INTERNATIONAL
Agrophysics
www.international-agrophysics.org

Int. Agrophys., 2013, 27, 283-290
doi: 10.2478/v10247-012-0096-5

Measurements of methane emission from a temperate wetland by the eddy covariance method**

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Received May 26, 2012; accepted March 19, 2013

A b s t r a c t. Methane emission from a wetland was measured with the eddy covariance system. The location of the system allowed observation of methane efflux from areas that were covered by different vegetation types. The data presented in this paper were collected in the period between the13th of June and the 31st of August 2012. During the warmest months of the summer, there was no strong correlation between methane emissions and either the water table depth or peat temperature. The presence of reed and cattail contributed to a pronounced diurnal pattern of the flux and lower methane emission, while areas covered by sedges emitted higher amounts more with no clear diurnal pattern.

K e y w o r d s: eddy covariance, methane emission, wetland

INTRODUCTION

There is agreement among most scientists that the temperature increase observed recently in the atmosphere is related to the rise in the concentration of greenhouse gases (IPCC 2007), but simultaneously this statement is questioned by others (Kutilek, 2011). Methane from wetlands is one of the major sources of this gas in the atmosphere. After water vapour and carbon dioxide, methane is the third most important greenhouse gas, although its concentration in the atmosphere is two hundred times lower than that of CO_2. Taking into account the atmospheric life time of methane (12 years) and its radiative properties, we arrive at the Global Warming Potential (GWP) of methane being 25 times that of carbon dioxide (emission of 1 g of CH_4 is equal to 25 g of CO_2) for 100-year time horizon. Both CH_4 and CO_2 are the major components of the wetland carbon budget regarding the exchange with the atmosphere (Rinne *et al*., 2007). An undisturbed wetland is typically a sink of CO_2 and source of CH_4 in the atmosphere on an annual scale (Aurela *et al*., 2001; Rinne *et al*., 2007). The emission of CH_4 is strongly related to the anaerobic conditions, which are the result of the high water table in this type of environment.

The emission of CH_4 intensity is also related to the type of vegetation. This is due to convective flow through shoots and rhizomes, which is a mechanism for below-ground aeration of wetland plants. A convective flow of gases is caused by internal gas movement in plants by pressurization of shoot aerenchyma (Sorrel *et al.*, 2010). This mechanism can be explained by pressurization caused by diffusion of gases from the air into the roots. Gases that enter the plant through diffusion pass through the submerged parts of the plant, as their escape into the atmosphere takes place in different parts of plants. In *Phragmites australis*, the flow convection is substantial and often greater than diffusion (Armstrong *et al*., 1991). In this study, a relationship between methane emission and the type of vegetation was found.

The gas exchange between wetlands and atmosphere has traditionally been measured in chambers (Christiansen *et al*., 2011; Juszczak *et al*., 2012a; Juszczak, 2013; Lund *et al*., 2010; Rask *et al*., 2002; Schrier-Uijl *et al*., 2009), but recently the eddy covariance technique has become a common tool for ecosystem-scale mass and energy exchange (Baldocchi, 2003). However, even though the eddy covariance method has been used for studies of the ecosystem-scale CO_2 exchange for over a decade (Launiainen *et al*.,

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**This work was supported by COST Action ES0804, National Science Centre project No. 628/N-COST/2009/0, 2008-2013; and partly by InGOS FP7 grant agreement No. 284274) and ESF TTORCH, 2009-2013.

2005; Lee *et al*., 2004), ecosystem-scale methane emission remains much more poorly studied due to the instrumental limitations until very recently (Hendriks *et al*., 2008; Kroon *et al*., 2007, 2009). So far, the wetland ecosystems on which the eddy covariance method has been used to obtain methane emissions include *eg* boreal fens, rewetted systems. There have been no measurements in Eurasian temperate natural wetlands.

Thus, the main goal of this paper is to present and discuss preliminary results of CH_4 efflux values that were measured with the eddy covariance technique.

MATERIAL AND METHODS

The data set presented in this paper was obtained during the period between the 13th of June and the 31st of August 2012. The area studied (140 ha) is located about 70 km NW of Poznań (Chojnicki *et al*., 2007, 2012). The wetland is a georgenous mire, where the most common are moss (*Sphagnum* spp.), moss (*Dicranum* spp.), sedge (*Carex* spp.), reed (*Phragmites australis*), cattail (*Typha latifolia*), cranberry (*Vaccinium oxycoccus*), round-leaved sundew (*Drosera rotundifolia*), purple marshlocks (*Potentilla palustris*), meadow buttercup (*Ranunculus acris*) and bog-bean (*Menyanthes trifoliata*). The average annual air temperature is 8.5°C, the sum of precipitation is 526 mm, and westerly winds prevail (Farat *et al*., 2004). The measurements were carried out on a platform located in the centre of the wetland surveyed (Fig. 1). To the north of the measurement platform, the vegetation consisted of *Phragmites* spp., whereas to the south it consisted of *Carex* spp., *Sphagnum* spp., *Menyanthes trifoliata*, and *Potentilla palustris*.

The net CH_4 exchange (F_{CH_4}) was measured with the eddy covariance technique. The eddy covariance technique is the most widely used accurate and direct method presently available for quantifying exchanges of carbon dioxide, water vapour, methane, various other gases and energy between the surface of earth and the atmosphere. Eddy covariance provides an accurate way to measure surface-to-atmosphere fluxes, gas exchange budgets and emissions from a variety of ecosystems, including agricultural and urban plots, landfills, and various water surfaces. Emissions and fluxes can be measured by instrumentation on either a stationary or mobile tower, floating vessel (such as ship or buoy), or aircraft. The undertaken research provides knowledge about methane emission from wetlands depending on the type of plants.

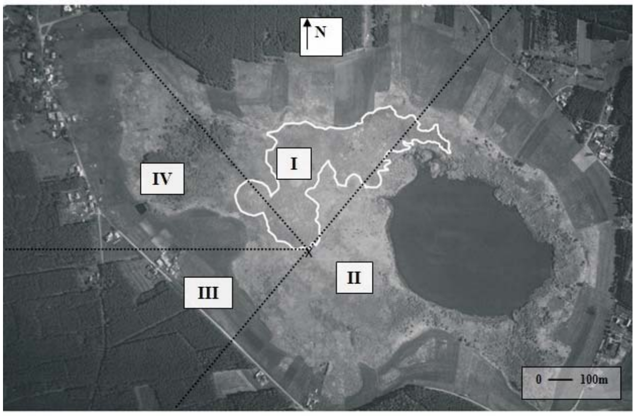

Fig. 1. Airborne image of Rzecin wetland. The black cross indicates the location of the measuring platform, with a white line drawn around the reed (*Phragmites australis*) dominated area; Roman numerals indicate wind direction sectors.

The system consisted of two basic elements: a sonic anemometer (R3-100, Gill Instruments Ltd., Lymington, UK) and a closed-path gas analyzer (DLT-100 Los Gatos Research Inc., Mountain View, CA, USA) (Fig. 2). Suitability of the DLT-100 for eddy covariance measurements was described by Hendriks *et al*. (2008).

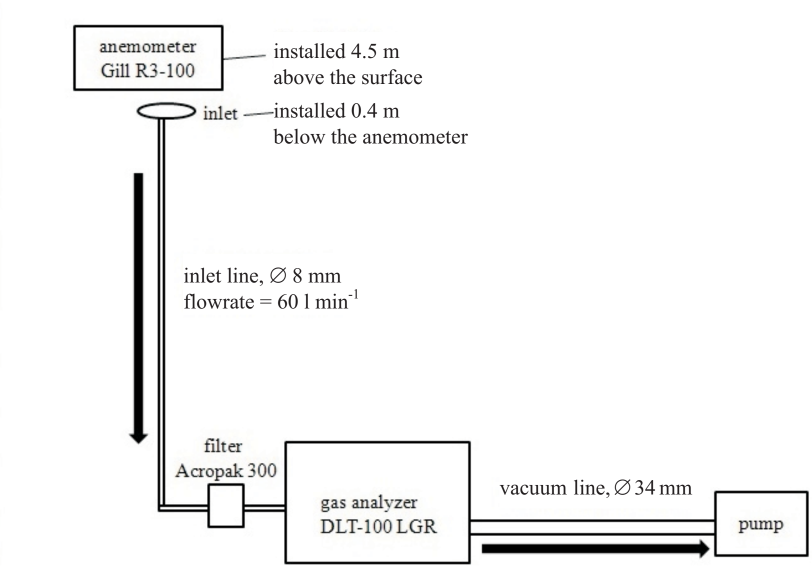

Fig. 2. Scheme of the eddy covariance system for measuring methane. The arrows indicate the direction of the intake air.

The 4 m long heated teflon tube (inner diameter 8 mm) was applied to carry on the air to the gas analyzer. A flow rate of 60 l min^{-1} was achieved by an oil recirculating vane pump (R5 0021B, Busch, USA). A funnel was mounted at the inlet to protect it from rain, and a 0.2 μm PTFE (Polytetrafluoroethylene) membrane (AcroPak 300, Pall, Port Washington, NY, USA) was installed on the tube 10 cm before the inlet to the gas analyzer. The teflon tube was heated with resistance wire (JLC Electromet Pvt. Ltd., Jaipur, Rajasthan, India) with total heating power of 32W in order to prevent condensation of water vapour.

The anemometer was installed 4.5 m above the peat surface, whereas the tube inlet was 40 cm below. The gas analyzer and pump were placed in separate metal boxes 1m above the surface. This device was installed beside of anemometer. The net CO_2 exchange (F_{CO_2}) was measured in parallel to F_{CH_4} with an open path infrared H_2O/CO_2 analyzer LI-7500 (LI-COR Inc., Lincoln, NE, USA).

Methane, carbon dioxide and water vapour concentrations were measured with a frequency of 10 Hz and the data obtained were recorded by a field computer installed in the gas analyzer. The pump box was also equipped with a telemetric module that allows remote monitoring of power supply and the pump temperature.

The temperature of substrate was measured with a temperature probe (T107, Campbell Scientific Ltd.) at 2 cm depth.

The EddyPro software, version 4.0.0 (LI-COR Inc., USA) was used to calculate 30 min average values, such as methane flux (F_{CH_4}), carbon dioxide flux F_{CO_2}), and friction velocity (u*).

The use of the eddy covariance method requires well developed atmospheric turbulence. Friction velocity (u_m*) is regarded as a measure of turbulence intensity. Normally, the u* threshold value, below which the turbulent mixing is assumed to be insufficient for the eddy covariance method, is used to filter the data (Foken and Wichura, 1996).

According to Baldocchi (2003), the u* threshold values (u_m*) are normally in the range from 0.1 to 0.6 m s^{-1}. However, exact estimation of u_m* needs to be always done locally on the basis of obtained data. The u_m* was estimated within the analysis of methane flux values obtained. The median values of F_{CH_4} become independent of friction velocity, and flux standard deviation is substantially reduced for u* values higher than 0.15 m s^{-1}(Fig. 3). Thus, further analysis in this paper was performed on data where u* >=0.15 m s^{-1}. The application of this threshold value removed about 26% of data (Fig. 4).

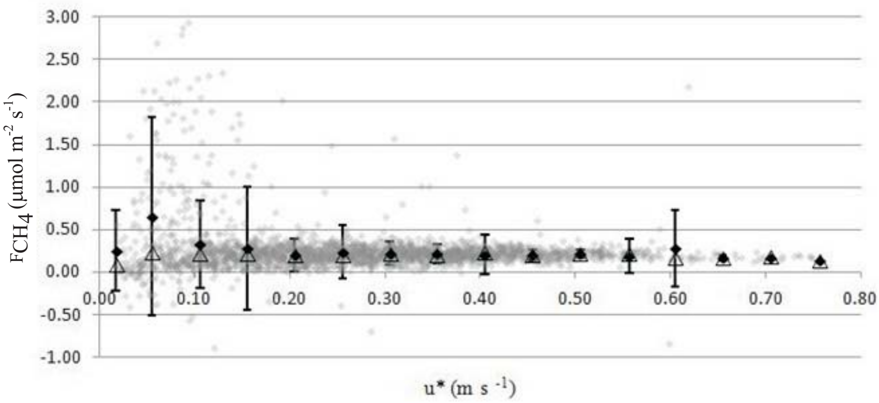

Fig. 3. Methane efflux density (F_{CH_4}) versus friction velocity (u*). The triangles indicate the median values, black diamonds indicate the mean values, and bars indicate standard deviations.

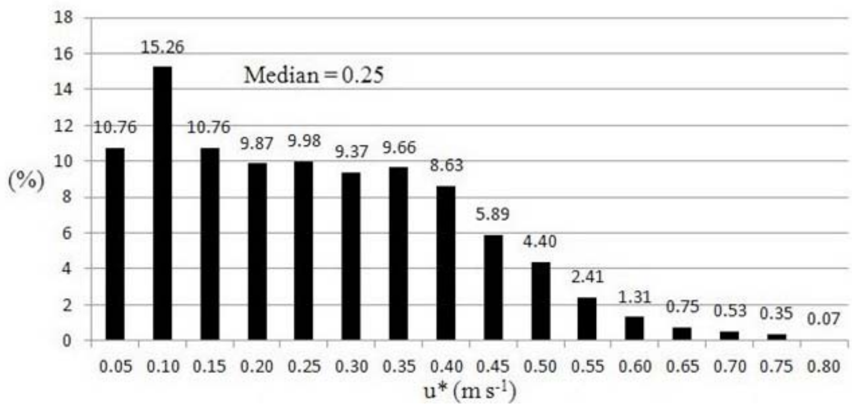

Fig. 4. Friction velocity (u*) distribution.

RESULTS

The eddy covariance technique applied at the wetland studied allows estimation of the net gas exchange averaged over the so-called footprint area downwind of the measurement system. Since the eddy covariance tower was located on the border between different vegetation types, the dependence between F_{CH_4} and the vegetation type was studied by selecting the data by the wind direction.

The data were divided into four wind direction sectors (WDS) selected after initial analysis of methane effluxes against wind direction and by dominant vegetation in the different sectors (Figs 1 and 5). The following sectors were chosen: I – 330-30, II – 30-190, III – 190-270, and IV – 270-330°. The average effluxes in these sectors were 0.20, 0.22, 0.27, and 0.22 µmol m^{-2} s^{-1}, respectively (Table 1). The lowest mean methane efflux value (0.20 µmol m^{-2} s^{-1}) was observed for wind sector I, where the vegetation was dominated by a mixture of reed (*Phragmites australis*) and cattail (*Typha latifolia*). The area was covered mostly by different species of sedges (*Carex* spp.) (wind sector III) was found to be the strongest emitter of CH_4 (0.27 µmol m^{-2} s^{-1}). The efflux variability expressed by standard deviation (STD) values was the highest within sector III as well (0.67 µmol m^{-2} s^{-1}), while the lowest one was observed for sector IV (0.05 µmol m^{-2} s^{-1}) (Table 1).

A pronounced diurnal pattern of F_{CH_4} was found only for sectors I and IV (Fig. 6I, 6IV). The reed and cattail were the dominating species in those two sectors. The average F_{CH_4} values were the lowest during the night with a clear decrease in the late afternoon, while the highest F_{CH_4} were observed during the day and the strongest increase in the methane efflux values was observed about 6AM LT.

Sector II had a high variability of the flux, but no clear diurnal cycle. Both the daily minimum (-0.05 µmolCH_4 m^{-2} s^{-1}) and maximum (0.70 µmolCH_4 m^{-2} s^{-1}) values of F_{CH_4} were the lowest for wind direction sector II in average daily run.

The variability of F_{CO_2} in average daily run from WDS III was the highest, and the maximum and minimum values were equal to 27.00 µmol CO_2 m^{-2} s^{-1} and -21.36 µmol CO_2 m^{-2} s^{-1}, respectively (Table 2).

The average net ecosystem exchange (F_{CO_2}) diurnal cycles had typical daily patterns in all four sectors but their values were reversed compared to F_{CH_4}. Minimum values of F_{CO_2} (-21.36 µmol CO_2 m^{-2} s^{-1}, sector III) (absorption of CO_2 by the canopy) were observed around noon due to photosynthesis, while the highest emission due to respiration was observed during the night (CO_2 emission) (Fig. 6I, 6II, 6III, 6IV).

There was no diurnal pattern in the soil water level (WDS) and substrate temperature (Ts) in any of the wind sectors.

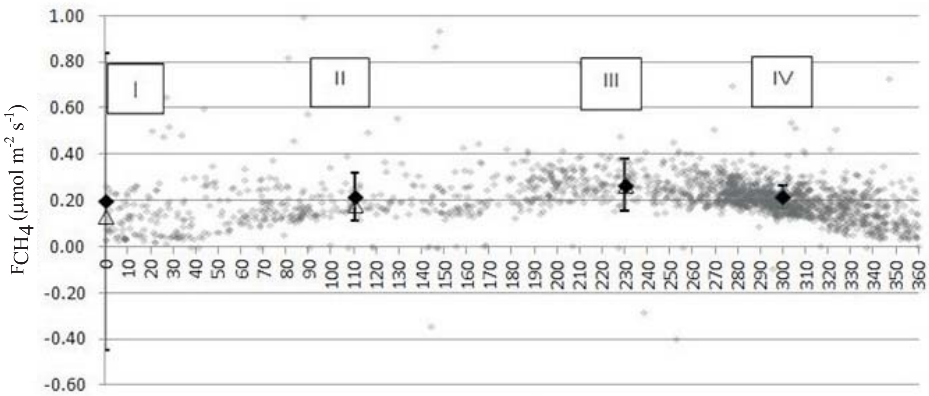

Fig. 5. Methane efflux (F_{CH_4}) versus wind direction (WD), the black diamonds indicate the average values, bars indicate standard deviation, dotted lines indicate selected wind direction sectors.

T a b l e 1. The mean (AVG), standard deviation (STD), and median values of methane efflux for four selected wind sectors

Wind sector	Degrees (°)	AVG	STD	Median
		(µmol m^{-2} s^{-1})		
I	330-30	0.20	0.64	0.13
II	30-190	0.22	0.10	0.18
III	190-270	0.27	0.11	0.26
IV	270-330	0.22	0.05	0.21

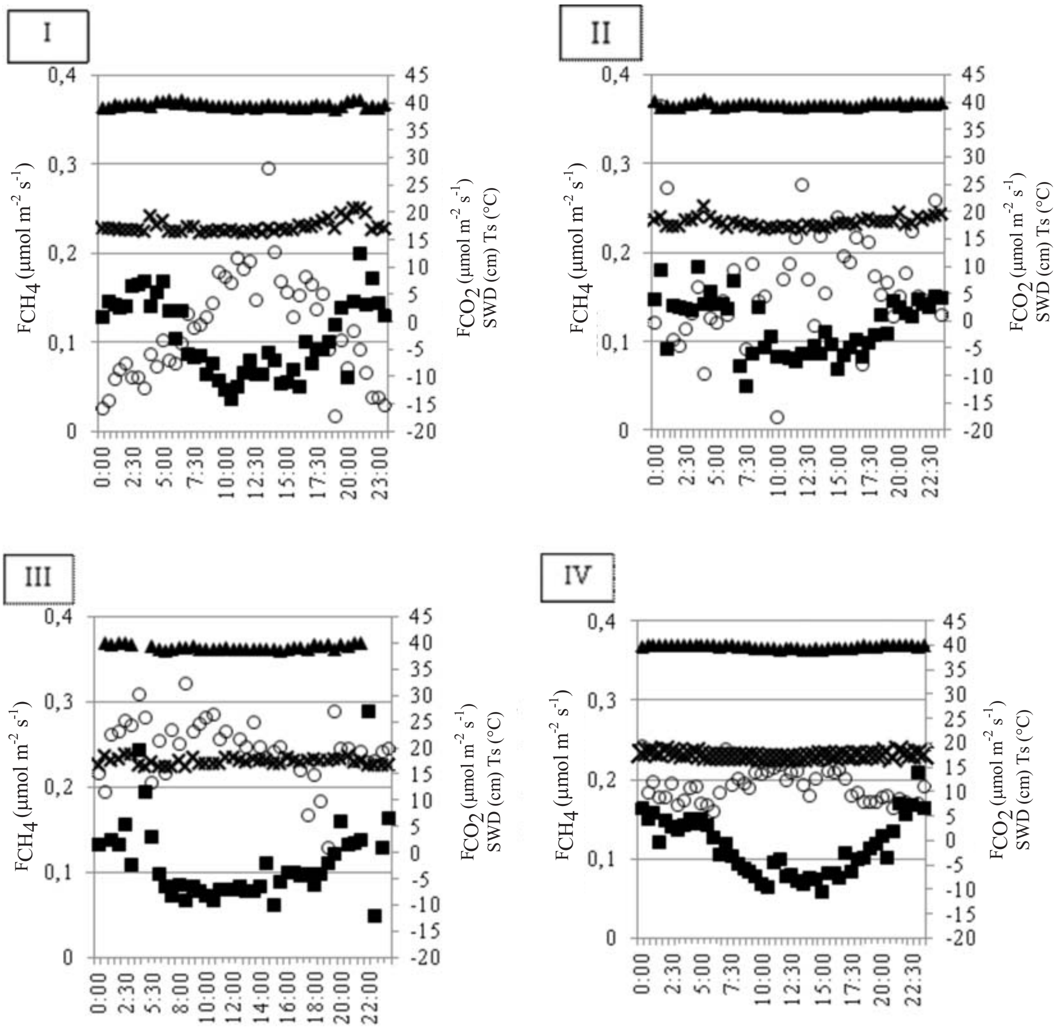

Fig. 6. Average diurnal cycles of methane efflux (F_{CH_4}) - circles, net ecosystem exchange (F_{CO_2}) – squares, soil water depth (SDW) – triangles, soil temperature (Ts) – crosses. I, II, III, IV – wind sectors.

T a b l e 2. Minimum (Min) and maximum (Max) values of methane effluxes (F_{CH_4}) and net ecosystem exchange (F_{CO_2}) in average runs of wind direction sectors (WDS)

Wind sector	F_{CH_4}		F_{CO_2}	
	Min	Max	Min	Max
	(µmol CH_4 m^{-2} s^{-1})		(µmol CO_2 m^{-2} s^{-1})	
I	0.02	0.3	-13.84	12.57
II	-0.05	0.7	-11.70	10.13
III	0.13	0.6	-21.36	27.00
IV	0.16	0.2	13.97	-10.32

The 30 min average substrate temperature measured at 5 cm depth (Ts) ranged from 14.7 to 20.3°C during the measurement period. The correlation between the 30 min average values of methane efflux (F_{CH_4}) and Ts was found to be very low (R^2=0.0049), even though F_{CH_4} was slightly increasing with increasing Ts (Fig. 7).

There was a negative correlation between F_{CH_4} and F_{CO_2} in all four wind sectors. This is the consequence of the inverse diurnal cycles of F_{CH_4} and F_{CO_2}, especially in sectors I and IV with the clear diurnal pattern in F_{CH_4}. The lowest highest coefficient value was found for WDS I (-23.77), while the highest one was found for WDS IV (-7.48).

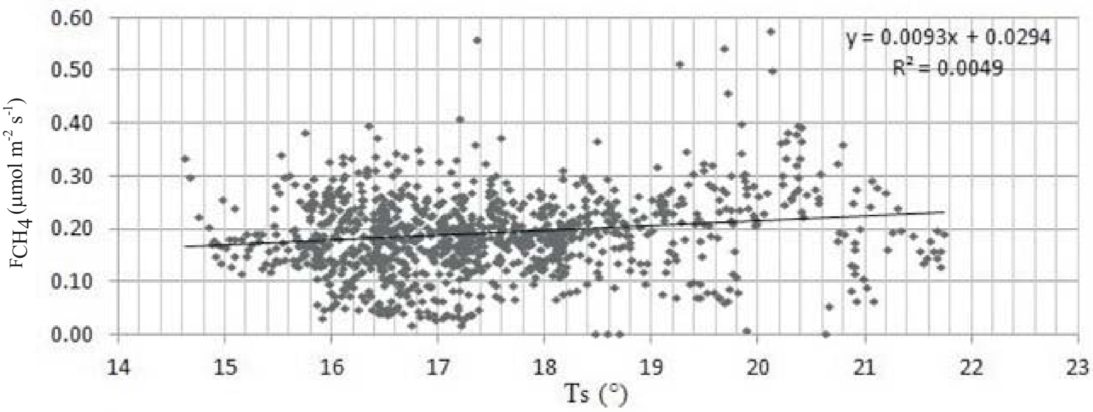

Fig. 7. Methane efflux (F_{CH_4}) versus substrate temperature (Ts) measured at 5 cm depth.

DISCUSSION

The wetland studied has a complex structure of vegetation with different dominant vegetation types in the different parts of the area (Chojnicki, 2007). Thus, the values of both F_{CH_4} and F_{CO_2} observed and their diurnal cycles obtained by application of the eddy covariance technique vary depending on the vegetation type, and wind direction was used to determine above which area the air comes.

The highest averaged methane efflux during the study period was reported from the area covered by vegetation dominated by sedges (wind sector III), while the lowest emission was found from the reed/cattail habitat (wind sector I) (Fig. 5). The highest emission rate from WDS III and the lowest from WDS I suggests that presence of reed and cattail plants reduces F_{CH_4}. These results are similar to flux values observed in North East Siberia (Parmentier, 2011).

Methane production is a result of organic matter decomposition in anoxic conditions. Organic matter is a product of photosynthesis; therefore, long-term CH_4 production depends on F_{CO_2}. There is a clear daily pattern in F_{CH_4} from sectors WDS I and WDS IV, which is inverse to that of F_{CO_2}. The diurnal pattern of CH_4 emission can be explained by the convective gas flow in reed, which is absen t in sedges (Riutta *et al.*, 2007). The pronounced diurnal pattern of F_{CH_4} from reed/cattail sector indicates that these plants influence the F_{CH_4} daily dynamics via convective gas transport in their bodies. The relatively low emission from this area supports this hypothesis, since the convective flow would also aerate the root zone reducing the emission rate from this area. The presence of cattail and sparse reed within WDS IV can also explain the daily pattern of F_{CH_4} and averaged low emission (Kim *et al.*, 1998).

The lack of reed and cattail plants in the areas within sectors II and III lead to absence of the diurnal pattern in F_{CH_4} from these sectors (Fig. 6II and 6III). Even though the aerenchyma of sedges does serve as a conduit for gas transport from the root zone to the atmosphere, this transport proceeds through diffusion and does not create a diurnal pattern. It has been well established that the impact of plant processes on the net CH_4 emission is important. Plants can influence the methane emission through different ways (King *et al.*, 1998). Many studies show that plants play a significant role in determining net CH_4 emissions through transport (Shannon *et al.*, 1996; Yavitt and Knapp, 1995). In one study, the CH_4 emission from a measurement site overgrown by sedge was higher than the emission from sites without sedge coverage. The influence of sedges on methane emission was observed also in other studies (Thomas *et al.*, 1996).

Methane production in a substrate is dependent on its temperature (Juszczak *et al.*, 2012b). However, we did not observe a strong dependence of CH_4 net emission on temperature (Fig. 7). For comparison, the correlation between methane flux and soil temperature (measured at 20 cm depth) in arctic polygonal tundra was very strong, and R^2 =0.67 (Wille *et al.*, 2008). The strongest dependence is supposed to be found in long term Ts versus F_{CH_4} dependence.

The dependence between the methane efflux and net carbon dioxide exchange in an hourly-time scale is not strong and only a weak correlation between those two fluxes was observed (Fig. 8I, 8II, 8III, 8IV).

The observations presented in this paper support the hypothesis about varying influences of different vascular plants to the methane transport from the root zone to the atmosphere. The different diurnal patterns of methane emission observed from the different vegetation types indicate differences in transport mechanisms in *Phragmites* and in *Carex*. The more effective aeration of the root zone by *Phragmites* can also reduce methane emission from this vegetation type.

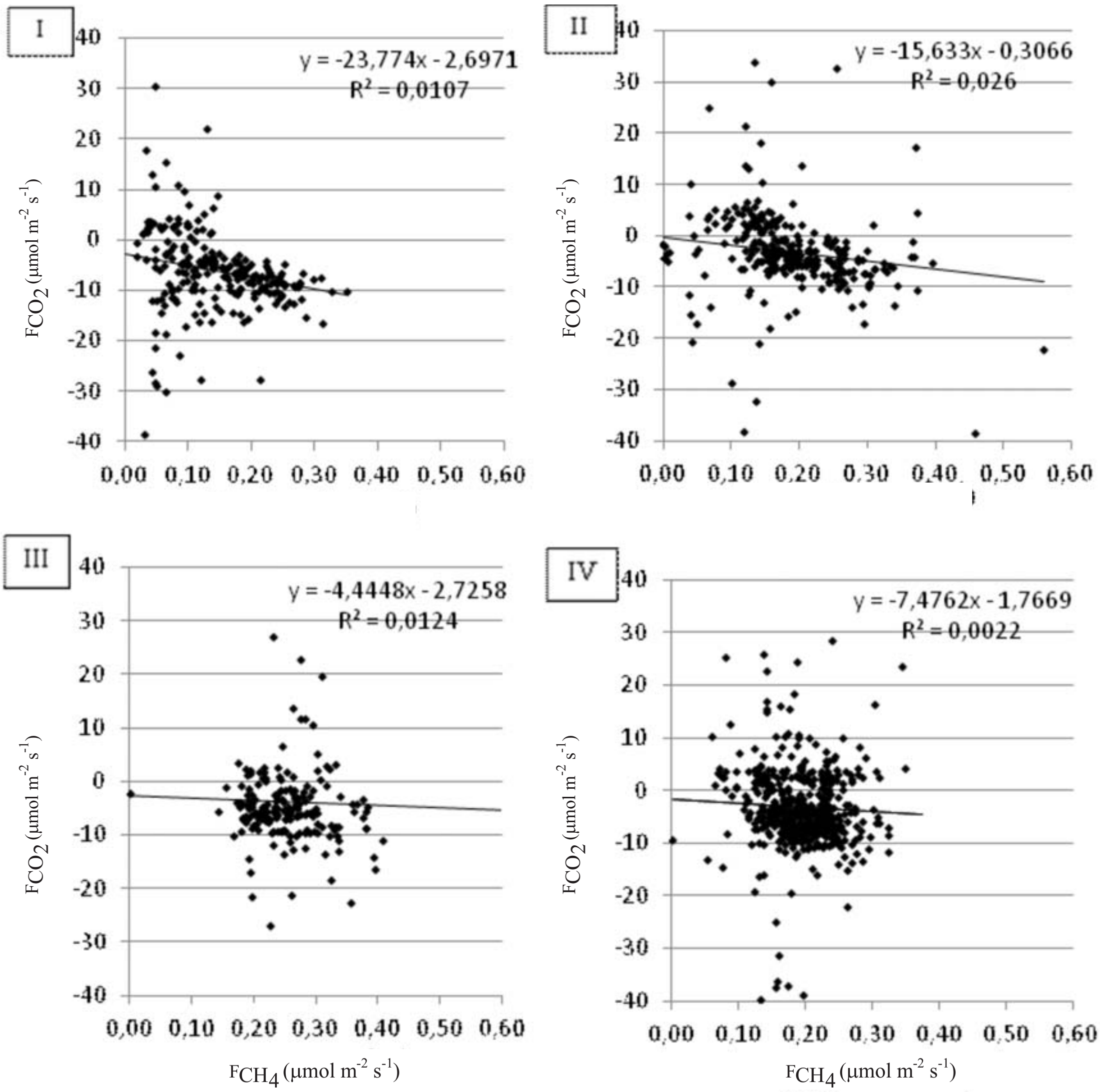

Fig. 8. Net ecosystem exchange (F_{CO_2}) versus methane efflux (F_{CH_4}). I, II, III, IV – wind sectors.

CONCLUSIONS

1. There was no clear dependence between methane efflux and either soil water depth or substrate temperature due to the shortness of the study period during the warmest months of the summer.

2. The highest methane efflux was observed from the sedge covered area, while the presence of reed and cattail plants caused the lowest emission from the northern part of the site studied.

3. There was a distinct daily dynamics of methane emission from the reed covered areas, which was absent in the sedge covered areas. This can be explained by convective gas transport in reed, which does not occur in sedges. Both low emission and daily runs of methane efflux is an effect of reed and cattail aerating properties.

REFERENCES

Armostrong W., Armstrong J., Beckett P.M., 1991. Convective gas-flows in wetland plant aeration. In: Plant Life Under Oxygen Deprivation (Eds M.B. Jackson, D.D. Davies, H. Lambers). SPB Academic Press, the Hague, The Netherlands.

Aurela M., Laurila T., and Tuovinen J.P., 2001. Seasonal CO_2 balances of a sub-arctic mire. J. Geophys. Res., 106, 1623-1637.

Baldocchi D.D., 2003. Assessing the eddy covariance technique for evaluating carbon dioxide exchange rates of ecosystems: past, present and future. Global Change Biol., 9, 479-492.

Chojnicki B.H., Michalak M., Konieczna N., and Olejnik J., 2012. Sedge community (*Caricetum elatea*) carbon dioxide exchange seasonal parameters in a wetland. Polish J. Environ. Stud., 21(3), 579-587.

Chojnicki B.H., Urbaniak M., Józefczyk D., Augustin J., and Olejnik J., 2007. Measurement of gas and heat fluxes at Rzecin wet-land. In: Wetlands: Monitoring, Modeling and Management (Ed. T. Okruszko). Taylor Francis Group Press, London, UK.

Christiansen J.R., Korhonen J., Juszczak R., Giebels M., and Pihlatie M., 2011. Assessing the effects of chamber placement, manual sampling and headspace mixing on CH_4 fluxes in a laboratory experiment. Plant Soil, 343, 171-185.

Farat R., Mager P., and Pijewska I., 2004. Climate Atlas of the Wielkopolska region. Institute of Meteorology and Water Management, Poznań Branch, Poland.

Foken T. and Wichura B., 1996. Tools for quality assessment of surface-based flux measurements. Agric. For. Meteorol., 78, 83-105.

Hendriks D.M.D., Dolman A.J., and van der Molen M.K., and van Huissteden J., 2008. A compact and stable eddy covariance set-up for methane measurements using off-axis integrated cavity output spectroscopy, Atmos. Chem. Phys., 8, 1-13.

Juszczak R., 2013. Biases in methane chamber measurements in peatlands. Int. Agrophys., 27, 159-168.

Juszczak R., Acosta M., and Olejnik J., 2012a. Comparison of daytime and nighttime ecosystem respiration measured by the closed chamber technique on temperate mire in Poland. Polish J. Environ. Stud., 21(3), 643-658.

Juszczak R., Humphreys E., Acosta M., Michalak-Galczewska M., Kayzer D., and Olejnik J., 2012b. Ecosystem respiration in a heterogeneous temperate peatland and its sensitivity to peat temperature and water table depth. Plant and Soil, DOI 10.1007/s11104-012-1441-y.

Kim J., Verma S.B., and Billesbach D.P., 1998. Seasonal variation of methane emission from a temperate *Phragmites* -dominated marsh: effect of growth stage and plant- mediated transport. Global Change Biol., 5, 433-440.

King J.Y., Reeburgh W.S., and Shannon K.R., 1998. Methane emission and transport by arctic sedges in Alaska: Results of a vegetation removal experiment. J. Geophys. Res., 103(D22), 29083-29092.

Kroon P.S., Hensen A., Jonker H.J.J., Ouwersloot H.G., Vermeulen A.T., and Bosveld F.C., 2009. Uncertainties in eddy covariance flux measurements assessed from CH_4 and N_2O observations, Agric. Forest Meteorol., 150, 806-816.

Kroon P.S., Hensen A., Jonker H.J.J., Zahniser M.S., van't Veen W.H., and Vermeulen A.T., 2007. Suitability of quantum cascade laser spectroscopy for CH_4 and N_2O eddy covariance flux measurements. Biogeosciences, 4, 715-728.

Kutilek M., 2011. Soils and climate change. Soil Till. Res., 117, 1-7.

Launiainen S., Rinne J., Pumpanen J., Kulmala L., Kolari P., Keronen P., Siivola E., Pohja T., Hari P., and Vesala T., 2005. Eddy covariance measurements of CO_2 and sensible and latent heat fluxes during a full year in a boreal pine forest trunk-space. Boreal Environ. Res., 10(6), 569-588.

Lee X., Massman W., and Law B.E., 2004. Handbook of micrometeorology. A Guide for Surface Flux Measurement and Analysis. Kluwer Press, Dordrecht, the Netherlands.

Lund M., Lafleur P.M., Roulet N.T., Lindroth A., Christensen T.R., Aurela M., Chojnicki B.H., Flanagan L.B., Humphreys E.R., Laurila T., Oechel W.C., Olejnik J., Rinne J., Schubert P., and Nilsson M.B., 2010. Variability in exchange of CO_2 across 12 northern peatland and tundra sites. Global Change Biol., 16(9), 2436-2448.

Parmentier F.J., 2011. Any Way the Wind Blows Dynamics of Greenhouse Gas Exchange in Northeastern Siberian Tundra. PhD. Thesis, VU University Amsterdam, The Netherland.

Rinne J., Riutta T., Pihlatie M., Aurela M., Haapanala S., Juha-Pekka T., Eeva-Stiina T., and Vesala T., 2007. Annual cycle of methane emission from a boreal fen measured by the eddy covariance technique. Tellus, 59B, 449-457.

Riutta T., Laine J., Aurela M., Rinne J., VesalaT., Laurila T., Haapanala S., Pihlatie M., and Tuittila E.S., 2007. Spatial variation in plant community functions regulates carbon gas dynamics in a boreal fen ecosystem. Tellus, 59B, 838-852.

Schrier-Uijl A.P., Kroon P.S., Hensen A., Leffelaar P.A., Berendse F., and Veenendaal E.M., 2009. Comparison of chamber and eddy covariance based CO_2 and CH_4 emission estimates in heterogenous grass ecosystem on peat. Agric. For. Meteorol., doi:10.1016/j. agrformet. 11.007

Shannon R.D., White J.R., Lawson J.E., and Gilmour B.S., 1996. Methane efflux from emergent vegetation in peatlands. J. Ecol., 84, 239-246.

Sorrel B.K. and Hawes I., 2010. Convective gas flow development and the maximum depths achieved by helophyte vegetation in lakes. Annals Botany, 105, 165-174.

Thomas K.L., Benstead J., Davies K.L., and Lloyd F., 1996. Role of wetland plants in the diurnal control of CH_4 and CO_2 fluxes in peat, Soil Biol. Biochem., 28, 17-23.

Wille C., Kutzbach L., Torsten S., Wagner D., and Pfeiffer E.M., 2008. Methane emission from Siberian arctic polygonal tundra: eddy covariance measurements and modeling. Global Change Biol., 14, 1395-1408.

Yavitt J.B. and Knapp A.K., 1995. Methane emission to the atmosphere through emergent cattail (*Typha latifolia* L.) plants. Tellus, 47B, 521-534.