

## Soil-atmosphere CO<sub>2</sub>, CH<sub>4</sub> and N<sub>2</sub>O fluxes in boreal forestry-drained peatlands

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### ABSTRACT

Greenhouse gas emissions from managed peatlands are annually reported to the UNFCCC. For the estimation of greenhouse gas (GHG) balances on a country-wide basis, it is necessary to know how soil-atmosphere fluxes are associated with variables that are available for spatial upscaling. We measured momentary soil-atmosphere CO<sub>2</sub> (heterotrophic and total soil respiration), CH<sub>4</sub> and N<sub>2</sub>O fluxes at 68 forestry-drained peatland sites in Finland over two growing seasons. We estimated annual CO<sub>2</sub> effluxes for the sites using site-specific temperature regressions and simulations in half-hourly time steps. Annual CH<sub>4</sub> and N<sub>2</sub>O fluxes were interpolated from the measurements. We then tested how well climate and site variables derived from forest inventory results and weather statistics could be used to explain between-site variation in the annual fluxes. The estimated annual CO<sub>2</sub> effluxes ranged from 1165 to 4437 g m<sup>-2</sup> year<sup>-1</sup> (total soil respiration) and from 534 to 2455 g m<sup>-2</sup> year<sup>-1</sup> (heterotrophic soil respiration). Means of 95% confidence intervals were ±12% of total and ±22% of heterotrophic soil respiration. Estimated annual CO<sub>2</sub> efflux was strongly correlated with soil respiration at the reference temperature (10 °C) and with summer mean air temperature. Temperature sensitivity had little effect on the estimated annual fluxes. Models with tree stand stem volume, site type and summer mean air temperature as independent variables explained 56% of total and 57% of heterotrophic annual CO<sub>2</sub> effluxes. Adding summer mean water table depth to the models raised the explanatory power to 66% and 64% respectively. Most of the sites were small CH<sub>4</sub> sinks and N<sub>2</sub>O sources. The interpolated annual CH<sub>4</sub> flux (range: -0.97 to 12.50 g m<sup>-2</sup> year<sup>-1</sup>) was best explained by summer mean water table depth ( $r^2 = 64\%$ ) and rather weakly by tree stand stem volume ( $r^2 = 22\%$ ) and mire vegetation cover ( $r^2 = 15\%$ ). N<sub>2</sub>O flux (range: -0.03 to 0.92 g m<sup>-2</sup> year<sup>-1</sup>) was best explained by peat CN ratio ( $r^2 = 35\%$ ). Site type explained 13% of annual N<sub>2</sub>O flux. We suggest that water table depth should be measured in national land-use inventories for improving the estimation of country-level GHG fluxes for peatlands.

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### 1. Introduction

Soil plays a major role in the greenhouse gas (GHG) balance of peatlands. Following drainage for forestry, the top layer of peat that has accumulated throughout the millennia is potentially decomposed faster because of water-level drawdown and consequent increase in oxic layer thickness (Silvola et al., 1996). Moreover, both quantity and composition of litter production and thus the input of carbon (C) into the soil gradually change after drainage (Laiho et al., 2003). Methane (CH<sub>4</sub>) emissions decrease and, in fertile sites, nitrous oxide (N<sub>2</sub>O) emissions increase (von Arnold et al., 2005b, c; Martikainen et al., 1995; Nykänen et al., 1998). In countries such as Finland, where 4.8 million ha of drained peatlands are used for forestry (Finnish Forest Research Institute, 2009), knowledge on soil-atmosphere GHG fluxes in drained areas is needed for annual GHG reporting (UNFCCC, 1997) and to consider ways to mitigate climate change.

Several studies have examined soil-atmosphere carbon dioxide (CO<sub>2</sub>), CH<sub>4</sub> and N<sub>2</sub>O fluxes in forestry-drained peatlands using the

**Abbreviations:**  $R_{HET}$ , heterotrophic soil respiration;  $R_{TOT}$ , total soil respiration; GHG, greenhouse gas;  $T_{Am}$ , mean air temperature;  $T_A$ , mean air temperature 1971–2000;  $TAS_m$ , May–October (summer) mean air temperature;  $TAS_{mn}$ , May–October mean air temperature 1971–2000;  $TAW_m$ , November–April (winter) mean air temperature;  $TAW_{mn}$ , November–April mean air temperature 1971–2000;  $TSUM$ , temperature sum (threshold + 5 °C);  $TSUM_r$ , temperature sum 1971–2000;  $PSUM$ , precipitation sum;  $PSUM_r$ , precipitation sum 1971–2000;  $T5_m$ , mean peat temperature at 5 cm depth;  $T5_{mn}$ , May–October mean peat temperature at 5 cm depth;  $T5W_m$ , November–April mean peat temperature at 5 cm depth;  $PT$ , peat layer thickness;  $WT_m$ , May–October mean water table depth; CN, peat carbon to nitrogen ratio; BD, peat bulk density; V, tree stand stem volume; FMI, Finnish Meteorological Institute; B, temperature sensitivity of soil respiration; NFI, Finnish National Forest Inventory; R, respiration;  $R_{ref}$ , soil respiration at the reference soil temperature 10 °C.

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closed chamber method (von Arnold et al., 2005b,c; Martikainen et al., 1995; Minkkinen et al., 2007b; Minkkinen and Laine, 2006; Nykänen et al., 1998; Silvola et al., 1996). Yet, these studies cover only a very limited range of variation caused by varying climate and site properties. In addition, comparisons of the studies are difficult because of differences in measuring and calculating methods. This is especially true for soil respiration as the components of respiration measured differ between these studies.

$\text{CH}_4$  and  $\text{N}_2\text{O}$  balance can be estimated with the closed chamber method, because the measured fluxes represent net gas exchange between soil and the atmosphere. Instead, soil  $\text{CO}_2$  balance of a forest cannot be directly measured by chambers, because trees actively take part in  $\text{CO}_2$  cycling between soil and the atmosphere through root respiration and litter production.  $\text{CO}_2$  efflux data is, however, feasible for soil  $\text{CO}_2$  balance estimation when used in connection with C cycling models.

In the Finnish GHG reporting (Statistics Finland, 2006), the calculation of peat soil  $\text{CO}_2$ -C balance is based on an estimation of litter production and soil organic matter decomposition. Below ground organic matter decomposition is estimated by using heterotrophic soil respiration ( $R_{HET}$ ) rates that are measured in trenched measuring points, from which the ground vegetation and litter layers have been removed (Minkkinen et al., 2007b). Litter production and above ground litter decomposition are modelled according to several studies (Laiho et al., 2003; Lehtonen et al., 2004; Liski et al., 2005, 2006; Muukkonen and Lehtonen, 2004; Starr et al., 2005). Reliable estimation of  $R_{HET}$  is difficult, because trenching and removal of the litter layer may alter soil respiration due to decomposition of cut roots, altered temperature and moisture conditions, and priming effects (see Kuzyakov et al., 2000; Subke et al., 2006). Moreover, the division between litter layer and peat is ambiguous.

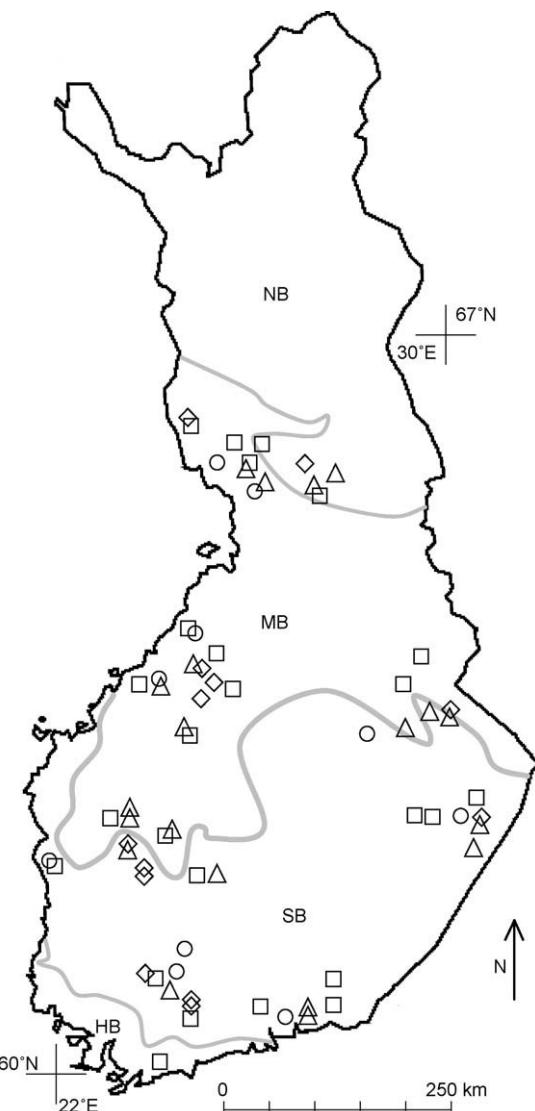
Soil C balance estimation can also be based on total soil respiration ( $R_{TOT}$ ) measurements as in the Swedish GHG reporting (von Arnold et al., 2005a; Swedish Environmental Protection Agency, 2009). In that method, the disturbance to ecosystem is small, since no manipulation of measuring points is needed. On the other hand, the estimation of annual  $R_{TOT}$  is complicated by phenological changes in vegetation (Högberg et al., 2001). In order to determine C balance, there is a need to estimate the gross photosynthesis of ground vegetation and tree stand allocation to below ground, since respiration related to tree roots and ground vegetation is included in  $R_{TOT}$  measurements.

This study aims at covering the geographical variation of soil-atmosphere GHG fluxes in forestry-drained boreal peatlands. We hypothesized that with an extensive data we could find regularities that can be used to scale up fluxes to a country-wide basis. We measured  $\text{CO}_2$ ,  $\text{CH}_4$ , and  $\text{N}_2\text{O}$  fluxes in a network of National Forest Inventory (NFI) sample plots in Finland using the closed chamber method. Both  $R_{TOT}$  and  $R_{HET}$  were measured. We then examined the possibility of using readily available NFI and weather statistics derived variables to explain GHG fluxes. Our data is from Finland, but the results should be applicable to other countries with boreal peatlands as well.

## 2. Materials and methods

### 2.1. Study sites

We subsampled 68 study sites (Fig. 1) from the permanent sample plots of the 8th NFI to include equally different site types of forestry-drained peatlands of those parts of Finland where drainage for forestry is economically viable. Northernmost Finland was excluded, because forest growth in peatlands is very slow due to the low temperatures of this region. We used the site type clas-



**Fig. 1.** The study sites by site type (Laine, 1989) from the most to the least fertile: ○ Herb-rich type (Rhtkg,  $n=10$ ), □ *Vaccinium myrtillus* types I and II (Mtkg I and II,  $n=25$ ), △ *Vaccinium vitis-idaea* types I and II (Ptkg I and II,  $n=20$ ), ◇ Dwarf shrub type (Vatkg,  $n=13$ ). Grey lines denote the boundaries of vegetation zones (Ahti et al., 1968): HB, hemiboreal; SB, south boreal; MB, middle boreal; NB, north boreal.

sification by Laine (1989; see Vasander and Laine, 2008), which lists seven drained peatland site types: *Herb-rich* type (Rhtkg), *Vaccinium myrtillus* types (Mtkg I and II), *Vaccinium vitis-idaea* types (Ptkg I and II), *Dwarf shrub* type and *Cladina* type (Jätkg). The *Vaccinium* types were further divided into two classes according to the original mire site type: *I* those, which before drainage were forested mires and *II* those, which before drainage were sparsely treed or totally treeless mires. Types *I* and *II* also differ from each other in their tree species and peat characteristics. Sites classified as *Cladina* type (the least fertile site type) were excluded from this study, since they are too poor for forestry use regardless of climate. This leaves us four categories of fertility from *Herb-rich* to *Dwarf shrub* site type (Fig. 1).

The study sites were divided into two classes according to vegetation: (1) mire vegetation (includes such species as *Sphagnum* spp., *Carex* spp., *Eriophorum* spp.) dominated and (2) forest vegetation dominated, which division is available in NFI. The exact drainage year of each site is not known, but they were all drained before 1995. The sites were selected in the vicinity of five of the

**Table 1**

Mean, minimum and maximum values of climate and site variables for the study sites. Climate variables are calculated for July 2007 to June 2008 and as average values for the years 1971–2000 (subscript *r* = reference period).

Variable	Abbreviation	Unit	Mean	Min	Max
Climate variables (from weather statistics)					
Mean air temperature	TA <sub>m</sub>	°C	4.7	2.3	7.1
Mean air temperature 1971–2000	TA <sub>mr</sub>	°C	2.7	0.5	5.1
May–October (summer) mean air temperature	TAS <sub>m</sub>	°C	10.9	9.4	12.6
May–October mean air temperature 1971–2000	TAS <sub>mr</sub>	°C	10.4	8.7	12.0
November–April (winter) mean air temperature	TAW <sub>m</sub>	°C	-1.6	-5.0	1.5
November–April mean air temperature 1971–2000	TAW <sub>mr</sub>	°C	-5.0	-7.9	-1.7
Temperature sum (threshold + 5 °C)	TSUM	dd	1173	919	1448
Temperature sum 1971–2000	TSUM <sub>r</sub>	dd	1117	898	1351
Precipitation sum	PSUM	mm year <sup>-1</sup>	738	579	881
Precipitation sum 1971–2000	PSUM <sub>r</sub>	mm year <sup>-1</sup>	523	408	604
Climate variables (measured at sites)					
Mean peat temperature at 5 cm depth	T <sub>5m</sub>	°C	4.5	2.9	6.2
May–October mean peat temperature at 5 cm depth	T <sub>5S<sub>m</sub></sub>	°C	8.9	6.5	11.0
November–April mean peat temperature at 5 cm depth	T <sub>5W<sub>m</sub></sub>	°C	0.1	-1.0	1.4
Site variables					
Peat layer thickness	PT	cm	99	9	>310
May–October mean water table depth	WT <sub>m</sub>	cm	31	1	80
Peat carbon to nitrogen ratio (0–20 cm)	CN	—	28	16	45
Peat bulk density (0–20 cm)	BD	kg m <sup>-3</sup>	118	40	222
Tree stand stem volume	V	m <sup>3</sup> ha <sup>-1</sup>	134	14	301

research units of the Finnish Forest Research Institute to facilitate field work. Other selection criteria were: average peat layer thickness of over 20 cm, no clear-cut areas, and no sites in which ditching had not detectably altered hydrology or vegetation. Variation in site properties is shown in Table 1.

In addition to NFI measurements conducted throughout 1985–1986 and 1995 periods (Hökkä et al., 1997), most of the permanent NFI8 peatland sample plots, including ca. 500 forestry-drained plots, were sampled for soil nutrient and bulk density analyses in 2002 (Jukka Alm, unpublished data). Six to eight soil samples (area of one sample 60 mm × 60 mm) were taken at each. Samples were separated into three layers: surface layer (litter and humus layer formed after drainage), 0–10 cm below surface layer, and 10–20 cm below surface layer. Samples of each layer were pooled and analysed in the laboratory. For each plot and layer, dry mass and concentrations of elements were determined. We calculated bulk densities (BD) and carbon to nitrogen ratios (CN) for the topmost 20 cm of the soil for our study sites using the 2002 data.

Air temperature and rainfall data for the study sites for the period 1971–2008 inclusive were obtained from a database with a 10 km × 10 km grid of daily weather data from the Finnish Meteorological Institute (FMI). Values for the grid points were interpolated from data measured at the observation stations of FMI.

## 2.2. Site preparation and measurements

$R_{TOT}$  and  $R_{HET}$  (g m<sup>-2</sup> h<sup>-1</sup> of CO<sub>2</sub>) were both measured from 5 points at each study site. Points were placed systematically within an 11 m radius of the site centre.  $R_{HET}$  points were trenched by installing a 30 cm deep metal cylinder (ø 400 mm) into the soil to exclude living roots and root litter input. After trenching, ground vegetation and litter layers were removed. This was done 6–12 months before starting the measurements in order to reduce the impacts of soil disturbance and fresh litter decomposition on the heterotrophic flux. Litter and germinated vegetation were removed every time before measuring the points. Vegetation and litter were left untouched on the  $R_{TOT}$  points. No collars were used to preserve roots. Instead, a 2 cm deep groove (ø 315 mm) was carved on the soil surface (above the root layer) to seal the chamber during measurements.

Respiration was measured every 2–3 weeks over May–October period in 2007 and in 2008. Respiration measurements were taken

by a portable infrared gas analyzer (EGM-4, PP-Systems) with an opaque closed chamber (modified SRC-1, ø 315 mm, h 149 mm, PP-systems; NSF11 in Pumpanen et al., 2004). Chamber closure time was 81 s. Water table depth from the peat surface (WT, cm) was measured in a perforated tube each time that respiration was measured. If WT was below the bottom of the peat layer in thin peated sites, peat layer thickness (PT) was used instead. Thus the thickness of peat layer under oxic conditions was described.

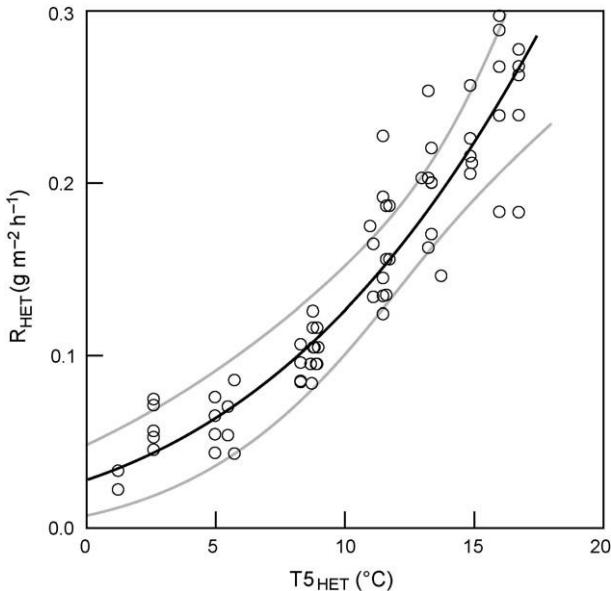
Gas samples for calculating CH<sub>4</sub> and N<sub>2</sub>O fluxes were taken from 4 of the  $R_{TOT}$  points for 5–7 times during May–October in 2007 and 2008. An opaque closed chamber (ø 315 mm, h 295 mm) that was equipped with a fan was used. Samples were taken from the chamber headspace using syringes at 5, 15, 25 and 35 min after inserting the chamber into the point. Each gas sample was injected into a 12 ml glass vial, which was sealed with a rubber septum to minimise gas leakage during transport and storage. Samples were analysed in laboratory within two weeks from sampling. The analytical equipment used was a gas chromatograph fitted with a FI-detector for CH<sub>4</sub> and an EC-detector for N<sub>2</sub>O detection. Gas fluxes (mg m<sup>-2</sup> h<sup>-1</sup> of CH<sub>4</sub>/N<sub>2</sub>O) were calculated from the slope of linear regression between the respective gas concentration and chamber closure time.

Soil temperatures (°C) at 5 cm depth below the peat surface at two  $R_{TOT}$  points ( $T_5$ ) and two  $R_{HET}$  points ( $T_{5HET}$ ) were recorded every 2–3 h using temperature loggers (i-Button DS1921G, Maxim Integrated Products). Mean temperatures of the two  $R_{TOT}$  and two  $R_{HET}$  points were calculated and then linearly interpolated to every half hour. Soil temperatures were estimated separately for  $R_{TOT}$  and  $R_{HET}$  points because the removal of the moss and litter layer from the  $R_{HET}$  points was assumed to affect soil temperature.

## 2.3. Analysis of CO<sub>2</sub> fluxes

In well-drained peatlands, temperature is usually the only significant variable that explains temporal variation in momentary soil respiration (Mäkiranta et al., 2008). Therefore, for the calculation of annual  $R_{TOT}$  and  $R_{HET}$  fluxes, the following nonlinear regression (Lloyd and Taylor, 1994) was fitted to the measured, momentary fluxes:

$$R = R_{ref} e^{B((1/(T_{5ref}) - 1/(T_5))}, \quad (1)$$



**Fig. 2.** An example of fitting temperature regression (model 1) to momentary heterotrophic soil respiration ( $\text{CO}_2$ ) data. Each circle is a single measurement of one point at a *Dwarf shrub* type (Vatkg) study site in southern Finland. Parameters of model 1 are:  $R_{\text{ref}} = 0.126 \text{ g m}^{-2} \text{ h}^{-1}$ ,  $B = 391$ . Grey lines denote the approximate 95% confidence interval estimated with Eq. (2).

where  $R_{\text{ref}}$  ( $\text{g m}^{-2} \text{ h}^{-1}$  of  $\text{CO}_2$ ) is soil respiration at reference soil temperature ( $T5_{\text{ref}}$ , set at  $10^\circ\text{C}$ ).  $T5_0$  is the soil temperature at which respiration would reach zero, set at  $-46.02^\circ\text{C}$  according to Lloyd and Taylor (1994). Parameter  $B$  describes the temperature sensitivity of respiration. We also tested adding water table depth ( $WT$ ) to the model as a scalar parameter but for most sites it was insignificant and did not raise the  $r^2$  value.

Model 1 was fitted separately for each site for  $R_{\text{TOT}}$  and  $T5$  data and for  $R_{\text{HET}}$  and  $T5_{\text{HET}}$  data. Combining the data of five points at each site caused heteroscedasticity. Points had different levels of respiration and the nonlinear relationship between respiration and temperature caused the variation in respiration to be higher at higher temperatures. Thus, we used the inverse of the variance of  $R$  data to weight the measurements. An example of fitting the model is given in Fig. 2.

As reported by Tuomi et al. (2008), model 1 is not applicable throughout a very wide temperature range. However, the model performed well in the data (observed temperature range from +2 to  $+16^\circ\text{C}$ ) measured in this study and produced unbiased estimates of  $R$ . Thus, model 1 in this temperature range was capable of adapting to the by increasing temperature decreasing temperature sensitivity often observed (Vanhala et al., 2008). Only minor extrapolation was needed when calculating the annual  $R$  (temperature range from  $-2$  to  $+17^\circ\text{C}$ ).

Annual values ( $\text{g m}^{-2} \text{ year}^{-1}$  of  $\text{CO}_2$ ) of  $R_{\text{TOT}}$  and  $R_{\text{HET}}$  were estimated for each site with model 1 using  $T5$  (soil temperature from the undisturbed points) as the driving variable.  $T5$  was also used for calculating annual  $R_{\text{HET}}$ , since we wanted to estimate respiration under undisturbed temperature conditions. Values were calculated for the period July 2007 to June 2008 inclusive using the soil temperature data measured by temperature loggers that had been installed at each site.

Approximate 95% confidence interval upper and lower limits ( $R_+$ ,  $R_-$ ) were calculated for each estimated momentary  $R$  value as (Bates and Watts, 1988):

$$R_{\pm} = R \pm \text{RMSE} \sqrt{u_0^T (UU^T)^{-1} u_0 t_{0.025}}, \quad (2)$$

where RMSE is the root mean square error of the fitting,  $U$  is a matrix containing values of  $\partial R / \partial R_{\text{ref}}$  in the first column and  $\partial R / \partial B$  in the second column conditional on the  $T5$  values,  $R_{\text{ref}}$  and  $B$  of the fitting,  $u_0$  is a vector containing values of  $\partial R / \partial R_{\text{ref}}$  in the first column and  $\partial R / \partial B$  in the second column conditional on the  $T5$  value of estimated  $R$  and  $t_{0.025}$  is 0.025% quantile of the Student distribution. Upper and lower limits for the expected annual  $R$  values were calculated for each site by summing up the values of  $R_+$  and  $R_-$ .

We analysed the relationship between soil respiration and site and climate variables (Table 1) using general linear models (Systat 12, Systat Software) in two steps. First, variation in soil respiration at  $10^\circ\text{C}$  and in temperature sensitivity of soil respiration (parameters  $R_{\text{ref}}$  and  $B$  of model 1) was studied. These two parameters along with temperature (the driving variable in model 1) define annual soil respiration. Moreover, the dependency of annual  $R$  on these parameters was tested to see how sensitive annual  $R$  is to variation in them. Second, variation in estimated annual  $R$  values was studied to provide a method for upscaling fluxes to country-wide levels.

#### 2.4. Analysis of $\text{CH}_4$ and $\text{N}_2\text{O}$ fluxes

The means of the  $\text{CH}_4$  and  $\text{N}_2\text{O}$  fluxes from the four points were calculated on each measuring occasion. Summer (May 16th to November 15th) fluxes were then interpolated from these values. The winter (November 16th to May 15th) share of the annual flux was estimated by using data from Rhtkg–Ptkg sites measured by Alm et al. (1999) and Minkkinen et al. (2007c). The winter share was estimated at 25% (range: 11–43%) for  $\text{CH}_4$  and 34% (range: 26–42%) for  $\text{N}_2\text{O}$ . The relationship of annual fluxes with the variables in Table 1 was then tested using general linear models and nonlinear models (Systat 12, Systat Software) in order to identify suitable variables for upscaling. All published data from Finnish and Swedish forested peatlands (Klemmedsson et al., 2005; Minkkinen et al., 2007a; Regina et al., 1996, 1998) were included in the analysis of annual  $\text{N}_2\text{O}$  flux.

### 3. Results

#### 3.1. $\text{CO}_2$

The measured momentary fluxes of  $\text{CO}_2$  varied between  $-0.01$  and  $2.14 \text{ g m}^{-2} \text{ h}^{-1}$  for  $R_{\text{TOT}}$  and  $-0.03$  and  $1.38 \text{ g m}^{-2} \text{ h}^{-1}$  for  $R_{\text{HET}}$ . Close to the EGM detection limit, random measurement error of small fluxes sometimes resulted in negative values.  $\text{CO}_2$  fluxes at the reference soil temperature of  $10^\circ\text{C}$  (parameter  $R_{\text{ref}}$  of model 1) gave a mean of  $0.22 \text{ g m}^{-2} \text{ h}^{-1}$  (range:  $0.10$ – $0.41 \text{ g m}^{-2} \text{ h}^{-1}$ ) for  $R_{\text{TOT}}$  and  $0.51 \text{ g m}^{-2} \text{ h}^{-1}$  (range:  $0.24$ – $0.78 \text{ g m}^{-2} \text{ h}^{-1}$ ) for  $R_{\text{HET}}$ . Both  $R_{\text{ref}}$  and temperature sensitivity of  $\text{CO}_2$  flux (parameter  $B$ ) varied considerably between sites (Table 2). All the tested site variables (Table 1), except peat layer thickness ( $PT$ ), had statistically significant correlations with parameter  $R_{\text{ref}}$  for both  $R_{\text{TOT}}$  and  $R_{\text{HET}}$  (Table 3). Correlations of  $R_{\text{ref}}$  with air temperature and with peat temperature were significant only for  $R_{\text{HET}}$ . The best model with tree stand stem volume ( $V$ ), peat bulk density ( $BD$ ) and summer mean water table depth ( $WT_m$ ) as explanatory variables combined explained 43.7% of  $R_{\text{ref}}$  for  $R_{\text{TOT}}$  and 55.9% of  $R_{\text{ref}}$  for  $R_{\text{HET}}$ . Residuals of this model for  $R_{\text{HET}}$  did not correlate with summer mean air temperature ( $TAS_m$ ) at all ( $p = 0.879$ ). The positive correlation between  $TAS_m$  and  $R_{\text{ref}}$  was a consequence of the positive correlations of  $TAS_m$  with  $V$  and with  $WT_m$ .

In a preliminary analysis, parameter  $B$  correlated positively with  $WT_m$ . A more comprehensive look at the data revealed that this was due to sites at which model 1 fitted poorly ( $r^2 < 0.4$ ) because they had lower  $B$  values than the rest of the sites. At those sites that had low  $B$ , water table fluctuated close to the peat surface (low  $WT_m$ )

**Table 2**

Values of parameters  $R_{ref}$  (soil respiration at 10 °C,  $\text{g m}^{-2} \text{h}^{-1}$  of  $\text{CO}_2$ ) and  $B$  (temperature sensitivity of soil respiration) and  $r^2$  (%) of temperature regression model 1 fitted for each of the 68 sites to total ( $R_{TOT}$ ) and heterotrophic ( $R_{HET}$ ) soil respiration data.

	$R_{TOT}$	$R_{HET}$
$R_{ref}$		
Mean	0.51	0.22
Min	0.24	0.10
Max	0.78	0.41
$B$		
Mean	420	350
Min	286	132
Max	607	475
$r^2$		
Mean	72.8	70.5
Min	34.4	7.5
Max	91.9	92.9

which caused a temperature-independent variation in respiration. At the rest of the sites ( $r^2 > 0.40$ ,  $n = 66$  for  $R_{TOT}$  and 62 for  $R_{HET}$ ), the  $B$  values did not correlate with  $WT_m$  (Table 4).  $B$  for  $R_{HET}$  had statistically significant correlations with several other variables, but the  $r^2$  values were generally low.  $TAS_{mr}$ ,  $BD$  and  $PT$  combined explained 25.7% of  $B$ . As for  $R_{TOT}$ ,  $B$  correlated statistically significantly only with  $PT$ .

Estimated annual  $\text{CO}_2$  effluxes showed substantial between-site variation, the highest values being several times higher than the lowest. Mean  $R_{TOT}$  was  $2588 \text{ g m}^{-2} \text{ year}^{-1}$  (range:  $1165$ – $4437 \text{ g m}^{-2} \text{ year}^{-1}$ ) and mean  $R_{HET}$  was  $1196 \text{ g m}^{-2} \text{ year}^{-1}$  (range:  $534$ – $2455 \text{ g m}^{-2} \text{ year}^{-1}$ ), which accounted for 46% of  $R_{TOT}$ . The mean uncertainty of annual  $\text{CO}_2$  estimates, calculated as the approximate 95% confidence interval, was  $\pm 12\%$  of annual  $R_{TOT}$  (range:  $\pm 5$  to  $\pm 22\%$ ) and  $\pm 22\%$  of annual  $R_{HET}$  (range:  $\pm 11$  to  $\pm 67\%$ ). The broad range for  $R_{HET}$  was caused by one site with high water table ( $WT_m = 1 \text{ cm}$ ), for all other sites the confidence interval was below  $\pm 42\%$ .

**Table 3**

Results of fitting a general linear model with site and climate variables to explain between-site variation in heterotrophic ( $R_{HET}$ ) and total ( $R_{TOT}$ ) soil respiration at 10 °C (parameter  $R_{ref}$  in model 1,  $\text{g m}^{-2} \text{ h}^{-1}$  of  $\text{CO}_2$ ). For  $R_{TOT}$ , only statistically significant fittings ( $p < 0.05$ ) are shown. Error = standard error of coefficient for coefficients and standard error of estimate for models with several independent variables. TKG = site type. See Table 1 for other abbreviations and units.  $n = 68$ .

Independent variables	p-Value	Coefficient	Error	$r^2$ , %
$R_{HET}$				
$TAS_{mr}$	<0.001	0.036	0.094	19.0
$PSUM_r$	0.712	$-6.8 \times 10^{-5}$	$18.4 \times 10^{-5}$	0.2
$TSS_m$	0.070	0.015	$8.1 \times 10^{-3}$	4.9
$PT$	0.444	$-1.0 \times 10^{-4}$	$1.3 \times 10^{-4}$	0.9
$WT_m$	0.001	$2.0 \times 10^{-3}$	$4.7 \times 10^{-4}$	20.6
$CN$	0.007	$-3.0 \times 10^{-3}$	$1.1 \times 10^{-3}$	10.6
$BD$	<0.001	$1.1 \times 10^{-3}$	$2.1 \times 10^{-4}$	28.7
$V$	<0.001	$5.4 \times 10^{-4}$	$7.7 \times 10^{-5}$	42.2
$TKG$	<0.001			37.4
$V, BD, WT_m$			0.049	55.9
$V$	<0.001	$3.7 \times 10^{-4}$	$7.9 \times 10^{-5}$	
$BD$	0.005	$5.4 \times 10^{-4}$	$1.9 \times 10^{-4}$	
$WT_m$	0.007	$1.2 \times 10^{-3}$	$4.2 \times 10^{-4}$	
$R_{TOT}$				
$WT_m$	0.001	$3.0 \times 10^{-3}$	$8.6 \times 10^{-4}$	15.4
$CN$	0.001	$-6.5 \times 10^{-3}$	$1.8 \times 10^{-3}$	16.2
$BD$	<0.001	$1.7 \times 10^{-3}$	$3.8 \times 10^{-4}$	23.7
$V$	<0.001	$8.4 \times 10^{-4}$	$1.5 \times 10^{-4}$	33.6
$TKG$	<0.001			36.2
$V, BD, WT_m$			0.097	43.7
$V$	<0.001	$5.9 \times 10^{-4}$	$1.6 \times 10^{-4}$	
$BD$	0.017	$9.1 \times 10^{-4}$	$3.7 \times 10^{-4}$	
$WT_m$	0.075	$1.5 \times 10^{-3}$	$8.4 \times 10^{-4}$	

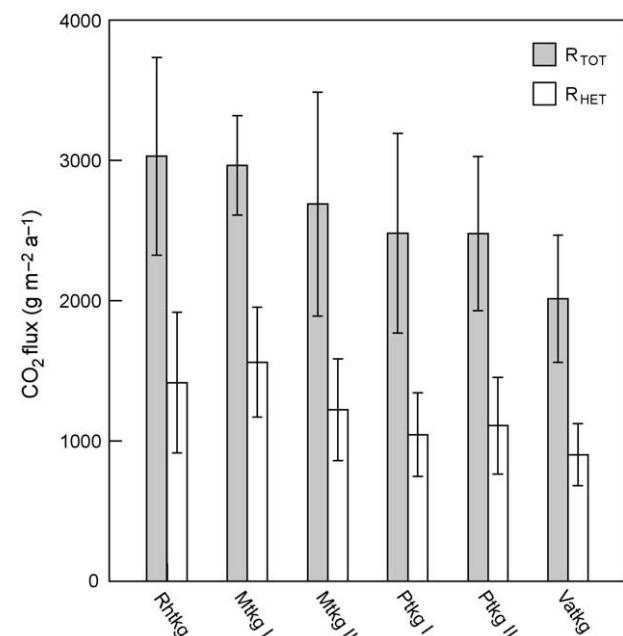
**Table 4**

Results of fitting a general linear model with site and climate variables to explain between-site variation in temperature sensitivity of heterotrophic ( $R_{HET}$ ) and total ( $R_{TOT}$ ) soil respiration (parameter  $B$  in model 1). For  $R_{TOT}$ , the sole significant fitting ( $p < 0.05$ ) is shown. Only parameters from models with  $r^2 > 0.4$  were included in the analysis ( $n = 66$  for  $R_{TOT}$  and 62 for  $R_{HET}$ ). See Table 1 for units and abbreviations. Error = standard error of coefficient for coefficients and standard error of estimate for the model with several independent variables. TKG = site type.

Independent variables	p-Value	Coefficient	Error	$r^2$ , %
$R_{HET}$				
$TAS_{mr}$	0.021	16.0	6.7	8.4
$TSUM_r$	0.017	0.114	0.046	9.1
$PSUM_r$	0.655	0.056	0.125	0.3
$PT$	0.058	$-0.166$	0.086	5.8
$WT_m$	0.829	0.082	0.377	0.1
$CN$	0.085	$-1.32$	0.75	4.9
$BD$	0.004	0.463	0.156	12.9
$V$	0.003	0.199	0.065	13.3
$TKG$	0.286			10.1
$TAS_{mr}, PT, BD$				41.7
$TAS_{mr}$	0.014	16.5	6.5	
$PT$	0.017	$-0.196$	0.080	
$BD$	0.022	0.354	0.150	
$R_{TOT}$				
$PT$	0.012	$-0.288$	0.112	9.4

Annual  $\text{CO}_2$  effluxes were strongly correlated with the reference flux at 10 °C ( $R_{ref}$ ): As much as 76% of the annual  $R_{TOT}$  and 90% of the annual  $R_{HET}$  could be explained by  $R_{ref}$  alone ( $B$  and  $R_{ref}$  correlated weakly for  $R_{HET}$ ,  $r^2 = 6.4\%$ , though).  $R_{ref}$  and  $TAS_m$  combined explained 90% of  $R_{TOT}$  and 95% of  $R_{HET}$ , which suggests that the observed variation in temperature sensitivity had little effect on the variation in the estimated annual effluxes.

There was a clear diminishing trend in annual  $R$  from the most to the least fertile site type (Fig. 3). Moreover,  $R_{TOT}$  showed substantial variation within site type. The variables that best explained annual respiration were the same as those for explaining  $R_{ref}$ . However, the temperature variables were also found to be important (Table 5).  $TAS_m$  was the best predictor ( $r^2$ :  $R_{TOT}$  28.3%,  $R_{HET}$  34.5%) of the temperature variables. The models with  $V$ ,  $BD$ ,  $WT_m$  and  $TAS_m$  as the independent variables explained 64.2% of annual  $R_{TOT}$  and



**Fig. 3.** Site type arithmetic means of annual total ( $R_{TOT}$ ) and heterotrophic ( $R_{HET}$ ) soil respiration ( $\text{CO}_2$ ) displayed from most to least fertile site type. Error bars are  $\pm$  standard deviations.

**Table 5**

Results of fitting a general linear model with different site and climate variable combinations to explain estimated annual total ( $R_{TOT}$ ) and heterotrophic ( $R_{HET}$ ) soil respiration ( $\text{g m}^{-2} \text{ year}^{-1}$  of  $\text{CO}_2$ ). TKG = site type (categorical variable). Error = standard error of estimate for models and standard error of coefficient/effect for coefficients/effects. See Table 1 for other abbreviations and units.  $n=67$ .

Independent variables	$R_{TOT}$				$R_{HET}$				
	p-Value	Coeff./eff.	Error	$r^2, \%$	p-Value	Coeff./eff.	Error	$r^2, \%$	
V, $WT_m$ , $TAS_m$ , BD				431	64.2			260	62.5
Constant	0.856	-139	760		0.059	-884	459		
V	<0.001	3.21	0.803		0.002	1.58	0.484		
$WT_m$	0.001	12.9	3.85		0.010	6.15	2.33		
$TAS_m$	0.095	124	73.0		0.007	123	44.0		
BD	0.007	4.66	1.68		0.007	2.85	1.01		
V, $WT_m$ , $TAS_m$ , TKG				434	66.1			259	65.3
Constant	0.796	-117	806		0.164	-850	481		
V	0.009	2.69	0.99		0.166	0.833	0.593		
$WT_m$	<0.001	16.9	4.1		<0.001	8.96	2.43		
$TAS_m$	0.079	140	78		0.005	135	47		
TKG	0.069				0.038				
Rhtkg		674	215			382	128		
Mtkg I		330	236			402	141		
Mtkg II		353	180			200	108		
Ptkg I		309	198			115	118		
Ptkg II		237	191			110	114		
Vatkg		Included in constant				Included in constant			
V, $TAS_m$ , TKG				490	56.0			285	57.2
Constant	0.753	-545	902		0.078	-1077	525		
V	0.001	3.70	1.09		0.034	1.37	0.63		
$TAS_m$	0.014	216	86		0.001	175	50		
TKG	0.208	.			0.165				
Rhtkg		492	237			286	138		
Mtkg I		215	265			341	154		
Mtkg II		447	202			250	118		
Ptkg I		320	224			121	130		
Ptkg II		169	215			74	125		
Vatkg		Included in constant				Included in constant			

64.0% of annual  $R_{HET}$  (Table 5). Models with site type gave higher  $r^2$  values (Table 5) than those with BD, a variable that is generally not available in NFI. Leaving  $WT_m$  out clearly reduced those models' potentials to explain R. Fig. 4 illustrates the relationship of annual  $R_{TOT}$  and  $R_{HET}$  with different variables. We further investigated, if there was a correlation between annual R and location in south–north or east–west axis, by testing the residuals of the  $WT_m$ –V–BD– $TAS_m$  models against the north and east coordinates of the sites. No correlation was found as p-values were around 0.5 for all cases.

### 3.2. $\text{CH}_4$ and $\text{N}_2\text{O}$

Measured momentary  $\text{CH}_4$  fluxes varied between  $-0.53$  and  $24.5 \text{ mg m}^{-2} \text{ h}^{-1}$ , and  $\text{N}_2\text{O}$  fluxes varied between  $-0.07$  and  $0.45 \text{ mg m}^{-2} \text{ h}^{-1}$ . Negative fluxes indicate consumption, i.e. flux from the atmosphere to soil. Estimated annual  $\text{N}_2\text{O}$  flux (range:  $-0.03$  to  $0.92 \text{ g m}^{-2} \text{ year}^{-1}$ ) had a diminishing trend from the most to the least fertile site type (Fig. 5).  $\text{CH}_4$  flux (range:  $-0.97$  to  $12.50 \text{ g m}^{-2} \text{ year}^{-1}$ ) did not show such a trend. Dwarf shrub type was the only site type that mostly had (9 sites out of 13) positive  $\text{CH}_4$  fluxes. Other site types had mainly small negative fluxes, and positive fluxes were estimated only at few sites.

Annual  $\text{CH}_4$  flux showed a clear negative nonlinear relationship with  $WT_m$  ( $r^2=64\%$ ), and a positive, though weaker relationship with V ( $r^2=22\%$ , Fig. 6). Residuals of  $WT_m$  and V models did not show any correlation with temperature variables. We included only those sites for which WT was permanently less than peat layer thickness ( $n=57$ ) for the  $WT_m$  model. As mire vegetation is dependent on  $WT_m$  (Fig. 6.), the vegetation cover classification was significant as well ( $p=0.001$ ,  $r^2=14.8\%$ ,  $n=68$ ). Arithmetic means ( $\pm$ standard error of mean) of  $\text{CH}_4$  flux were  $-0.28 \pm 0.04 \text{ g m}^{-2} \text{ year}^{-1}$  for the

forest vegetation dominated sites and  $1.16 \pm 0.48 \text{ g m}^{-2} \text{ year}^{-1}$  for the mire vegetation dominated sites.

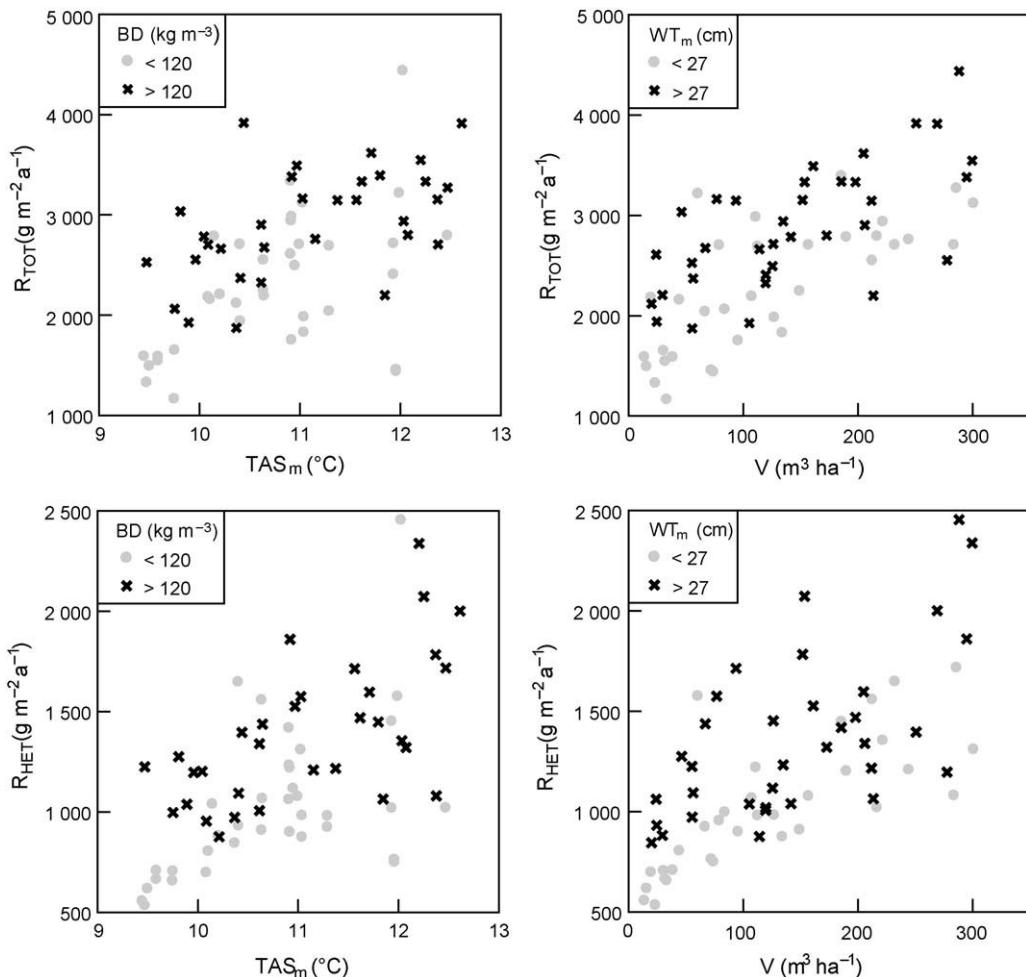
Annual  $\text{N}_2\text{O}$  flux had a nonlinear negative relationship with CN ratio (Fig. 7). All published data from Finnish and Swedish forested peatlands were included in the analysis for comparison. Two of the three forested peatlands that had an agricultural history clearly showed higher emissions than any of the forestry-drained sites. Emissions from forestry-drained spruce-dominated peatlands estimated by Minkkinen et al. (2007a) were generally higher than emissions estimated in this study with a similar measuring technique. Thereby, the regression between CN ratio and  $\text{N}_2\text{O}$  flux varied greatly depending on which parts of those data were included (Fig. 7). Including the sites which had an agricultural history caused the model to slightly underestimate the fluxes for virtually all the forestry-drained sites with CN ratio between 25 and 50, and grossly overestimate emissions for forestry-drained sites with CN ratio below 20.

Residuals of the CN-regression for all forestry-drained sites had statistically significant positive correlations with  $TAS_m$  ( $p<0.001$ ) and  $WT_m$  ( $p<0.001$ ). Combined they explained 20.4% of the residuals. Site type, which strongly correlates with the CN ratio, can be used to estimate  $\text{N}_2\text{O}$  fluxes instead of CN, which is not generally available in NFI data (Table 6). The data in Table 6 includes only the Finnish sites, since site type data were unavailable for the Swedish sites.

## 4. Discussion

### 4.1. Factors affecting $\text{CO}_2$ efflux

The temporal dynamics of  $\text{CO}_2$  fluxes at most study sites were well explained by soil temperature and no significant impact of



**Fig. 4.** Annual total ( $R_{TOT}$ ) and heterotrophic ( $R_{HET}$ ) soil respiration ( $\text{CO}_2$ ) plotted against summer (May–October) mean air temperature ( $TAS_m$ ) and tree stand stem volume ( $V$ ). Sites are divided into two classes according to bulk density ( $BD$ ) and summer mean water table ( $WT_m$ ).

water table depth was observed. Similar observation was made by Mäkiranta et al. (2008). In boreal drained peatlands the water table usually fluctuates below 30 cm. A major part of new organic matter (including root litter), which holds the highest potential rate of decomposition, is deposited into the surface (10 cm) peat layer. The water table would have to rise to this top 10 cm layer to limit significantly the decomposition of new organic matter. This rarely happens in forestry-drained peatlands.

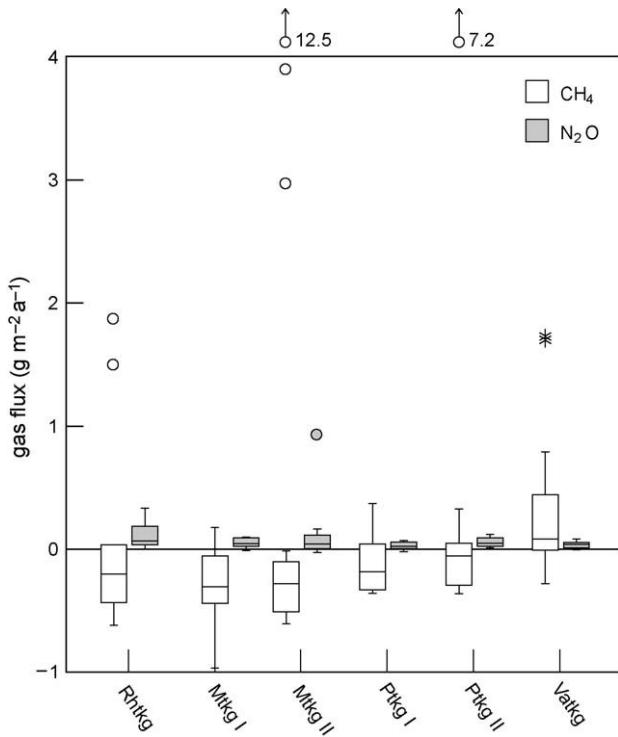
Soil respiration at reference temperature ( $R_{ref}$ ) correlated with several variables that describe the amount and quality of respiring tissue and decomposing material: water table depth, tree stand stem volume, soil CN ratio and site type. Although the water table dynamics did not affect the temporal behaviour of  $\text{CO}_2$  fluxes within the sites, mean water table depth significantly explained

the between-site variation in  $\text{CO}_2$  fluxes. Water table depth and peat bulk density combined determine the amount of peat under oxic conditions and thus the amount available to decomposers. Therefore, deeper water level may enhance soil respiration to some extent providing no drought occurs (Mäkiranta et al., 2009; Silvola et al., 1996). Tree stand considerably affects litterfall in forestry-drained peatlands (Laiho et al., 2003). The more litter, the more fresh organic matter to be decomposed. Tree root related respiration also contributes to total soil respiration. In heterotrophic respiration measured in trenched points, decomposing cut roots may play an important role as well (Ngao et al., 2007). Soil CN ratio and site type both indicate site fertility and, thus, substrate quality and quantity for both vegetation and decomposers. Generally, soil respiration has been found to be higher in fertile than in poor sites (von Arnold et al., 2005a; Minkkinen et al., 2007b; Silvola et al., 1996).

Most of the variation in temperature sensitivity of soil respiration ( $B$ ) remained unexplained. Indeed, in situ studies have often found variation but few coherent explanations have been put forward. Mäkiranta et al. (2009) found a significant negative correlation between temperature sensitivity of heterotrophic soil respiration and average water table depth in peatlands drained for agriculture and forestry but we did not. Peng et al. (2009) found a negative correlation for temperature sensitivity of total soil respiration in Chinese forest soils with annual mean air temperature and precipitation sum. We found no correlation with mean temperature and only weak insignificant negative correlation ( $p = 0.15$ ) with the

**Table 6**  
Arithmetic means ( $\pm$ standard error) of annual  $\text{N}_2\text{O}$  fluxes ( $\text{g N}_2\text{O m}^{-2} \text{year}^{-1}$ ) in Finnish sites in Fig. 7, according to peatland site type ( $p = 0.07$ ,  $r^2 = 12.8\%$ ,  $n = 80$ ).

Site type	$\text{N}_2\text{O}$ flux
Rhtkg	$0.185 \pm 0.065$
Mtkg I	$0.116 \pm 0.035$
Mtkg II	$0.167 \pm 0.072$
Ptkg I	$0.028 \pm 0.010$
Ptkg II	$0.071 \pm 0.016$
Vatkg	$0.029 \pm 0.007$

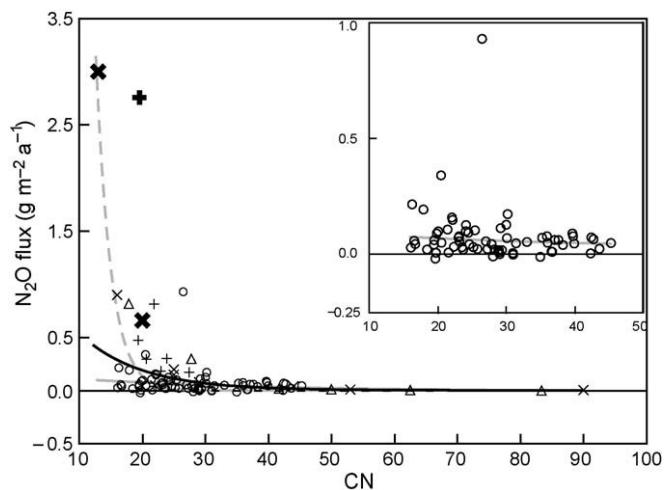


**Fig. 5.** Box plot of annual  $\text{CH}_4$  and  $\text{N}_2\text{O}$  fluxes displayed from most to least fertile site type. Inside the boxes are 50% of sites from median and band within box is median of sites.

precipitation sum. Minkkinen et al. (2007b) suggested that temperature sensitivity of peat decomposition could be higher in northern Finland than in southern Finland. Our much more extensive data do not support that hypothesis. It is more probable that that finding was an artefact confounded by the small number of study sites combined with high variation of temperature sensitivity (Table 2).

#### 4.2. Annual $\text{CO}_2$ effluxes

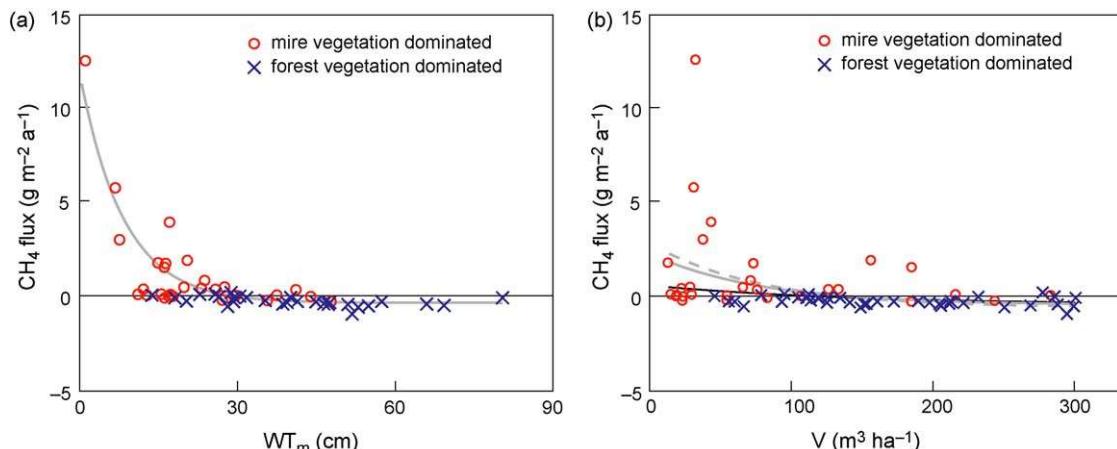
Estimated annual  $\text{CO}_2$  efflux was almost totally explained by soil respiration at the reference temperature ( $10^\circ\text{C}$ ) and summer mean air temperature. The negligible role of temperature sensitivity is due to the fact that summer temperatures, which mainly deter-



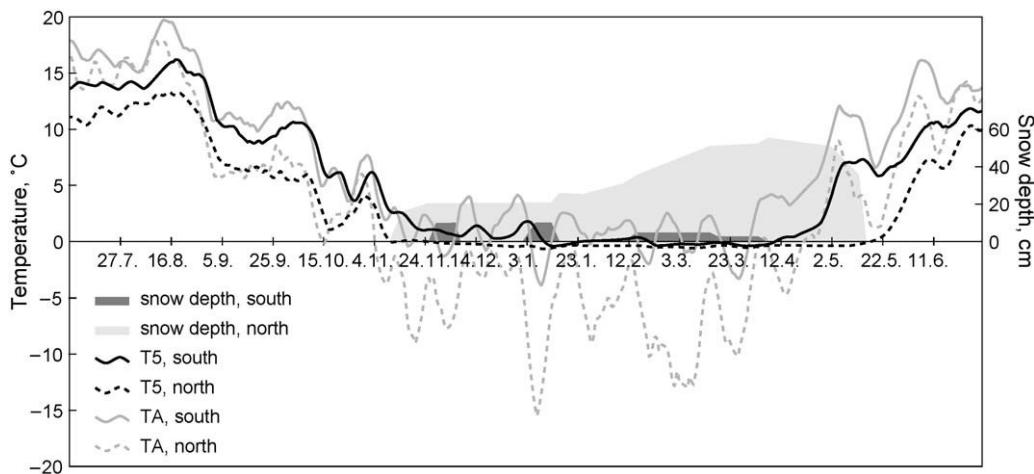
**Fig. 7.** The relationship of annual  $\text{N}_2\text{O}$  flux and soil carbon to nitrogen ratio (CN) of top 20 cm of soil. From Klemmedsson et al. (2005, diagonal crosses) treed peatlands in Sweden and Finland, from Minkkinen et al. (2007a, straight crosses) spruce-dominated peatlands in Finland and from Regina et al. (1996, 1998, triangles), forestry-drained peatlands in Finland were included besides our data (circles and small figure). The data of Regina et al. (1996, 1998) are here excluded from data of the other studies. The sites with bold symbols are forested peatlands with agricultural history. The curves are fittings of model  $\text{N}_2\text{O}$  flux =  $a e^{-b \text{CN}}$ . Parameters ( $\pm$ asymptotic standard error): All sites (grey dashed line,  $n=95$ ),  $a=630 (\pm 486)$ ,  $b=0.417 (\pm 0.054)$ ,  $b^2=49.8\%$ ; all forestry-drained sites (black solid line,  $n=92$ ),  $a=1.46 (\pm 1.07)$ ,  $b=0.103 (\pm 0.035)$ , and  $b^2=35.2\%$ ; our study sites (grey solid line,  $n=68$ ),  $a=0.161 (\pm 0.139)$ ,  $b=0.0328 (\pm 0.0335)$ , and  $b^2=24.2\%$ .

mined annual  $\text{CO}_2$  efflux, had a mean of about  $10^\circ\text{C}$ . If temperature sensitivity of respiration increases, then respiration increases at high temperatures but also decreases at low temperatures. Annual soil  $\text{CO}_2$  efflux could, thus, be explained by summer mean air temperature and the variables that explained soil respiration at  $10^\circ\text{C}$  (Table 5). Therefore, the unexplained phenomenon of variation in temperature sensitivity does not impede the estimation and subsequent upscaling of annual  $\text{CO}_2$  efflux.

The winter of 2007–2008 was exceptionally warm, with a mean air temperature that was  $3.4^\circ\text{C}$  higher than the mean of the winters of the 1971–2000 period (Table 1). By correlating the estimated winter respiration with the winter mean air temperature,  $\text{CO}_2$  fluxes for an average winter would be  $69 \text{ g m}^{-2} \text{ year}^{-1}$  lower for total and  $34 \text{ g m}^{-2} \text{ year}^{-1}$  lower for heterotrophic soil respiration. Those values correspond to only 2.7% and 2.8% of mean annual res-



**Fig. 6.** (a) Regression ( $\text{CH}_4$  flux =  $y_0 + ae^{-bWT_m}$ ) between average summer water table depth ( $WT_m$ ) and annual  $\text{CH}_4$  flux. Parameters ( $\pm$ asymptotic standard error):  $y_0 = -0.378 (\pm 0.053)$ ,  $a = 12.3 (\pm 2.7)$ ,  $b = 0.121 (\pm 0.014)$ ,  $r^2 = 0.64$ ,  $n = 57$ . Weighting by 1/variance. (b) Regressions ( $\text{CH}_4$  flux =  $y_0 + ae^{-bV}$ ) between tree stand stem volume ( $V$ ) and annual  $\text{CH}_4$  flux. Weighted fitting (black thin line):  $y_0 = -0.484 (\pm 0.515)$ ,  $a = 1.03 (\pm 0.39)$ ,  $b = 0.00681 (\pm 0.01088)$ , and  $r^2 = 0.22$ , not weighted (grey solid line):  $y_0 = -0.455 (\pm 0.618)$ ,  $a = 2.72 (\pm 0.90)$ ,  $b = 0.0129 (\pm 0.0116)$ , and  $r^2 = 0.16$ . Minkkinen et al. (2007c, not weighted, grey dashed line):  $y_0 = -0.613 (\pm 0.551)$ ,  $a = 3.42 (\pm 0.62)$ , and  $b = 0.0126 (\pm 0.0067)$ .



**Fig. 8.** Soil temperature at 5 cm depth (T5), air temperature (TA), and snow depth at five southernmost (south) and northernmost (north) study sites in July 2007 to June 2008. Temperatures are 7-day running averages of means of the five sites. Snow depths are rough estimates based on snow cover maps of Finnish Meteorological Institute (2008).

piration. Summer temperature was closer to the long term average, of only 0.5 °C higher than that of 1971–2000. However, this small difference in summer mean temperature would result in higher increases of annual CO<sub>2</sub> fluxes, of 126 and 51 g m<sup>-2</sup> year<sup>-1</sup>, corresponding to 4.9% and 4.3% of mean annual respiration.

Air temperature varied between sites more during winter than during summer whereas soil temperature varied less during winter (Table 1). Due to the insulating snow cover in the North during most of the winter, soil temperatures between northern and southern Finland were similar, despite the clearly different air temperatures (Fig. 8). This finding together with the small share of winter in annual respiration (18% of total and 22% of heterotrophic soil respiration) makes annual respiration relatively independent of variation in winter air temperature. Thus, summer mean air temperature can be used alone to estimate interannual variation in respiration with reasonable precision.

Drought periods and also excessive wetness can restrict soil respiration in peatlands during summer (Mäkiranta et al., 2009; Silvola et al., 1996). The mean rainfall for the years 2007–2008 was 20% higher than for the years 1971–2000 in our study sites and no summer drought periods occurred. Therefore, it is unlikely that drought would have restricted respiration during the study period. Instead, excessive soil moisture could have reduced respiration in northern Finland, where even normal summers are wet. More than two summers of measurements on the same sites would be needed to evaluate the effect of soil moisture on the annual soil respiration.

Soil CO<sub>2</sub> efflux of forestry-drained peatlands can be upscaled for the whole country using only one model that describes peat properties, tree stand and local temperature conditions (Table 5). NFI and weather statistics provide summer air temperatures, site type distributions and tree stand characteristics. However, water table depth and peat bulk density are not generally measured in NFI, which predisposes against using the best models.

#### 4.3. CH<sub>4</sub> and N<sub>2</sub>O fluxes

Earlier studies on Finnish forestry-drained peatlands (Alm et al., 1999; Minkkinen et al., 2007c; Nykänen et al., 1998) show annual CH<sub>4</sub> and N<sub>2</sub>O fluxes of the same magnitude as those found in our study, except for our highest CH<sub>4</sub> emissions which were several times higher than previously reported. The highest flux, 12.5 g m<sup>-2</sup> year<sup>-1</sup>, coincided with the 12.6 g m<sup>-2</sup> year<sup>-1</sup> value reported for a pristine oligotrophic fen in southern Finland (Rinne et al., 2007). Indeed, although ditched, the site was very poorly

drained and resembled a pristine peatland with water table fluctuating close to the peat surface all summer. Such wet sites were, however, not exceptional in our data (Fig. 6), which indicates that the NFI classified "drained peatlands" include a considerable proportion of very wet sites with little difference to pristine peatland conditions.

The summer mean water table explained the variation in CH<sub>4</sub> flux well. The water table affects CH<sub>4</sub> flux in two ways: A water table lying at lower depths directly results in lower production and higher oxidation of CH<sub>4</sub> in soil (Kettunen et al., 1999). Sedges are the main plant group that imports substrate to methanogenic microbes in anoxic soil layers and exports CH<sub>4</sub> to the atmosphere past the methanotrophic microbes (Joabsson et al., 1999; Kettunen, 2003). A water table drawdown changes vegetation composition from sedge and grass dominated towards tree and dwarf shrub dominated (Laiho et al., 2003), which decreases methane emissions. However, patches of mire vegetation remain scattered throughout the drained sites, which indicates wetter local conditions and higher CH<sub>4</sub> effluxes or smaller CH<sub>4</sub> sinks (Minkkinen and Laine, 2006). Consequently, mire vegetation cover was also a significant predictor for CH<sub>4</sub> flux on our drained sites.

The regression between annual CH<sub>4</sub> flux and tree stand stem volume (Fig. 6) should be used carefully. To some extent, evapotranspiration by a tree stand can contribute to keeping the water table down (Paavilainen and Päivinen, 1995), but the regression is largely based on a low water table that creates good conditions for tree growth. Over time, tree stands will change when trees grow and fellings occur. As a result, the relationship between tree stand stem volume and CH<sub>4</sub> flux will also eventually change. A very similar relationship was found by Minkkinen et al. (2007c) who used data obtained from different sites and over different study period to ours (Fig. 6), which indicates that summer emissions are at least quite stable over years.

We hypothesised that soil nitrogen quantities and their availability would correlate with N<sub>2</sub>O flux. Soil carbon to nitrogen ratio (CN) would therefore be a good predictor of N<sub>2</sub>O flux, as suggested by Klemedtsson et al. (2005). However, the sharp increase in N<sub>2</sub>O flux observed when CN ratio decreases below 25, shown by Klemedtsson et al. (2005), seems to occur only in those peatlands that have an agricultural history (Fig. 7). Such peatlands may retain high levels of N<sub>2</sub>O emissions even decades after afforestation (Mäkiranta et al., 2007). Therefore, the proposed regression model could not estimate N<sub>2</sub>O fluxes for both forestry-drained and forested agricultural peatlands without bias. We suggest that when

statistical models are used for estimating N<sub>2</sub>O emissions, land-use history must be accounted for: fluxes from forestry-drained peatlands should be estimated using a model based on data that includes forestry-drained peatlands only.

The correlation of N<sub>2</sub>O flux with summer mean air temperature and water table depth allows us to assume that interannual variation in fluxes is more than likely. [Regina et al. \(1996\)](#) found considerable interannual variation in their measurements taken over 2 years. The results on similar site types with similar methods obtained by [Minkkinen et al. \(2007a\)](#), Fig. 7, from different years and sites show considerably higher fluxes than does this study. By including results from several studies, we can at least partly take interannual variation into account.

As the summer CH<sub>4</sub> and N<sub>2</sub>O fluxes were interpolated from 5 to 7 measuring occasions only and winter fluxes were estimated based on earlier studies on other sites, annual CH<sub>4</sub> and N<sub>2</sub>O flux estimates cannot be considered to be very precise. They should be on a reasonable level anyhow, since the share of winter was relatively stable and temporal and spatial variation inside each site was modest compared to the number of measurements. The mean of site-specific standard error of mean/mean of measurements was 0.74 for CH<sub>4</sub> and 1.55 for N<sub>2</sub>O.

In our N<sub>2</sub>O data, possible short-living flux peaks during frost-thaw events ([Maljanen et al., 2010](#); [Pihlatie et al., 2009](#); [Saari et al., 2009](#)) were likely to go unnoticed, and their importance on annual emissions cannot be estimated here. However, the importance of peaks can be very high: [Maljanen et al. \(2010\)](#) found one peak during the winter, and the inclusion of that peak quadrupled the annual N<sub>2</sub>O emission estimate from 1.1 to 4.1 g m<sup>-2</sup>. We found only a couple of peaks in the whole data, and the sites with high annual emissions had high emissions throughout the whole measuring period. Moreover, [Minkkinen et al. \(2007a\)](#) did not find clear peaks in higher frequency (weekly-biweekly) year-round data. Therefore, it appears that peaks are rare in boreal forestry-drained peatlands or difficult to capture with manual chambers and, thus, very high frequency year-around data would be needed to evaluate their importance.

## 5. Conclusions

This study presents data applicable for estimating soil-atmosphere GHG fluxes for boreal forestry-drained peatlands. We found that annual soil CO<sub>2</sub> efflux can be reliably estimated by determining CO<sub>2</sub> efflux at summer mean soil temperature. Methane emissions from the drained peatlands were generally low: well-drained sites are CH<sub>4</sub> sinks, but a considerable share of the drained peatlands still emits methane because of high mean water table. N<sub>2</sub>O emissions were generally lower than earlier estimated and peak emissions were rare. CN ratio was a significant but not very strong predictor of annual N<sub>2</sub>O fluxes. Forest inventory data and weather statistics can provide useful data for explaining and upscaling fluxes. As water table depth proved to be an important variable for explaining variation in CO<sub>2</sub> and CH<sub>4</sub> fluxes, extensive data on water-level conditions of forestry-drained peatlands would significantly improve country scale predictions.

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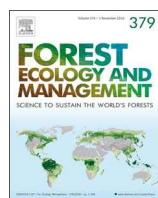
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## Update

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Corrigendum

Corrigendum to “Soil–atmosphere CO<sub>2</sub>, CH<sub>4</sub> and N<sub>2</sub>O fluxes in boreal forestry-drained peatlands” [For. Ecol. Manage. 260 (2010) 411–421]



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The authors regret that N<sub>2</sub>O fluxes for 40 of the 68 study sites (Fig. 1) have been found to be nonsensical due to instrument failure in the EC detector in the laboratory that analyzed the gas samples from the northern study sites. N<sub>2</sub>O fluxes for those sites have to be rejected. N<sub>2</sub>O fluxes for the rest of the sites and all CO<sub>2</sub> and CH<sub>4</sub> fluxes remain unaltered.

Results and conclusions are otherwise unaltered, but updated results, figures and tables for N<sub>2</sub>O fluxes are reported below. While the CO<sub>2</sub> and CH<sub>4</sub> fluxes cover both the south and middle boreal zones, the accepted N<sub>2</sub>O fluxes mainly represent the south boreal zone.

Annual N<sub>2</sub>O fluxes varied between 0.04 and 0.92 g m<sup>-2</sup> year<sup>-1</sup> and

types (Table 6).

The finding of sites with annual level N<sub>2</sub>O sink was due to the instrument failure and all the sites in the updated results are N<sub>2</sub>O sources (Fig. 7).

The updated results are more in line with the earlier results from forestry-drained peatlands, showing small but consistent emissions of N<sub>2</sub>O with occasional higher emissions at N rich sites. Exponential fit between CN ratio and N<sub>2</sub>O emission showed similar parameters for our updated data and all forestry-drained peatland data (Fig. 7).

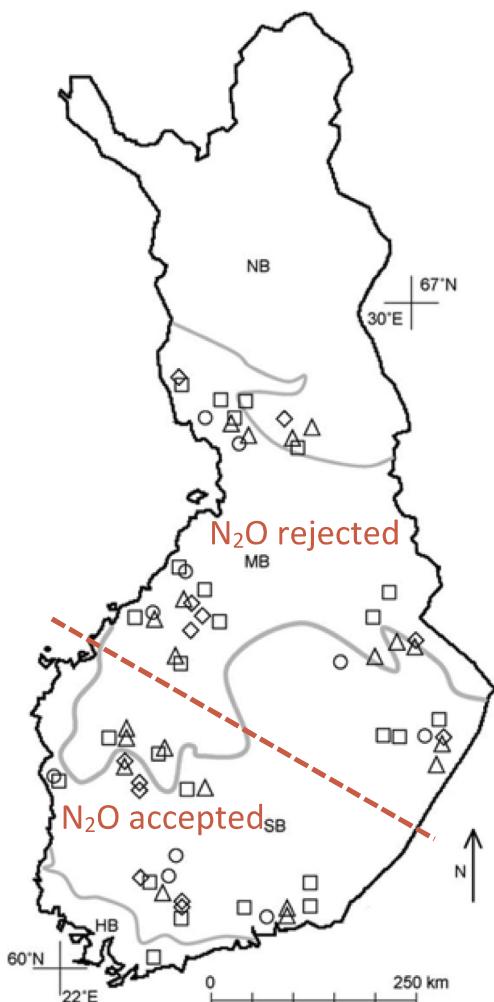
The authors would like to apologise for any inconvenience caused.

and a diminishing trend towards nitrogen poorer sites (Fig. 7) and site

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**Fig. 1.** Division between sites for which  $\text{N}_2\text{O}$  fluxes were accepted and rejected. The study sites by site type (Laine, 1989) from the most to the least fertile: Herb-rich type (Rhtkg, n = 4 accepted/6 rejected, circles), *Vaccinium myrtillus* types I and II (Mtkg I and II, n = 10/15, squares), *Vaccinium vitis-idaea* types I and II (Ptkg I and II, n = 8/12, triangles), Dwarf shrub type (Vatk, n = 6/7, diamonds). Grey lines denote the boundaries of vegetation zones (Ahti et al., 1968): HB, hemiboreal; SB, south boreal; MB, middle boreal; NB, north boreal.

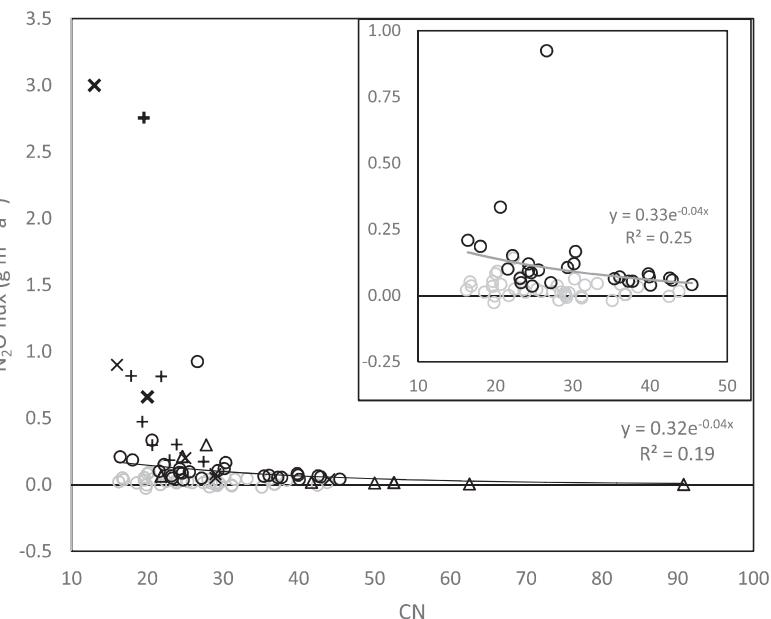
**Table 6**

Arithmetic means of annual  $\text{N}_2\text{O}$  fluxes ( $\text{g N}_2\text{O m}^{-2} \text{year}^{-1}$ ) in Finnish sites in Fig. 7 according to peatland site type. SE = standard error of the mean, n = number of sites.

Site type	$\text{N}_2\text{O}$ flux	SE	n
Rhtkg	0.331	0.101	6
Mtkg I	0.177	0.052	8
Mtkg II	0.323	0.123	8
Ptkg I	0.064	0.004	3
Ptkg II	0.098	0.022	7
Vatk	0.043	0.009	9

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**Fig. 7.** The relationship of annual  $\text{N}_2\text{O}$  flux and soil carbon to nitrogen ratio (CN) of top 20 cm of soil. Black circles: accepted data, grey circles: rejected data. The grey curve is a fitting to our accepted data. The black curve is a fitting to all the accepted data for forestry-drained sites in the figure. The sites with bold symbols are forested peatlands with agricultural history and are not used for the fitting. From Klemmedsson et al. (2005, diagonal crosses) treed peatlands in Sweden, from Minkkinen et al. (2007a, straight crosses) spruce dominated peatlands in Finland and from Regina et al. (1996, 1998, triangles), forestry-drained peatlands in Finland were included besides our data (circles and small figure).