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Seasonal variability as a source of uncertainty in the West Siberian regional CH_4 flux upscaling

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Abstract

This study compares seasonal and spatial variations in methane fluxes as sources of uncertainty in regional CH_4 flux upscaling from the wetlands of West Siberia. The study examined variability in summertime CH_4 emissions from boreal peatlands, with a focus on two subtaiga fen sites in the southern part of West Siberia (Novosibirskaya oblast). We measured CH_4 flux, water table depth, air and peat temperature, pH and electric conductivity of peat water during three field campaigns in summer 2011 (9–12 July, 26–28 July and 20–21 August). Fluxes were measured with static chambers at sites chosen to represent two of the most widespread types of wetlands for this climatic zone: soligenous poor fens and topogenous fens. In both sites the water table level acts as the primary control on fluxes. For the poor fen site with good drainage, water table controls CH_4 fluxes on the seasonal scale but not on a local spatial scale; for the fen site with weak drainage and microtopographic relief, the water table controls fluxes on the local spatial scale, but does not drive seasonal variations in the flux magnitude. This difference in hydrology shows the necessity of including detailed wetland type classification schemes into large-scale modeling efforts. From these three measurement periods, we estimated the relative seasonal variation in CH_4 emissions as 8% for the fen site and 26% for the poor fen site. These results were compared to estimates of other sources of uncertainty (such as interannual variation and spatial heterogeneity) to show that quantifying seasonal variability is less critical than these other variations for an improved estimate of regional CH_4 fluxes. This research demonstrates and ranks the challenges in upscaling measured wetland CH_4 fluxes across West Siberia and can guide future field campaigns.

Keywords: methane emission, mires, seasonal cycle, West Siberia

1. Introduction

High-quality, quantitative estimates of the CH_4 budget are crucial to predicting climate change, managing Earth's carbon reservoirs, and understanding atmospheric chemistry (Mikaloff-Fletcher *et al* 2004). Therefore, the contribution of different sources to the atmospheric concentration of CH_4 is important to determine in addressing the problem of global warming (Heimann 2011). Since wetlands are considered to be the major natural source of methane, accurate estimation of their emissions at the regional scale is required (Fung *et al* 1991) though a recent model inter-comparison project still reveals significant disagreement in simulated CH_4 emissions (Melton *et al* 2013).

West Siberia has a special importance in this respect as it is one of the most paludified regions in the world with a mire area of 68.5 Mha or 27% of the region's area (Peregon *et al* 2009). However, several estimates based on field studies exhibit a large spread in annual regional fluxes, from 2 (Bleuten 2007) to >22 $MtCH_4$ yr^{-1} (Panikov 1995), as reviewed previously (Glagolev *et al* 2012). Closer examination of these studies (Glagolev *et al* 2008) attributed this uncertainty to a lack of field measurements. Furthermore, the extrapolation of higher flux measurements taken in southern zones to northern zones has likely generated over-estimates at the higher end of the range (Bohn *et al* 2013). Aiming at the reliable estimation of the regional emission from West Siberia mire systems, a long-term (2007–2011) and large-scale (from forest steppe to tundra wetlands of Western Siberia) investigation was organized resulting in a narrower estimate range of 2.6–5.2 $MtCH_4$ yr^{-1} (Glagolev *et al* 2011). This estimate was obtained using an inventory concept of methane emissions (Glagolev *et al* 2011), and using the so-called standard model (Glagolev *et al* 2012). This model generates a bottom-up estimate of West Siberian wetland methane emissions by multiplying the average emission rates of each mire ecosystem type with the area coverage of these ecosystems and accounts for changes in the length of the peak methane production period for each zone.

Such bottom-up inventories are susceptible to several categories of errors leading to the incorrect evaluation of the resulting flux estimate:

- unrepresentative data about methane fluxes caused by a limited number of potentially non-representative field observations and strong flux variability among the different sites and observation periods;
- the low quality of wetland maps upon which to define the relative area of different wetland ecosystems;
- uncertain estimates of the length of the methane emission period (MEP).

In this study we do not take into consideration errors introduced by potential mistakes in mapping (Frey and Smith 2007) and rely on a map of West Siberia dividing the region into 8 bioclimatic zones and reducing of the natural range of wetland forms to 8 wetland typologies (Peregon *et al* 2008, 2009). Of the contributors to upscaling uncertainty, we analyze questions of flux variability and the duration of the MEP. We compare uncertainties in the regional flux estimate from the following four contributing factors:

- interannual variability;
- seasonal variability (caused by seasonal changes of the environmental factors controlling CH_4 emissions);
- variability among different mires (caused by local climate, hydrology or geochemistry);
- spatial variability within the mire ecosystem (caused by local microrelief, plant or microbial communities).

In this study attention is paid to contributors of both spatial and seasonal variability. There are only a few studies of the seasonal variability of methane emission from Russian mires. Most of these studies have focused on tundra mires (Nakano *et al* 2000, Heikkinen *et al* 2002, 2004, Wagner *et al* 2003, Sachs *et al* 2010, etc) and the south taiga zone of Western Siberia (Friborg *et al* 2003, Krasnov *et al* 2013). In other climate zones the seasonal dynamics have not been studied specifically despite comparatively high methane emissions and seasonal changes in water temperature and phenology, including middle and north taiga wetland lakes (Repo *et al* 2007), forest–tundra and north taiga bogs (Naumov *et al* 2007), and forest-steppe bogs (Naumov 2011). The relative weight of the climate factors driving seasonal variations in methane emissions may also differ between zones. For example, the period when emissions from wet sites exceed 2 $mgCH_4$ m^{-2} h^{-1} has been estimated as 70 days for a tundra site (Heikkinen *et al* 2004) and 125 days for a south taiga site (Friborg *et al* 2003) even though the mean July fluxes are similar for these sites (about 7.5 $mgCH_4$ m^{-2} h^{-1}). In this sense, extrapolation of seasonal dynamics obtained in one zone to another zone could lead to a critical bias in the regional estimate. Thus, it is necessary to investigate seasonal dynamics in each climatic zone, an investigation missing in previous work (including Glagolev *et al* 2011). In this paper we estimate uncertainty deriving from seasonal variations in methane emissions and try to understand how knowledge of these variations improves the regional CH_4 flux estimate from West Siberian wetlands in comparison with other sources of uncertainty. Then several weak points of the inventory method are examined by comparing different contributors of uncertainty and suggest an optimal field campaign strategy.

The objectives of the study were (i) to quantify the uncertainty in the flux estimation caused by the seasonal variation of environmental parameters in a case study from two study sites within the subtaiga zone (a zone of deciduous birch-aspen forests); (ii) to compare the relative importance of different contributors to uncertainty on the regional flux estimate and (iii) to identify the main controlling factors which influence seasonal dynamics of CH_4 fluxes.

2. Materials and methods

2.1. Test sites

The field experiments were carried out during the 2011 summer period. For comparability, these measurements were taken in the same season as the majority of the measurements in a previous study (Glagolev *et al* 2011): 9–12 July, 26–28 July and 20–21 August. Methane fluxes were measured at two test sites in the subtaiga zone of Western Siberia:

'Biaza' (56.50°N, 78.31°E) a topogenous fen, and 'Chuvashi' (56.41°N, 78.80°E), a soligenous poor fen, according to a Russian mire classification scheme (Masing *et al* 2010). Detailed test site descriptions are in appendix A.

2.2. Study methods

2.2.1. CH_4 flux measurements. CH_4 exchange to the atmosphere was measured using the static, opaque chamber method, in 82 measurements each at the fen and poor fen mires. Of these measurements, triplicate measures at each chamber site were taken to average short-term variations in flux strength. The chamber consisted of two parts: (i) a permanent stainless steel square collar (40 cm × 40 cm, embedded 15 cm into the peat surface), and (ii) a removable plexiglass box (30 or 40 cm height). To minimize the changes of chamber temperature, the plexiglass box was covered with reflecting aluminum fabric. Mechanical disturbances of the peat layer were minimized by using portable or permanent footbridges.

The fan-mixed chamber headspace was sampled at four equal intervals and the CH_4 concentration in these samples was measured on a calibrated gas chromatograph (see appendix B for details). Methane fluxes were calculated from linear regression with weights inverse to concentration measurement uncertainty (Kahaner *et al* 1989) for the chamber headspace CH_4 concentration versus measurement time. Throughout the manuscript the convention that CH_4 fluxes to the atmosphere are positive is adopted.

At each site the following environmental characteristics were measured: air and peat temperatures (at the depths of 0, 5, 15, 45 cm) by the temperature loggers 'TERMOCHRON' iButton DS 1921–1922 (DALLAS Semiconductor, USA), pH and electrical conductivity by a Combo 'Hanna 98129' ('Hanna Instruments', USA) and concentration of dissolved oxygen by an 'Ecotest-2000' ('ECONYX', Russia). Botanical descriptions were also made to describe the vegetation community within each chamber site.

2.2.2. Data analysis. The STATISTICA 8 software ('StatSoft', USA) was used for statistical analyses. Ordinary-least square regression ($\alpha = 0.05$) is used to determine the significance of the relationship between the environmental variables and measured CH_4 flux (averaged across the three temporal replicates). Stepwise multiple regressions ($\alpha = 0.05$) included parameters for air T_{air} and peat temperatures T_0, T_5, T_{15}, T_{45} at the depths of 0, 5, 15, 45 cm respectively (°C), minimal, mean and maximal pH and electric conductivity (μS cm^{-1}) pH_{min}, pH_{mean}, pH_{max}, EC_{min}, EC_{mean}, EC_{max}, and water table level WTL (cm). The variables from this list that were not statistically significant were omitted from the reported results of the multiple regression analyses.

2.2.3. Mire ecosystem concept. The objectives of this study are based on an assumption that even in complex mire landscapes, areas that are similar in geochemical and hydrological conditions and have homogeneous vegetation cover can be distinguished. Consequently, these areas have similar methane production and consumption rates. In this study these units are called 'mire ecosystems'. This term is equivalent to the term 'mire micro-landscape' used in Peregon *et al* (2008, 2009) and Glagolev *et al* (2011). From the diversity of mire ecosystems, in this study we focused only on fens (various types of minerotrophic fens, poor fens and wooded swamps). The full diversity of Russian mire ecosystems has been described elsewhere (Masing *et al* 2010).

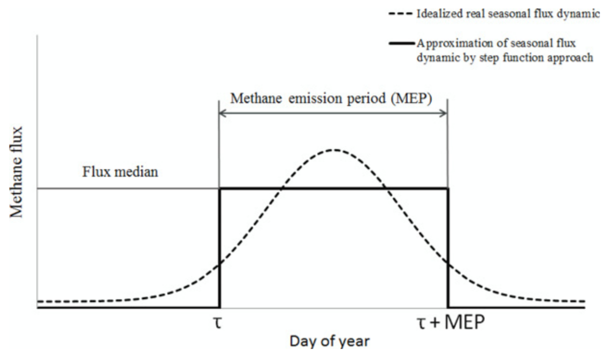

Figure 1. Schematic representation of the step function approach for approximation of seasonal CH_4 flux dynamics (see text for details).

2.2.4. The methane emission period model. The inventory concept (as well as other inventories, for example, Bartlett and Harriss 1993, Christensen *et al* 1995, Wang *et al* 2005) accounts for seasonal variations of methane emissions by dividing the year into three periods (Suvorov and Glagolev 2007). The methane flux is first assumed to increase from winter to summer and then after peaking it regularly decreases (figure 1). In the modeled version a step function is used to represent this seasonality, where the flux is

(a) zero: from the beginning of the year to the day τ corresponding to the beginning of the methane emission period (MEP);
(b) the flux median for each mire ecosystem types in each climatic zone: from τ to $\tau + \text{MEP}$, corresponding to the end of MEP;
(c) zero: from $\tau + \text{MEP}$ to the end of the year.

The parameters defining the MEP were chosen on (1) the basis of the biologically active period whose start is determined from the date when mean daily air temperature becomes higher than 10 °C and ends the when mean daily temperature becomes lower than 0 °C (Rihter 1963) and (2) the analysis of seasonal variations in methane flux from several south taiga wetlands. For the south taiga zone, the MEP was calculated as the ratio of the total emission in the snow-free period (calculated by a numerical integration of the methane emission curve during the snow-free period) and the median flux from the same wetland and was about 10% longer than the biologically active period (Suvorov and Glagolev 2007). Because the MEP is derived from the median value of the flux measurements and the integrated annual flux, asymmetry in the flux measurement distribution would not distort the use of the median (Glagolev *et al* 2010). The MEP values for other zones were calculated assuming that their MEP value is proportionately larger than the biological activity period by as much as the MEP value is larger than biological activity period in the south taiga.

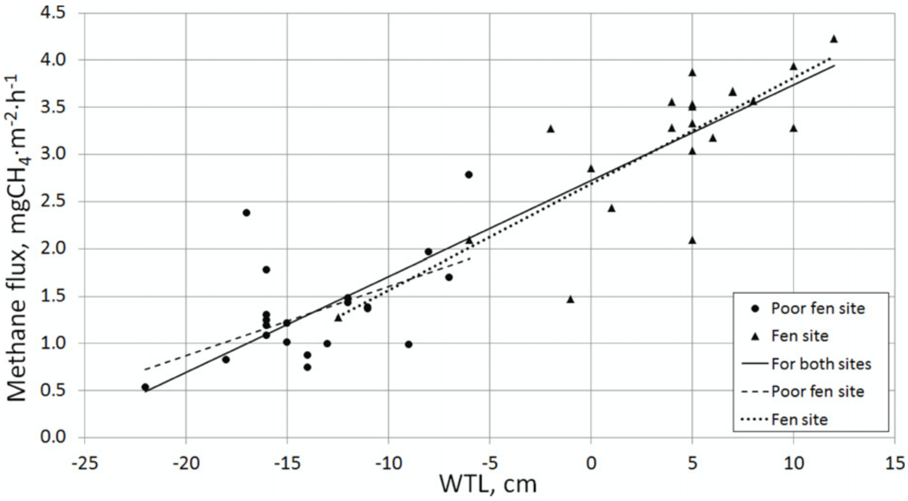

Figure 2. Individual water table level versus CH_4 flux (the median flux of each triplicate measurement session at each chamber site). All relationships are significant ($\alpha = 0.05$). Regression lines are shown for both sites ((CH_4 flux) = (0.10 ± 0.01)(WTL) + 2.72 ± 0.08, $R^2 = 0.82$), for the poor fen site ((CH_4 flux) = (0.07 ± 0.03)(WTL) + 2.33 ± 0.38, $R^2 = 0.28$), for the fen site ((CH_4 flux) = (0.11 ± 0.02)(WTL) + 2.68 ± 0.13, $R^2 = 0.64$).

3. Results

3.1. CH_4 fluxes

Fluxes from the two field sites are reported in appendix C and table 1. At the fen site, the CH_4 fluxes were found always higher compared to the poor fen site (the median across the summer season at the fen site is 3.20 mgCH_4 m^{-2} h^{-1}). The fen site fluxes showed a clear seasonal trend, with the occurrence of the lowest fluxes at the beginning of July followed by an increase in the each measurement period's median flux until the end of August. The water level was above the moss surface during most of the measurement periods at this site except for the beginning of July when it was slightly below the moss surface. At the poor fen site the average CH_4 fluxes were about one-third lower (the median for all seasons is 1.25 mgCH_4 m^{-2} h^{-1}) than the fen site and showed the highest median values in the second session of measurements in the end of July. There was more scatter in these data during the final measurement period, with the highest fluxes (2.83 mgCH_4 m^{-2} h^{-1}) measured then. The water level in the poor fen site remained 10 cm below the moss surface and never reached the surface during the full measurement period.

Typically, the uncertainty of the individual measurements was around ±0.2 mgCH_4 m^{-2} h^{-1} for both sites, with the highest uncertainty contributed by scatter in the measured gas concentrations. The temporal variability within the test site was estimated as the standard deviation of the average across the three measurements taken in a row (i.e., within 1.5 h) and was also around 0.2 mgCH_4 m^{-2} h^{-1}.

3.2. Seasonal variability

The relative seasonal variability (calculated as the ratio between the standard deviation of the median flux of each measurement session to median fluxes across the whole season) were 26% and 8% for the poor fen and fen, respectively. The significantly higher seasonal flux variations in the poor fen derive from seasonal fluctuations of the water table level. In the second half of July precipitation in this region was high (about 120 mm) and resulted in a ~40 mm rise in the water table of both study sites (see table 1). At the end of August the hydrological conditions were changed: the poor fen with the better drainage became slightly dryer, while the inundation level of the weakly drained fen continued to grow. Thus, the water table level of the poor fen varied more widely across the measurement period. Since both mires have similar regression lines between CH_4 flux and water table level, their hydrological differences resulted in a higher variability of methane emissions in the poor fen.

3.3. Controls on CH_4 fluxes

Regression analysis revealed that it was possible to construct a multidimensional model with independent and significant parameters for all microsites as well as separately for the fen and poor fen (figure 2). The model for all microsites (F_a, mgCH_4 m^{-2} h^{-1}) contains WTL and T_{15}:

$$F_a = 5.13 \pm 0.91 + (0.086 \pm 0.009)\mathrm{WTL} - (0.19 \pm 0.07)T_{15}; \qquad R^2 = 0.83,$$
$$\mathrm{RMSE} = 0.45 \text{ mgCH}_4 \text{ m}^{-2} \text{ h}^{-1}.$$

The model of CH_4 fluxes in the fen (F_f, mgCH_4 m^{-2} h^{-1}) also contains WTL and T_{15} as explanatory variables:

$$F_f = 4.74 \pm 0.98 + (0.11 \pm 0.02)\mathrm{WTL} - (0.17 \pm 0.08)T_{15}; \qquad R^2 = 0.77,$$
$$\mathrm{RMSE} = 0.42 \text{ mgCH}_4 \text{ m}^{-2} \text{ h}^{-1}.$$

For the poor fen (F_{pf}, mgCH_4 m^{-2} h^{-1}), WTL and pH_{mean} are the key explanatory variables:

Table 1. Dynamics of CH_4 fluxes and their main environmental controls (± standard deviation) during the 2011 summer period (negative or positive values of the water table level (WTL) correspond to situations when WTL is lower or higher than the mean level of the moss surface, respectively).

	9–12 July		26–28 July		20–21 August	
Parameter	Fen	Poor fen	Fen	Poor fen	Fen	Poor fen
Median of CH_4 flux ($mgCH_4\ m^{-2}\ h^{-1}$)	2.89 ± 0.39	0.89 ± 0.29	3.24 ± 0.98	1.62 ± 0.68	3.56 ± 0.49	1.31 ± 0.34
Number of measurements	28	36	36	27	18	19
Mean WTL (cm)	−0.3 ± 1.3	−16.5 ± 2.9	3.7 ± 3.9	−11.4 ± 2.9	5.6 ± 1.4	−13.7 ± 4.1
Mean temperature at 5 cm depth (°C)	14.0 ± 0.1	15.4 ± 0.3	15.2 ± 1.5	15.7 ± 0.8	12.2 ± 0.2	16.5 ± 1.6
Mean temperature at 15 cm depth (°C)	13.1 ± 0.2	12.3 ± 0.2	13.3 ± 1.1	14.1 ± 0.9	11.0 ± 0.1	13.2 ± 0.2
Mean pH of peat water for upper 50 cm of peat	6.36 ± 0.10	4.78 ± 0.18	6.26 ± 0.12	5.15 ± 0.09	6.1 ± 0.15	5.38 ± 0.11
Mean EC of peat water for upper 50 cm of peat ($\mu S\ cm^{-1}$)	133 ± 19	43 ± 19	121 ± 24	48 ± 20	149 ± 33	42 ± 10

$$F_{pf} = (0.07 \pm 0.02)\mathrm{WTL} + (0.45 \pm 0.06)\mathrm{pH}_{mean};$$
$$R^2 = 0.92, \qquad \mathrm{RMSE} = 0.43\ \mathrm{mgCH_4\ m^{-2}\ h^{-1}}.$$

A simple one-dimensional regression reveals that for both sites as well as for each site separately WTL is the single best predictor of emissions (where the median flux for the three temporal replicate measurements is used; see table 2). For the poor fen site, the peat water chemical characteristics (EC and pH) are also significant. Conversely, for the fen site only T_5 and T_{15} are also significant. The highest deviations from the WTL regression curve for the fen site (i.e., the two significantly lower values) may be caused by the relatively small coverage of vascular plants (10–20%) compared to the other points whose coverage is more than 30%. For the poor fen site, the substantially higher and lower residuals were correlated with the highest and the lowest values of pH_{max}, respectively.

Table 2. Coefficients of determination of simple regressions between environmental parameters and CH_4 flux for the sites grouped together and for each site separately. Bold font indicates the significance level ($\alpha = 0.05$).

Environmental variable	Both sites	Poor fen	Fen
WTL	**0.82**	**0.28**	**0.64**
T_{air}	**0.27**	0.07	0.04
T_0	**0.39**	0.01	0.15
T_5	**0.31**	0.01	**0.21**
T_{15}	**0.15**	0.01	**0.25**
T_{45}	**0.54**	0.16	0.21
pH_{min}	**0.55**	**0.23**	0.12
pH_{mean}	**0.46**	**0.26**	0.19
pH_{max}	**0.58**	**0.27**	0.12
EC_{min}	**0.35**	**0.19**	0.19
EC_{mean}	**0.49**	**0.22**	0.11
EC_{max}	**0.44**	0.14	0.15

4. Discussion

4.1. Seasonal variability

The seasonal variation of our methane flux data is 8% for the fen with weak drainage and 26% for the poor fen site with relatively good drainage. Similar calculations using various published data (Heikkinen *et al* 2002, 2004, Friborg *et al* 2003, Ding and Cai 2007) give the seasonal variation of 11–30% (see table 3). For the fen intermediate flark site (Heikkinen *et al* 2004) the relative seasonal variability is 11% and for non-degraded and slightly degraded polygon tundra sites (Sachs *et al* 2010) it was 21% and 16%, respectively. Because other fen sites even in different climatic zones also have seasonal variability sufficiently less than 30%, this low variation may be presumed to be a general pattern for fens. In their general characteristics these mires are similar—they all are fens on watersheds with relatively shallow peat depth and weak drainage (caused by clay parent rock or permafrost). In general the bell-shaped curve of methane emission for Western Siberia mires has two main contributors, which are the similarly shaped seasonal precipitation and air temperature curves (Heikkinen *et al* 2004, Naumov *et al* 2007, Naumov 2011). Such a pattern is typical for all regions with a continental climate.

At this study's poor fen site, where water continuously drains from the mire during the summer period, the methane emissions generally follow the changes in WTL. This relationship has also been discovered for the poor fen site in Friborg *et al* (2003) and the bog site in Ding and Cai (2007). As an example, the seasonal dynamics from Friborg *et al* (2003) were successfully predicted with a WTL model (Bohn *et al* 2007). But if the drainage from a fen is very poor, then there is often no significant correlation between WTL and CH_4 flux and only temperature acts as a control of emission (e.g., Heikkinen *et al* 2004, Sachs *et al* 2010). Thus based on the available data two types of seasonal emission dynamics could be defined:

(1) with a significant correlation between CH_4 fluxes and WTL on a seasonal time scale as typical for the raised

Table 3. Comparison of different sources of CH_4 flux variability for West Siberian and ecologically similar wetlands.

Type of variability	Level of relative variability[a] (%)	Contributing flux range[b] ($mgCH_4\ m^{-2}\ h^{-1}$)	Number of contributing measurements	References	Notes
Interannual variability	±61	2–6	200	Heikkinen *et al* (2002, 2004)	For 2 years (season average fluxes)
	±40	3–15	—[c]	Sasakawa *et al* (2012)	For 5 years (season average fluxes)
	±26	5.7–19.4	220	Panikov and Dedysh (2000) and Friborg *et al* (2003)	For 6 years (July average fluxes)
Intraseasonal variability[d]	±8	0.5–2.8	82	This study	Fen site
	± 26	1.2–4.3	82		Poor fen site
	±11 and ±28	1–12	46 and 46	Heikkinen *et al* (2004)	For 2 mires
	±21 and ±16	0.2–11.5	111 and 114	Sachs *et al* (2010)	For 2 sites
	± 29	1–11	80	Friborg *et al* (2003)	
	± 30	1–50	82	Ding and Cai (2007)	
Variability among different mires	Remains uncertain, may be more then	0.05–4.0	48	Glagolev *et al* (2010)	For 4 mires
		0.04–9.7	53	Glagolev *et al* (2012)	For 2 mires
Spatial within mire ecosystem	± 50%				
	±(20–30)	0.3–10.7	81	Glagolev *et al* (2012)	For 26 sites in 4 mires
	± 35	1.2–7.6	240	Sabrekov *et al* (2011)	For 9 sites in 1 mire

[a] The level of relative variability is defined as one half of interquartile range divided by median of methane flux sample and multiplied by 100% (a nonparametric analog of coefficient of variation) and the size of sample is presented in column 'Notes'.
[b] The contributing flux range is the range of flux values in each portion of the dataset used to derive the level of relative variability.
[c] Not available because in this work the methane emissions measured in 2005–2009 at two different sites were calculated using inverse modeling.
[d] Intraseasonal variability was calculated for the period for which the majority of flux data used for inventory in Glagolev *et al* (2011) was obtained—for late June–late August period.

bogs and transition (or soligenous) poor fens; the relative seasonal variability is about ±30% (Friborg *et al* 2003, Ding and Cai 2007);

(2) without a significant correlation between CH_4 fluxes and WTL on a seasonal time scale as typical for the poorly drained fens; the relative seasonal variability is ±(10–20)% (Heikkinen *et al* 2004, Sachs*et al* 2010).

The sites in our study also are in agreement with this pattern (see below in section 4.4). It additionally should be noted that local weather conditions and climatic anomalies can change this general pattern. However, the two divergent seasonal flux–WTL patterns should encourage the inclusion of detailed wetland type classification schemes into large-scale modeling efforts because different wetland types can have opposite responses to changing climate characteristics.

4.2. Comparison with other sources of variability

An estimate of seasonal variability can be compared with other sources of variability to determine the greatest contributor to uncertainty in the regional flux estimate. This comparison can help to generate more effective field campaigns to improve the quality of regional flux estimates. Contributions of other types of variability were determined using measurement data from a methane emissions database (Glagolev *et al* 2011) and elsewhere and are synthesized in table 3. The potential influence of diurnal variability was not analyzed in contrast with studies from China (Ding and Cai 2007), because significant evidence of CH_4 flux diurnal variations have not been found in previous West Siberian studies (Heyer *et al* 2002, Sabrekov *et al* 2011).

Unfortunately, there are not enough data to estimate variability among different mires properly. This type of variability is especially hard to determine in the field because fluxes in different places should be measured at more or less the same time. With the unknown strength of inter-mire variability and the high contribution of local heterogeneity in flux upscaling (table 3), we conclude that for regional flux estimates the spatial coverage of a field investigation is more critical than temporal coverage. We can then advise as a best strategy that field campaigns should investigate more sites with only a few days of observations per site. There may be diminishing benefits to conducting more than 50–70 flux measurements on each site, since according to table 3 this number is adequate to represent spatial variability within mire ecosystems and a greater number of measurements is not necessary. Improvements in constraining site-to-site variations in flux strength should lead to improvements of the regional flux estimate because they allow the aggregated flux estimate to incorporate spatial variations within the ecological diversity of mires. It will help to remove the highest uncertainties in the regional flux estimate despite the continued difficulty in accounting for interannual (including climate-related trends) and interseasonal variations.

The fact that spatial variability is of more importance than temporal variability implies that such factors as local hydrology, geochemistry, and plant community are more important than seasonal variations in environmental conditions. These factors can vary among different mires within one climatic zone (Glagolev *et al* 2010, 2012) and also within a single mire (Wagner *et al* 2003, Kutzbach *et al* 2004, Kao-Kniffin *et al* 2010), and hence should be evaluated with a spatially oriented sampling approach. These local factors may also be particularly susceptible to climate changes that induce shifts in vegetation community and regional hydrology. Furthermore, an emphasis on greater spatial, rather than temporal, coverage during field investigations may allow the detection of methane emission hot spots that can have proportionately large impacts on the regional estimate. This approach may generate a trade-off with 'hot moments' of flux emissions, such as through ebullition, although these events are often also missed in temporally intensive campaigns (Stamp *et al* 2013).

4.3. Other questions of seasonal dynamic variability

The seasonal variability of methane emissions needs analysis from some other points of view, including whether the step function approach is justified for climatic zones outside the south taiga. In this respect a comparison between the most northern (tundra) and the most southern zone (forest steppe) of West Siberia can be instructive. For the tundra zone the comparison can be based on measurements carried out near Vorkuta in the European part of Russia near the border with West Siberia (67.38°N, 63.37°E) (Heikkinen *et al* 2002, 2004). These studies indicate MEP values (95 days) similar to the MEP of 101 days used in Glagolev *et al* (2011). Wetlands of north-eastern China (47.58°N, 133.52°E) are close to the forest-steppe mires of Western Siberia by their climatic conditions (see the methane flux measurements in Ding and Cai 2007). For these mires the calculated value of MEP ranges between 195–210 days; thus slightly higher than the MEP of 196 days taken for forest steppe in Glagolev *et al* (2011). Therefore we can conclude that the MEP values reported in our previous regional flux estimate are reliable and therefore median is here a more statistically robust characteristic than the mean.

Another critical question is whether the method generates an overestimation of the regional flux because the median flux is calculated for the months with the most intensive methane emissions and is further multiplied by the MEP as calculated from flux data from the full snow-free period. The majority of the measurements used to calibrate the model (Glagolev *et al* 2011) were carried out during the period from late June to early September. In reality, methane fluxes become higher than the mean winter flux earlier (from April to beginning of June, depending on climatic zone) and decrease again only after the measurement period (i.e., from September to November, also depending on climatic zone). To determine this excess seasonal methane flux variation, data from other studies were analyzed. On a preliminary basis, our data was linearly interpolated on a daily basis to compensate for data gaps in different parts of the emission season. Other studies have suggested that the ratio of median fluxes for the entire snow-free period to the period from the end of June until the beginning of September was 0.8 for tundra mires (Heikkinen *et al* 2004), 0.65 for south taiga mires (Maksyutov *et al* 1999) and 0.54 for the Chinese analog of Siberian forest-steppe mires (Ding and Cai 2007). The reduction of this ratio from north to south probably results from the longer period of ideal methane production in the more southern zones. Thus, the artificial overestimation caused by measurements conducted in the most intensive periods of methane emission may be 20–45%, with greater errors in more southern climate zones.

Another question, arising from lack of flux data in spring and autumn periods, is the reliability of the estimate of seasonal variations. Of course when the wider time range is considered a higher level of seasonal variation is obtained: methane emissions starts from near-zero fluxes in the spring and decrease to near-zero in autumn. It is important to mention that our work is not about seasonal dynamics of methane emissions directly but about the influence of these variations on the regional flux estimate. The changes of the total warm season flux (which is the area under the curve of season emission) are determined due to uncertainties deriving from the seasonal dynamics of methane emissions. All of the data for the previous regional flux estimate (Glagolev *et al* 2011) were obtained for the late-June–late-August period and so the estimate of seasonal variability should be calculated within this time. According to the MEP concept the exact variation in fluxes from spring to autumn is not important, rather it is important how fluxes vary within the period for which our flux data was obtained. Of course, this period should not be very short. The summer flux is the largest part of the warm season flux (as described above it composes 65–90% of the total flux depending on the climatic zone). Thus, a lack of flux data in the spring and autumn periods is less critical for our analysis. But, for example, if the flux and seasonal variability had been measured only in July, it would become critical for the total warm season flux and variability estimation because the July flux is not the biggest part of the warm season flux. Calculating the potential overestimation in this case would also be statistically unfounded.

Seasonal methane flux dynamics are more or less symmetric relative to the maximum of the methane emission for West Siberia mires (this study, Maksyutov *et al* 1999, Friborg *et al* 2003 and Heikkinen *et al* 2004) or for ecologically similar mires from other regions (Ding *et al* 2004, Ding and Cai 2007). Taking into account this fact and the overestimation described above we can make a conclusion about the time of year when the observation would be most accurate from the seasonal dynamic point of view if it is possible to only observe fluxes on a few days of the year per site. These 'optimal' times are the end of the June through the beginning of the July and the second half of August. Measurements taken in these periods would both exclude the overestimation described above and will account for nearly all seasonal variations in flux strength. While this approach has some uncertainty, if the level of seasonal variability is not higher than 30% then the benefits of higher spatial coverage outweigh the potential error in temporal coverage.

4.4. Controls of CH_4 emissions

It was observed that CH_4 fluxes increased significantly with increases in the water table. This finding is generally expected because lower water table levels favor aerobic respiration and CH_4 oxidation (Dise *et al* 1993, Bubier *et al* 1995). A reduction in methane fluxes with increasing T_{15} does not fit a directly causal pattern (see Dise *et al* 1993 and Pelletier *et al* 2007 for counter observations) but can be caused by evapotranspiration. It has been suggested that greater evapotranspiration under the influence of higher soil temperatures will lower the water table and hence methane fluxes will decline (Moore and Roulet 1993, Ehhalt *et al* 2001). Also hummocks with lower WTL (and hence CH_4 flux) tend to have higher peat temperatures (see appendix C). Methane emissions in the poor fen are positively correlated with mean pH of the surface water. Because the poor fen is soligenous, the chemical characteristics of the peat water change during the season in response to hydrological events; the lack of such changes in the fen may help preclude a significant correlation with pH there. WTL may be the best predictor of emissions across a landscape because there has not been much variability observed in subsurface temperatures (Heikkinen *et al* 2004, Sachs *et al* 2010).

The sensitivity of CH_4 fluxes in subtaiga mires to WTL fluctuations (both in the multidimensional and one-dimensional models) was slightly higher than for mires of the same type in New Hampshire, USA (Treat *et al* 2007). Probably in the New Hampshire study the reduced fluxes result from a low WTL (30–40 cm below the surface) which results in a larger aerobic zone conducive to methane oxidation (see Kalyuzhnyi *et al* 2009). Fluctuations of WTL in this range do not play a significant role in the CH_4 flux. For example, in a previous peatland study (Pelletier *et al* 2007) WTL varied in range −30 to 20 cm, as well as in our investigation, and the coefficients are similar (0.10–0.13).

Generally, in our flux measurements we have both types of variability: seasonal and spatial within the mire ecosystem. To distinguish them the simple one-dimensional regression between CH_4 flux and WTL for each site for each of three sessions is provided (see table 4).

A comparison between the coefficients of determination in table 4 and table 2 reveals that for the fen site on the local spatial scale the correlation between WTL and CH_4 flux is as strong and significant as for whole fen site's combined data (where $R^2 = 0.64$, see table 2). Hence for the fen site the spatial variability of WTL is more important than seasonal changes in WTL. For the poor fen the WTL-flux relationship within a single measurement period is insignificant but taken together across the season, the correlation is significant (see table 2). Therefore, for the poor fen site the significance of the WTL-CH_4 relationship derives from correlated seasonal changes in both WTL and CH_4 flux while spatial variations for each measurement session do not generate significant correlation between WTL and CH_4 flux. However, the seasonal and spatial coefficients of determination are very similar, so both these potential sources of uncertainty should be considered.

Table 4. Coefficients of determination (R^2) of a simple regression between WTL and CH_4 flux for each test site and three measurement sessions. Bold font denotes significance ($\alpha = 0.05$).

Period	Poor fen (R^2)	Fen (R^2)
9–12 July	0.27	**0.86**
26–28 July	0.36	**0.71**
20–21 August	0.26	**0.49**

The higher correlations between CH_4 flux and environmental controls for both sites together rather than for each site separately (see table 2) may be explained by the higher importance of spatial variability in methane flux than seasonal variability—combining the datasets significantly increases the spatial sampling range while similar seasonal characteristics affect each site. The alternate explanation is that these findings are just an artifact of including only two mires that differ in mean flux and WTL values. The following normalization procedure was used to test these ideas: we compute the anomalies of CH_4 flux and environmental variables relative to long-term mean values of these quantities at each site and then compute a two-wetland simple one-dimensional correlation between the flux and driver anomalies. In this approach only the correlation with WTL was significant (the coefficient of determination (R^2) is 0.51). So for all variables from table 2 the higher correlations derived from combining the two peatlands are artifacts from combining two quite different mires.

5. Conclusions

The level of relative seasonal CH_4 flux variability for West Siberian mires in the subtaiga zone is 8% for the study's fen site and 26% for the poor fen site. Comparisons between our field data and other studies reveal at least two patterns of seasonal CH_4 flux variability typical for mires with different hydrological characteristics. Therefore the inclusion of more detailed wetland type classification schemes into large-scale modeling efforts should be encouraged. A comparison with other types of variability shows that seasonal variability is of less magnitude than interannual and spatial variability. These findings allow us to suggest that for regional flux estimates the spatial coverage of a field investigation is more important than temporal coverage. Thus we advise as a best field campaign strategy to investigate more sites (with only a few days of observations per site) and make not more than 50–70 well-chosen flux measurements on each site. While interannual and intraseasonal variability may also have some importance, improvements in the regional flux estimate from increased spatial coverage may produce similar reductions in the uncertainty window with less time and resources than a time-intensive multi-annual or multi-seasonal campaign.

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Appendix A. Detailed test site description

(1) 'Biaza' (56.50°N, 78.31°E) is located 10 km south from the Biaza settlement between the Tartas and Tara Rivers on a weakly drained watershed. This territory is occupied by fens dominated by tussock-forming sedges (*Carex cespitosa, Carex acuta*) and mosses (see figure A.1); the depth of the peat layer is less than 40 cm. Mire plants are mainly dependent on atmospheric nutrient supply, but because of the shallow peat depth, they can also derive minerals from the clay parent material. According to a mire classification scheme (Masing *et al* 2010), this mire is a topogenous fen because it has a high water table that is maintained by its topography. This type of mire is common throughout the subtaiga zone's wetlands (Peregon *et al* 2009).

(2) 'Chuvashi' (56.41°N, 78.80°E) is located on the terrace of the Tartas River 3 km north–north–west from the Chuvashi settlement. The test site belongs to the Vasyugan mire system. Measurements were made at hummocks and depressions of a birch-dominated poor fen dominated by *Menyanthes trifoliata*, *Comarum palustre* and sphagnum mosses (see figure A.2). The maximal height of elevations is 30 cm. Peat depth was about 1.5 m. According to the scheme of Masing *et al* (2010), this mire can be classified as soligenous poor fen because it has a high water table maintained by lateral water movement. This type of mire is also widespread in the subtaiga zone (Peregon *et al* 2009).

Figure A.1. Sedge fen with tussocks 'Biaza' (26 July 2011).

Figure A.2. Birch-dominated poor fen 'Chuvashi' (date of photo—24 July 2011).

Appendix B. Methane flux measurements

The air inside of the chamber was circulated by a battery-operated internal fan; a water channel on the chamber rim acted as a lock against leaks into or out of the chamber. The bottom of the collar was inserted into the soil at the depth of 10 cm at the time of about 15 min before the start of the measurements. Gas was sampled in equal intervals at the times $t_0 = 0$, t_1, t_2 and t_3 into nylon syringes ('SFM', Germany). The total measurement time ($\Delta t = t_3 - t_0$) was chosen according to the ecosystem type and varied from 21 to 60 min on the sites with a probably high and low fluxes respectively. Syringes were sealed by rubber stoppers and delivered to the laboratory.

Methane concentrations were measured by a gas chromatograph 'Crystal-5000' ('Chromatec' Co., Ioshkar-Ola, Russia) with an FID and column (3 m) filled by HayeSep Q (80–100 mesh) at 70 °C with nitrogen as a carrier gas (flow rate 30 ml min^{-1}). These measured concentrations were corrected based on a test experiment of leakage from the syringes between sampling and measurement, which found that an initial CH_4 concentration of 5 ppm decreased with the rate of 0.02% per hour.

Appendix C. CH_4 emission from subtaiga fen and poor fen of Western Siberia

See table C.1.

Table C.1. CH_4 emission from subtaiga fen and poor fen of Western Siberia.

Point number	Coordinates		Date	WTL (cm)[a]	pH	The most abundant species[b]	CH_4 fluxes (mgC m^{-2} h^{-1})	
	Latitude	Longitude					Mean	STD[c]
Subtaiga, Birch poor fen, 2011								
1	56.413 05	78.796 71	9.07	−16	4.9	*Men, Com, Fal*	1.08	0.05
							0.95	0.23
							0.90	0.04
2	56.413 03	78.796 68	9.07	−18	4.9	*Men, Com, Fal*	0.64	0.06
							0.74	0.01
							0.47	0.03
3	56.413 05	78.796 75	9.07	−22	4.8	*And, Nan, Fal*	0.40	0.02
							0.50	0.03
							0.31	0.06
4	56.413 05	78.796 75	9.07	−14	4.7	*Men, Com, Sch*	0.67	0.06
							0.57	0.04
							0.72	0.03
5	56.413 05	78.796 75	9.07	−15	4.7	*Men, Com, Sch*	0.85	0.03
							0.87	0.03
							1.01	0.03
6	56.413 05	78.796 75	9.07	−14	4.7	*Com, Men, Sch*	0.66	0.11
							0.52	0.04
							0.49	0.05
7	56.422 05	78.794 05	10.07	1	5.3	*Men, Com, Fal*	2.01	0.08
							2.10	0.14
							2.21	0.05
8	56.422 05	78.794 05	10.07	3	5.3	*Men, Eqf, Fal*	2.26	0.06
							2.43	0.14
							2.55	0.10
9	56.422 05	78.794 05	10.07	1	5.3	*Men, Com, Eqf*	1.79	0.06
							1.92	0.12
							1.86	0.14
10	56.422 01	78.794 01	10.07	−18	5.1	*And, Nan, Fal*	0.33	0.07
							0.29	0.01
							0.41	0.07
11	56.422 01	78.794 01	10.07	−20	5.1	*And, Nan, Fal*	0.57	0.05
							0.52	0.04
							0.51	0.06
12	56.422 01	78.794 01	10.07	−23	5.1	*And, Nan, Fal*	0.29	0.01
							0.18	0.02
							0.21	0.03
13	56.422 01	78.793 98	11.07	−10	5.1	*Sch, Com, Fal*	0.92	0.06
							1.01	0.05
							0.87	0.05
14	56.422 01	78.793 96	11.07	−1	5.1	*Sch, Com Fal*	1.78	0.05
							1.84	0.06
							1.74	0.06
15	56.422 02	78.793 95	11.07	0	5.1	*Men, Com. Sch*	1.91	0.04
							1.74	0.04
							2.03	0.05
16	56.422 00	78.793 89	11.07	−10	5.8	*Men, Sch, Fal*	1.07	0.08
							0.98	0.13
							1.20	0.08

Table C.1. (Continued.)

Point number	Coordinates		Date	WTL (cm)[a]	pH	The most abundant species[b]	CH_4 fluxes (mgC m^{-2} h^{-1})	
	Latitude	Longitude					Mean	STD[c]
17	56.422 01	78.793 91	11.07	−2	6.6	*Men, Com, Eqf*	1.54	0.11
							1.78	0.08
							1.90	0.15
18	56.422 01	78.793 92	11.07	1	6.6	*Men, Com, Eqf*	1.41	0.08
							1.72	0.15
							1.76	0.08
Subtaiga, Reed cane-sedge fen, 2011								
19	56.500 42	78.311 85	12.7	0	6.4	*Ces, Com, Phr*	2.21	0.17
							2.04	0.17
							2.17	0.24
20	56.500 42	78.311 85	12.7	−2	6.4	*Ces, Com, Phr*	2.37	0.23
							2.42	0.16
							2.59	0.30
21	56.500 42	78.311 85	12.7	1	6.4	*Ces, Com, Phr*	1.70	0.13
							1.90	0.27
							1.87	0.13
22	56.500 42	78.311 85	26.7	10	6.3	*Ces, Com, Phr*	3.08	0.76
							2.84	0.10
							2.94	0.09
23	56.500 42	78.311 85	26.7	7	6.3	*Ces, Com, Phr*	2.54	0.21
							3.01	0.20
							2.71	0.13
24	56.500 42	78.311 85	26.7	−12.5	6.3	*Ces, Com, Phr*	0.73	0.36
							0.86	0.09
							1.28	0.38
25	56.500 42	78.311 85	26.7	6	6.3	*Ces, Com, Phr*	1.61	0.31
							1.49	0.12
							1.61	0.26
26	56.500 42	78.311 85	26.7	−1	6.3	*Ces, Com, Phr*	1.07	0.20
							1.23	0.16
							1.01	0.18
27	56.500 42	78.311 85	26.7	5	6.3	*Ces, Com, Phr*	2.26	0.43
							2.54	0.10
							2.34	0.32
Subtaiga, Birch poor fen, 2011								
28	56.411 45	78.797 12	27.7	−9	5.2	*Men, Com, Sch*	0.65	0.23
							0.71	0.08
							0.86	0.23
29	56.411 45	78.797 12	27.7	−11	5.2	*Men, Com, Sch*	0.98	0.10
							0.95	0.12
							1.14	0.06
30	56.411 45	78.797 12	27.7	−12	5.2	*Com, Men, Sch*	1.07	0.04
							1.23	0.17
							1.03	0.18
32	56.411 46	78.797 17	27.7	−12	5.2	*Men, Com, Sch*	1.12	0.07
							0.99	0.13
							1.12	0.24
33	56.411 46	78.797 17	27.7	−7	5.2	*Men, Com, Sch*	1.31	0.07
							1.28	0.23
							1.23	0.11

Table C.1. (Continued.)

Point number	Coordinates		Date	WTL (cm)[a]	pH	The most abundant species[b]	CH_4 fluxes (mgC m^{-2} h^{-1})	
	Latitude	Longitude					Mean	STD[c]
34	56.411 46	78.797 17	27.7	−8	5.2	*Com, Men, Sch*	1.50	0.19
							1.38	0.20
							1.55	0.28
35	56.411 41	78.797 26	27.7	−15	5.0	*And, Nan, Fal*	0.82	0.16
							0.78	0.03
							0.67	0.02
36	56.411 41	78.797 26	27.7	−13	5.0	*And, Nan, Fal*	0.66	0.03
							0.73	0.03
							0.85	0.22
37	56.411 41	78.797 26	27.7	−16	5.0	*And, Nan, Fal*	0.97	0.08
							0.94	0.10
							0.89	0.03
Subtaiga, Reed cane-sedge fen, 2011								
38	56.500 36	78.311 80	28.7	−4	6.3	*Ces, Com, Phr*	2.64	0.06
							2.40	0.07
							2.34	0.03
39	56.500 36	78.311 80	28.7	−6	6.3	*Ces, Com, Phr*	1.65	0.18
							1.57	0.07
							1.49	0.05
40	56.500 36	78.311 80	28.7	5	6.3	*Ces, Com, Phr*	3.07	0.07
							2.77	0.19
							2.87	0.03
41	56.500 33	78.311 78	28.7	10	6.3	*Ces, Com, Phr*	2.22	0.24
							2.49	0.76
							2.67	0.11
42	56.500 33	78.311 78	28.7	5	6.3	*Ces, Com, Phr*	2.17	0.30
							2.38	0.21
							2.30	0.08
43	56.500 33	78.311 78	28.7	12	6.3	*Ces, Com, Phr*	3.32	0.13
							3.18	0.36
							3.02	1.30
44	56.500 33	78.311 87	20.8	5	6.1	*Ces, Com, Phr*	2.79	0.13
							3.10	0.12
							2.48	0.17
							2.15	0.28
45	56.500 33	78.311 88	20.8	6	6.1	*Ces, Com, Phr*	2.47	0.27
							2.80	0.12
							3.02	0.23
							2.38	0.27
46	56.500 34	78.311 87	20.8	5	6.1	*Act, Com, Phr*	2.81	0.10
							2.60	0.14
							2.07	0.02
47	56.500 32	78.311 90	20.8	7	6.1	*Act, Com, Phr*	3.14	0.12
							2.83	0.14
							2.28	0.06
48	18.715 80	56.500 30	20.8	5	6.1	*Act, Com, Phr*	2.26	0.08
							2.74	0.10
							2.95	0.03

Table C.1. (Continued.)

Point number	Coordinates		Date	WTL (cm)[a]	pH	The most abundant species[b]	CH_4 fluxes (mgC m^{-2} h^{-1})	
	Latitude	Longitude					Mean	STD[c]
49	18.717 60	56.500 28	20.8	8	6.1	*Act, Com, Phr*	2.13	0.04
							3.36	0.05
							2.54	0.02
Subtaiga, Birch poor fen, 2011								
50	56.413 05	78.796 71	21.8	−17	5.3	*Men, Com, Fal*	1.62	0.03
							1.72	0.16
							2.02	0.04
51	56.413 03	78.796 68	21.8	−11	5.3	*Men, Com, Fal*	1.01	0.06
							1.27	0.07
							0.83	0.07
52	56.413 01	78.796 65	21.8	−16	5.3	*Men, Com, Fal*	1.52	0.08
							1.32	0.05
							1.16	0.02
53	56.412 99	78.796 62	21.8	−16	5.3	*Men, Com, Fal*	1.00	0.07
							0.94	0.03
							0.74	0.10
54	56.412 97	78.796 59	21.8	−6	5.6	*Men, Fal*	2.01	0.20
							1.82	0.08
							2.42	0.13
55	56.412 95	78.796 56	21.8	−16	5.6	*Men, Chm, Fal*	0.91	0.12
							0.81	0.05
							0.72	0.09

[a] Positive or negative values of WTL (water table level) correspond to situations when WTL is lower or higher than the mean level of mosses, respectively.
[b] *Act—Carex acuta*; *And—Andromeda polifolia*; *Ces—Carex cespitosa*;*Chm—Chamaedaphne calyculata*; *Com—Comarum palustre*; *Eqf—Equisetum fluviatile*; *Fal—Sphagnum fallax*; *Men—Menyanthes trifoliata*; *Nan—Betula nana*;*Phr—Phragmites australis*; *Sch—Scheuchzeria palustris*.
[c] Standard deviation of flux value given from propagation of uncertainty using the parameter errors through the linear regression.

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