periods. The largest variability was found in autumn and the lowest in the summer period. It is considered that this variability on consumption of CH_4 corresponded to the environmental conditions at the site. Tian et al. (2015) pointed out that consumption of CH_4 can be affected by different environmental factors (soil temperature, moisture) and by direct human interventions like fertilization. Air and soil temperatures were quite stable and slightly fluctuated only on the diurnal bases. Statistically significant differences were found between individual periods of the 2016 growing season (Kruskal-Wallis chi-squared = 9.03, *df* = 2, *P*-value = 0.01; Figure 2).

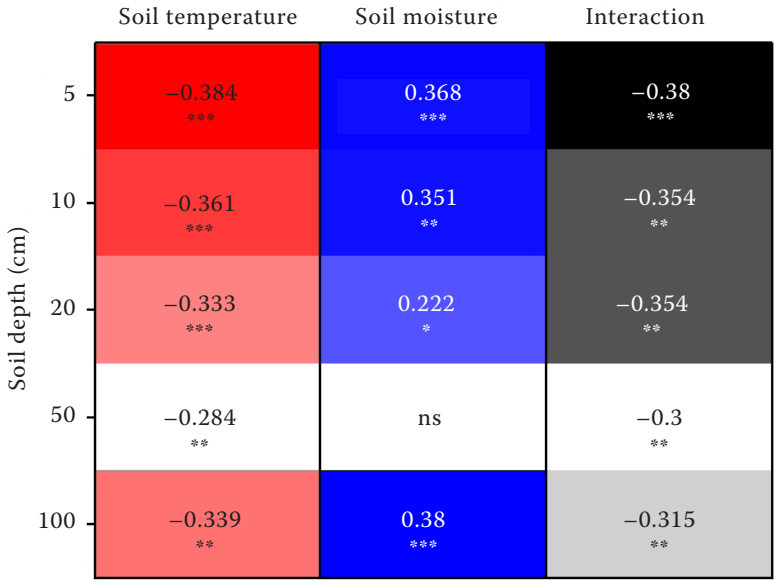

Figure 3. Spearman's correlation coefficients of CH_4 consumption (negative fluxes) with soil temperature, soil moisture and interaction between soil temperature and soil moisture at different soil depths during spring period. *P = 0.05; **P = 0.01; ***P = 0.001; ns – not significant

https://doi.org/10.17221/183/2018-PSE

Consumption of CH_4 in relation to soil temperature and soil moisture. The relationship between CH_4 consumption and soil temperature and moisture was statistically significant only during the spring period of the growing season (Figure 3). The consumption negatively correlated with soil temperature across the whole soil profile. The strongest correlation was found for the depth of 5 cm (rho = –0.384, *P*-value < 0.001). The consumption of CH_4 (negative fluxes) measured on the top of soil increased together with an increase of soil temperature. Statistically significant correlation between CH_4 consumption and soil moisture was found in 4 depths (5, 10, 20 and 100 cm) except the depth of 50 cm. Correlations were positive in a range of 0.222 to 0.380 at the probability level of 0.05, 0.01 and 0.001. Soil porosity can be reduced by soil moisture (Khalil and Baggs 2005). Higher soil moisture in this case decreased CH_4 consumption due to decreasing aeration of soil. For CH_4 consumption, appropriate soil porosity is necessary (Dörr et al. 1993), which was in range of 66% to 39% in the studied forest soil.

The interaction between soil temperature and moisture was statistically significant and correlated with CH_4 consumption during the spring period (Figure 3). Based on these results it can be assumed that during the spring period, processes of CH_4 consumption were limited by temperature and also controlled by soil moisture. In general, the consumption of CH_4 in soil is primarily controlled by soil physical properties that affect CH_4 diffusion, such as texture (Dörr et al. 1993), soil moisture (Del Grosso et al. 2000) and temperature (Crill 1991). Castro et al. (1995) pointed out that soil temperature is an important controller of CH_4 consumption at temperatures between –5°C and 10°C. A possible explanation why no statistically significant correlations were found between soil temperatures and soil moistures in summer and autumn periods is the effect of temperature which may be also explained by the vertical distribution of CH_4 consumption related to transport of CH_4 into the soil profile. Consumption of CH_4 by forest soil is highly stratified (Kolb 2009) with little or no CH_4 consumption in the uppermost soil horizons (King and Adamsen 1992).

Consumption of CH_4 in relation to CO_2 efflux and carbon balance at an ecosystem level. Soil CO_2 efflux differed significantly among the individual periods of the measurements (Kruskal-Wallis chi-squared = 121.94, *df* = 2, *P*-value < 0.01) with the highest CO_2 efflux recorded in summer (4.21 g CO_2-C/m^2/day on average). The average CO_2 efflux for spring and autumn was 2.86 g CO_2-C/m^2/day and 1.61 g CO_2-C/m^2/day, respectively. The relationship between fluxes of CO_2 and CH_4 for individual periods of the measurement campaign is shown in Figure 4.

According to our calculations prevailing consumption of CH_4 were summarised for individual

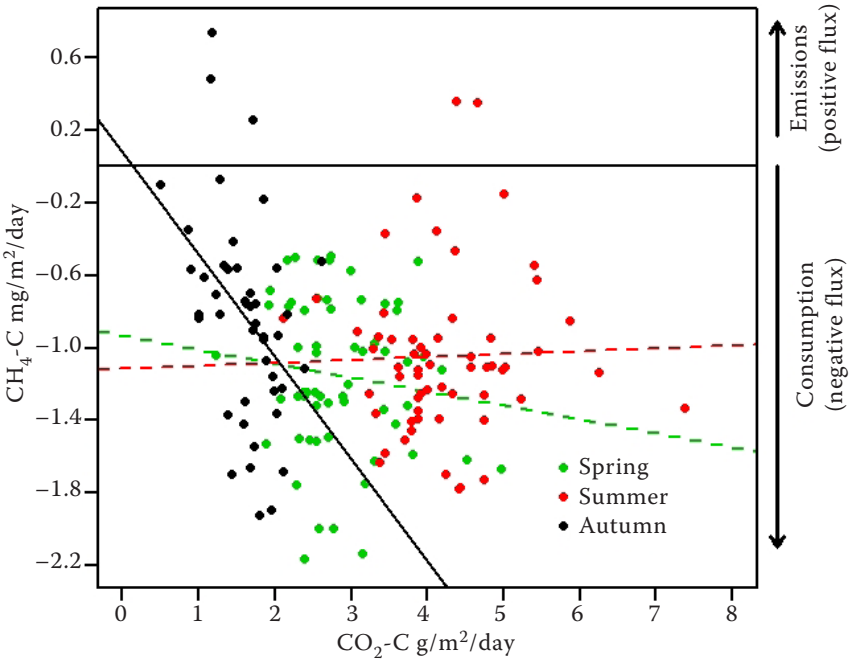

Figure 4. Linear relationship between soil CO_2 efflux and CH_4 consumption (negative flux)/emission (positive flux) measured from soil in the forest. Colour lines show linear trends of CH_4-C related to CO_2-C effluxes in different periods during the 2016 growing period (solid line – a significant trend; dash lines – non-significant trends)

https://doi.org/10.17221/183/2018-PSE

periods of the 2016 season. It was considered that this summarised CH_4 consumption for individual periods is a rough estimate due to the limited number of campaign measurements done during the experiment. However, this summarisation by season periods is considered appropriate for comparison of C cycle of the whole forest ecosystem. The measured CO_2 emissions from the studied forest soils during growing period ranged from 4.52 t to 24 t CO_2-C/ha/growing season. The averaged C emission for the 2016 growing season was 11.6 t (Acosta et al. 2017). Consumption of CH_4-C was only 0.02% of the averaged emissions of CO_2-C. The portion of consumed CH_4-C was also non-significant in comparison to CO_2-C emitted by respiration of the forest soil. These comparisons show that the importance of CH_4 consumption is not in the amount of C involved in this process and that the CH_4 consumption is governed by the processes occurring at small scales that are connected with soil. The C balance of the broadleaf mixed temperate forest season differed among the individual periods of the 2016 growing season (Figure 5). The highest amount of C released from the forest ecosystem was during autumn. Predominantly measured consumption of CH_4

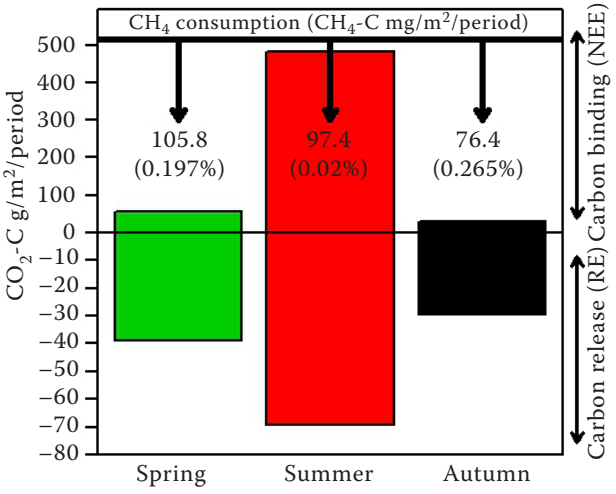

Figure 5. The CO_2-C measured in forest by the Eddy covariance technique. Positive parts of bars are net ecosystem production (NEP) and negative parts represent C release by the ecosystem respiration (RE). The whole bars represent gross ecosystem production (GEP). Values inside the graph are estimates of CH_4-C consumption by the soil during individual periods and percentage portion (in brackets) of the consumed CH_4-C as a portion of the CO_2-C (NEP)

was added to the context of C balance obtained at the ecosystem level. It was found that the portion of CH_4-C was 0.197, 0.02 and 0.265% of the net ecosystem production (NEP) for spring, summer and autumn period, respectively. Estimated seasonal consumption of CH_4-C was about 279.8 mg CH_4-C/m/growing period. It is in extreme contrast to CO_2-C sequestration by the forest ecosystem represented by NEP, and it means that the broadleaf mixed temperate forest bonded about 566.1 g CO_2-C/m^2/growing period. The forest soil was a minor sink for C in CH_4 form at the ecosystem scale.

In conclusion, the presented study confirmed the hypothesis about negligible methane emissions from the soil of a broadleaf mixed forest. However, a significant CH_4 consumption was measured by the soil. The average daily consumption of atmospheric CH_4 by soil ranged from 0.83 to 1.15 mg CH_4-C/m/day. The consumption during summer and autumn periods was not significantly affected by soil temperature and soil moisture, while during spring period consumption of CH_4 was significantly affected by soil temperature, moisture and interaction between them.

Estimated amount of carbon (CH_4-C) consumed within growing season periods by the forest was put in context to CO_2 fluxes of a broadleaf mixed forest ecosystem measured by the Eddy covariance technique. The results from this study showed that soil consumed a very small part of carbon (CH_4-C) in comparison to CO_2-C cycled in the forest ecosystem.

REFERENCES

Acosta M., Darenova E., Dušek J., Pavelka M. (2017): Soil carbon dioxide fluxes in a mixed floodplain forest in the Czech Republic. European Journal of Soil Biology, 82: 35–42.

Acosta M., Pavelka M., Montagnani L., Kutsch W., Lindroth A., Juszczak R., Janouš D. (2013): Soil surface CO_2 efflux measurements in Norway spruce forests: Comparison between four different sites across Europe – From boreal to alpine forest. Geoderma, 192: 295–303.

Aubinet M., Vesala T., Papale D. (eds.) (2012): Eddy Covariance. Dordrecht, Springer.

Castro M.S., Steudler P.A., Melillo J.M., Aber J.D., Bowden R.D. (1995): Factors controlling atmospheric methane consumption by temperate forest soils. Global Biogeochemical Cycles, 9: 1–10.

Crill P.M. (1991): Seasonal patterns of methane uptake and carbon dioxide release by a temperate woodland soil. Global Biogeochemical Cycles, 5: 319–334.

https://doi.org/10.17221/183/2018-PSE

Dörr H., Katruff L., Levin I. (1993): Soil texture parameterization of the methane uptake in aerated soils. Chemosphere, 26: 697–713.

Del Grosso S.J., Parton W.J., Mosier A.R., Ojima D.S., Potter C.S., Borken W., Brumme R., Butterbach-Bahl K., Crill P.M., Dobbie K., Smith K.A. (2000): General CH_4 oxidation model and comparisons of CH_4 oxidation in natural and managed systems. Global Biogeochemical Cycles, 14: 999–1019.

Hollander M., Wolfe D.A., Chicken E. (2014): Nonparametric Statistical Methods. Hoboken, New Jersey, John Wiley & Sons, Inc., 204–211.

Kang R.H., Mulder J., Duan L., Dörsch P. (2017): Spatial and temporal variability of soil nitric oxide emissions in N-saturated subtropical forest. Biogeochemistry, 134: 337–351.

Khalil M.I., Baggs E.M. (2005): CH_4 oxidation and N_2O emissions at varied soil water-filled pore spaces and headspace CH_4 concentrations. Soil Biology and Biochemistry, 37: 1785–1794.

King G.M., Adamsen A.P.S. (1992): Effects of temperature on methane consumption in a forest soil and in pure cultures of the methanotroph methylomonas rubra. Applied and Environmental Microbiology, 58: 2758–2763.

Kolb S. (2009): The quest for atmospheric methane oxidizers in forest soils: Atmospheric methane-oxidizing methanotrophs in forest soils. Environmental Microbiology Reports, 1: 336–346.

Maier M., Paulus S., Nicolai C., Stutz K.P., Nauer P.A. (2017): Drivers of plot-scale variability of CH_4 consumption in a well-aerated pine forest soil. Forests, 8: 193.

Murguia-Flores F., Arndt S., Ganesan A.L., Murray-Tortarolo G.N., Hornibrook E.R. (2017): Soil methanotrophy model (MeMo v1.0): A process-based model to quantify global uptake of atmospheric methane by soil. Geoscientific Model Development, 11: 2009–2032.

Pitz S., Megonigal J.P. (2017): Temperate forest methane sink diminished by tree emissions. New Phytologist, 214: 1432–1439.

R Core Team (2017): R: A Language and Environment for Statistical Computing. Vienna, R Foundation for Statistical Computing. Available at https://www.R-project.org/

Schlesinger W.H. (2012): Biogeochemistry: An Analysis of Global Change. 3rd Edition. New York, Elsevier/Academic Press.

Shvaleva A., Lobo-do-Vale R., Cruz C., Castaldi S., Rosa A.P., Chaves M.M., Pereira J.S. (2011): Soil-atmosphere greenhouse gases (CO_2, CH_4 and N_2O) exchange in evergreen oak woodland in southern Portugal. Plant, Soil and Environment, 57: 471–477.

Siegel S., Castellan N.J. (1988): Non Parametric Statistics for the Behavioural Sciences. New York, MacGraw Hill Int., 213–214.

Striegl R.G. (1993): Diffusional limits to the consumption of atmospheric methane by soils. Chemosphere, 26: 715–720.

Tian H.Q., Chen G.S., Lu C.Q., Xu X.F., Hayes D.J., Ren W., Pan S.F., Huntzinger D.N., Wofsy S.C. (2015): North American terrestrial CO_2 uptake largely offset by CH_4 and N_2O emissions: Toward a full accounting of the greenhouse gas budget. Climatic Change, 129: 413–426.

WMO (2016): World Meteorological Organization. Greenhouse Gas Bulletin 12. Geneva.

Received on March 20, 2018
Accepted on June 19, 2018
Published online on July 14, 2018