

Annual CO₂ and CH₄ fluxes of pristine boreal mires as a background for the lifecycle analyses of peat energy

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This study was conducted to improve the estimates of C gas fluxes in boreal ombrotrophic and minerotrophic mires used in the lifecycle analysis of peat energy. We reviewed literature and collected field data from two new sites in southern Finland. In the literature, annual estimates of net CO₂ exchange varied from –85 to +67 g C m⁻² a⁻¹ for ombrotrophic mires and from –101 to +98 g C m⁻² a⁻¹ for minerotrophic mires. Correspondingly, net CH₄ flux estimates varied from less than –1 up to –16 g C m⁻² a⁻¹ and from less than –1 up to –42 g C m⁻² a⁻¹ for ombrotrophic and minerotrophic mires, respectively. Negative values indicate net efflux from the ecosystem. The modelling of C gas fluxes for the 30 simulated years clearly highlighted the need for long-term records of multiple environmental factors from the same sites, and the need for a number of improvements in the modelling of fluxes, as well as the environmental conditions driving C fluxes. The reduction of uncertainty in the background values of lifecycle analyses requires more detailed knowledge of the mire types used for peat harvesting and long-term field measurements combined with the developed process models and meteorological information. The use of C gas fluxes in pristine mires as a background for anthropogenic emissions is, however, only one option. Another option could be to consider anthropogenic emissions from the use of peat energy as such.

Introduction

Autotrophic vegetation takes up carbon dioxide (CO₂) in photosynthesis and releases it back to the atmosphere in respiration. Although a relatively high proportion of the litter produced by mire plants is decomposed, another part of the

litter accumulates as peat due to the wet conditions that restrict the oxic decomposition processes (Clymo *et al.* 1984). Decomposition continues even in anoxic conditions where a small proportion of the assimilated carbon is converted to methane (CH₄). The rate of photosynthesis and decomposition vary both temporally and

spatially throughout the mires, and respond with high temporal resolution to changes in weather conditions. In years with a long dry period during the growing season, the annual C balance in certain mires may remain negative i.e. more carbon is lost to the atmosphere than is gained from it (e.g. Oechel *et al.* 1997, Alm *et al.* 1999b). Annual balances integrated over time form a long-term balance which has, up until now, been positive, i.e. peat deposits have been formed although the accumulation rate in mires varied greatly during the Holocene (e.g. Mäkilä 1997, Campbell *et al.* 2000).

The energy utilisation of peat involves mire drainage, removal of the living surface layer, peat harvesting, storage, transport and combustion, and finally the remaining cutaway area is forested, re-wetted or left to develop naturally (e.g. Frilander *et al.* 1996, Selin 1999). In the lifecycle analysis of peat, the Technical Research Centre of Finland (VTT) aims to take into account greenhouse gas fluxes from all phases of the energy production chain, including the initial status and after-use treatment of the harvested peatland (Savolainen *et al.* 1994, Kirkinen *et al.* 2007). This study was conducted in order to improve the estimates of C gas exchange in boreal ombrotrophic and minerotrophic mires used in the lifecycle analysis of peat energy. We made a literature review and collected field data from two new sites in southern Finland. New data were used to study the variation in CO₂ and CH₄ fluxes at the same sites over the longer period.

Materials and methods

Literature review

Many of the earlier studies have concentrated only on fluxes during the growing season. These values were complemented in accordance with the current knowledge of flux rates during the “dormant period” (Dise 1992, Alm *et al.* 1999a), i.e. by assuming that 15% of the annual CH₄ and CO₂ efflux is released outside the growing season in the case of values reported by Heikkinen *et al.* 2002, Huttunen *et al.* 2003, Nilsson

et al. 2001, Nykänen *et al.* 1998, Suyker *et al.* 1996, Waddington and Roulet 2000. A release rate of 30 g C m⁻² for an ombrotrophic site (Alm *et al.* 1999b) was used when the respiration sum for the growing season was not mentioned (tower measurement site, Shurpali *et al.* 1995).

Study sites

Two study sites were selected in southern Finland, Hangassuo (60°47'N, 26°54'E) and Haukkasuo (60°49'N, 26°57'E). The geological characteristics of both mires were investigated by the Geological Survey of Finland during the course of a national peat resource inventory (Mäkilä and Grundström 1984).

The Hangassuo study site represents a fen lagg of a raised bog complex (referred to hereafter as “minerotrophic site”). The thickness of the *Carex*-dominated peat layer varies from 1.6 to 2.3 m and the age of the basal peat is between 920–2340 cal BP (for methodological details see e.g. Mäkilä 1997). The apparent long-term rate of C accumulation for the lagg is 22 g m⁻² a⁻¹. The current vegetation is dominated by *Carex rostrata*, *Betula nana*, *Eriophorum vaginatum*, *Menyanthes trifoliata*, *Andromeda polifolia*, *Vaccinium oxycoccos*, *Sphagnum fallax*, *S. fuscum* and *S. magellanicum*.

The Haukkasuo study area (“ombrotrophic site”) is located in the centre of a raised bog where the thickness of the *Sphagnum*-dominated peat layer is 6.2 m. The age of the basal peat is 9930 cal BP and the apparent long-term C accumulation rate on the study area is 22 g m⁻² a⁻¹. The development of Haukkasuo bog has been described in more detailed by Mäkilä (1997) and Puranen *et al.* (1999). The current vegetation consists of *Calluna vulgaris*, *Empetrum nigrum*, *B. nana*, *E. vaginatum*, *Rubus chamaemorus*, *V. oxycoccos*, *A. polifolia* and *S. fuscum* on hummocks and *Rhynchospora alba*, *Scheuchzeria palustris*, *A. polifolia*, *V. oxycoccos*, *S. majus* and *S. balticum* on hollows. These two types of microsite account for 71% of the mire area. The rest of the area is characterised either as hollow areas turned into black peat surface by ground frost, some water pools and lawn surfaces.

Field measurements

Field data were collected from June 2002 until December 2004, except in November and December 2003, during monthly measuring periods. Permanent collars were installed on both study sites. In the ombrotrophic site, 6 were on the hollow surface, 2 on the lawn surface, 4 on hummocks, 4 on the black peat surface and 2 on a pool. In the minerotrophic site, 12 collars were located on a transect running from the mire margin towards the centre. Pair-wise measurements with a transparent chamber equipped with a cooling system that maintained the temperature at the level of the ambient temperature, and an opaque chamber connected to the portable CO₂ analyser were used to measure net CO₂ exchange and dark respiration 1–8 times in each collar during the different phases of the growing season. Methane efflux and winter time respiration were measured by taking gas samples from the headspace of the closed chambers and analysing them in the laboratory on a gas chromatograph and infra-red analyser. Irradiation, water table depth and temperatures in the air and down the peat profile were measured simultaneously during the flux measurements (for more details see Saarnio *et al.* 2003). Most of the measurements were made during the daytime (08:00–21:00). In addition, nighttime (22:00–00:00, 04:00–07:00) measurements were made in July 2003, July 2004 and August 2004.

The green surface area of all vascular vegetation in the gas exchange collars was estimated 2 times in 2002, 6–7 times in 2003 and 11 times in 2004 during the snow-free season. Individuals from all dominant species were marked outside the collars for measurement of leaf and shoot length and width. The number of shoots or leaves of each species in the gas exchange collars were also counted once a month using five 8 × 8 cm subplots inside the study collars. The number and area information of each species were used to calculate the total green area in each collar. The Gaussian Green Area Index was calculated separately for each dominant vascular plant species as follows:

$$\text{GAI}_{\text{species}} = a \times \exp\{-0.5[(x - x_0)/b]^2\}, \quad (1)$$

where a , x_0 and b are model parameters and x is the number of hours from the beginning of the year. Green area indices of individual species were summarised in order to obtain the seasonal development of the green area of all vascular vegetation (GAI_{total}) for the CO₂ models, or aerenchymatous vascular species (GAI_{aerenchymatous}) for the CH₄ models (for comparison see Wilson *et al.* 2007). Model parameters were estimated from two field-study years 2003 and 2004. Seasonally averaged GAI development, adapted for each of the dominant microsite types, was used in calculating the 30-year C gas balances for these microsities.

Regression and simulation models

CO₂ and CH₄ fluxes for the snow-free period were calculated using regression models and appropriate environmental data series. Model formulae were selected to represent the ecological relationship between environmental factors and the gas fluxes (cf. Tuittila *et al.* 2004, Alm *et al.* 2007). The rate of gross photosynthesis at the ecosystem level was described as a function of the light intensity and green area of the vascular vegetation, rate of respiration as a function of the soil temperature at the depth of 2 cm, depth of water table and living biomass (indicated here by GAI_{total}) and the CH₄ efflux as a function of peat temperature at the depth of 40 cm or 10 cm, water table, and transport capacity of vascular plants indicated here as the GAI of aerenchymatous plants.

Dynamics of soil temperature at different depths, groundwater table and the snow depth were simulated using the model by Granberg *et al.* (1999). The model is driven by hourly weather patterns which are not commonly available over decadal time scales. Therefore a 30-year-long time series of hourly air temperature, precipitation, and solar irradiation was generated using a regional weather simulator software. The weather simulator was modified by improving the statistical distribution of the temperature in the version earlier created for FINNFOR, a model used to assess the response of boreal forest ecosystems to climate change (see Kel-

lomäki *et al.* 1993, Strandman *et al.* 1993). The simulated weather patterns were calibrated using the field observations of irradiation, peat temperatures at the depths of 2, 10 and 40 cm and water tables in the different microsites, and the standard long-term monthly average temperature and precipitation records measured at Utti for the period of 1961–1990 (Ilmatieteen laitos 2002).

Wintertime efflux of CO₂ and CH₄ were estimated by multiplying the average observed flux rates (mg CO₂ or CH₄ m⁻² h⁻¹) by the number of hours with a snow cover (snow depth > 0.01 m) in each year.

The regression models and environmental time series were made only for the dominant microsites of the ombrotrophic site. According to the field measurements, the lawns resembled hollows in terms of the CH₄ efflux rates, but hummocks in terms of the CO₂ fluxes. Correspondingly, the CH₄ efflux rate of the black peat surfaces was at the level of hummocks, while their respiration rate was similar to hollows and their gross CO₂ uptake was about half of that in hollows. We applied the corresponding values from the dominating microsites for these minor ones in order to calculate the ecosystem level flux estimates for the ombrotrophic site. The minerotrophic site was considered to be one and the same microsite with slight variation in vegetation.

Results

According to the literature review, the average (\pm standard deviation) net CO₂ fluxes for ombrotrophic and minerotrophic mires were -15 ± 53 and 15 ± 63 g CO₂-C m⁻² a⁻¹, respectively (Table 1). Correspondingly, the average release rates of CH₄ from ombrotrophic and minerotrophic mires were 5 ± 4 and 13 ± 10 g CH₄-C m⁻² a⁻¹, respectively.

The regression models explained 37%–80% of the observed variation in C gas fluxes in our study sites (Table 2). In general, the modelled fluxes underestimated the highest peaks in the observed gas fluxes (Fig. 1) and overestimated the lowest values in both spring and autumn. The fluxes modelled by regression were not sensitive to a 10% change in the individual parameter

estimates of the regression models except under unrealistic circumstances (e.g. maximum summer peat temperature in combination with zero green area index). The amounts of C photosynthesised and C released as CH₄ were relatively stable over the simulated years. In contrast, the variation in the amount of C respired dictated the annual CO₂ balance on both the ombrotrophic and minerotrophic site (Table 3). The 30-year ranges of the CO₂ balance for the ombrotrophic and minerotrophic sites were -100 to $+17$ g C m⁻² a⁻¹ and $+36$ to $+91$ g C m⁻² a⁻¹, respectively. Correspondingly, the annual CH₄ effluxes varied from -7 to -9 g C m⁻² a⁻¹ on the ombrotrophic site and from -17 to -19 g C m⁻² a⁻¹ on the minerotrophic site. However, the environmental factors measured in the field and the simulated environmental variables did not always fully correspond with each other and this weakened the reliability of the simulated fluxes i.e. they should not be interpreted too precisely.

Discussion

Spatial and temporal variability of CO₂ and CH₄ fluxes

Carbon cycling in pristine boreal mires has been extensively studied (e.g. references in Table 1). Carbon gas fluxes have been found to vary widely both temporally and spatially. Both net CO₂ and CH₄ fluxes between the atmosphere and the mire ecosystem are the result of several processes. The net CO₂ flux is a sum of the rates of photosynthesis and autotrophic and heterotrophic respiration, and the net CH₄ flux is a result of CH₄ production, oxidation and transport processes. The rate of photosynthesis follows changes in irradiation, temperature, moisture and the amount of green biomass at the momentary, daily, seasonal and interannual level, and varies between microsites and mire types (e.g. Alm *et al.* 1997, Froelking *et al.* 1998). The rate of respiration, as well as the CH₄ flux, is mainly dependent on the variation in temperature, availability of oxygen, quantity and quality of substrates and the vegetation over time and space (e.g. Bubier and Moore 1994, Saarnio *et al.* 2003). In this study, all the temporal and spatial variations were reduced to an annual flux

Table 1. Review of annual CO₂ and CH₄ balances at pristine boreal ombrotrophic and minerotrophic mires. Several values on the same row represent annual flux estimates for different years for the same site. Negative values indicate net efflux from the ecosystem to the atmosphere.

Annual flux rate (g C m ⁻² a ⁻¹)	Location	Characteristics	References
Carbon dioxide, ombrotrophic mires			
-80	62°50'N, 30°53' E	open <i>S. fuscum</i> bog, hummock, lawn, hollow	Alm <i>et al.</i> 1999b
-85, -30, +20, +67	45°24'N, 75°30' W	raised bog, hummocks, hollows	Lafleur <i>et al.</i> 2001, Frolking <i>et al.</i> 2002
+48	60°45'N, 89°23' E	part of the bog complex, hollows and hummocks	Schulze <i>et al.</i> 2002
-13, -27 w	63°44'N, 20°06' E	eccentric raised bog, ridges, lawns, pools	Waddington & Roulet 2000
Carbon dioxide, minerotrophic mires			
+98	62°47'N, 30°56' E	oligotrophic fen, hummocks, lawns, flarks	Alm <i>et al.</i> 1997
+4, +21, +8, +6, +37, +53	69°08'N, 27°17' E	mesotrophic flark fen, strings, hollows	Aurela <i>et al.</i> 2004
-12, -11	55°45'N, 97°53' W	poor intermediate fen, hummocks, hollows	Potter <i>et al.</i> 2001
-101, +2 wg	47°32'N, 93°28' W	poor fen, hummock, hollows	Shurpali <i>et al.</i> 1995
Methane, ombrotrophic mires			
> -1, > -1, > -1	45°24'N, 75°30' W	raised bog, hummocks, hollows	Frolking <i>et al.</i> 2002
-2.2 aw	61°N, 15°E	marsh (ombrotrophic)	Nilsson <i>et al.</i> 2001
-2.3 aw	64.5°N, 17.5°E	marsh (ombrotrophic)	Nilsson <i>et al.</i> 2001
-2.7 aw	67°N, 20°E	marsh (ombrotrophic)	Nilsson <i>et al.</i> 2001
-7.5, -8.9 w	62°46'N, 29°50' E	dwarf shrub pine bog	Nykänen <i>et al.</i> 1998
-5.4 w	62°46'N, 29°50' E	dwarf shrub pine bog	Nykänen <i>et al.</i> 1998
-1.7, -1.7 w	61°47'N, 24°18' E	dwarf shrub pine bog	Nykänen <i>et al.</i> 1998
-3.8, -2.1 w	62°46'N, 29°50' E	<i>S. fuscum</i> pine bog	Nykänen <i>et al.</i> 1998
-6.7, -4.6 w	61°47'N, 24°18' E	cottongrass pine bog	Nykänen <i>et al.</i> 1998
-5.0, -3.3 w	61°47'N, 24°18' E	cottongrass pine bog with <i>S. fuscum</i> hummocks	Nykänen <i>et al.</i> 1998
-0.2, -0.9 w, -3.0	62°50'N, 30°53' E	<i>S. fuscum</i> bog, hummock, lawn, hollow	Nykänen <i>et al.</i> 1998, Alm <i>et al.</i> 1999b
-16.4, -13.7 pw	62°46'N, 29°50' E	ridge-hollow bog	Nykänen <i>et al.</i> 1998
-8.0, -7.1 w	61°47'N, 24°18' E	low-sedge bog	Nykänen <i>et al.</i> 1998
-4.7, -4.5 w	63°44'N, 20°06' E	eccentric raised bog, ridges, lawns, pools	Waddington & Roulet 2000
Methane, minerotrophic mires			
-14.6, -13.4, -10.5, -8.2, -14.1, -12.7, -15.3, -16.4, -8.6, -9.4, -8.2, -15.3, -20.5, -13.0, -14.0, -10.3, -16.4	64°11'N, 19°33' E	oligotrophic fen, lawn	Granberg <i>et al.</i> 2001

continued

Table 1. Continued.

Annual flux rate (g C m ⁻² a ⁻¹)	Location	Characteristics	References
-6.5 w	69°08'N, 27°17'E	mesotrophic fen, strings, hollows	Hargreaves <i>et al.</i> 2001, Heikkinen <i>et al.</i> 2002
-8.8, -13.2 w	67°N, 27°E	oligotrophic tall-sedge pine fen	Huttunen <i>et al.</i> 2003
-15.9, -23.8 w	67°N, 27°E	oligotrophic flark fen	Huttunen <i>et al.</i> 2003
-27.3, -27.3 w	67°N, 27°E	oligotrophic <i>Sphagnum</i> flark fen	Huttunen <i>et al.</i> 2003
-25.5, -28.2 w	67°N, 27°E	oligotrophic tall-sedge fen	Huttunen <i>et al.</i> 2003
-10.6, -15.9 w	67°N, 27°E	mesotrophic flark fen	Huttunen <i>et al.</i> 2003
-11.5, -22.9 w	67°N, 27°E	swamp fen (mesotrophic)	Huttunen <i>et al.</i> 2003
-18.5, -35.2 w	67°N, 27°E	mesotrophic mud- bottom flark fen	Huttunen <i>et al.</i> 2003
-17.6, -18.5 w	67°N, 27°E	eutrophic birch fen	Huttunen <i>et al.</i> 2003
-0.9, -1.6 w	67°N, 27°E	eutrophic pine fen	Huttunen <i>et al.</i> 2003
-0.086, -0.086 w	67°N, 27°E	herb-grass spruce mire (eutrophic)	Huttunen <i>et al.</i> 2003
-1.3 aw	61°N, 15°E	transitional fen	Nilsson <i>et al.</i> 2001
-2.5 aw	64.5°N, 17.5°E	transitional fen	Nilsson <i>et al.</i> 2001
-1.5 aw	67°N, 20°E	transitional fen	Nilsson <i>et al.</i> 2001
-4.7 aw	61°N, 15°E	low-sedge fen	Nilsson <i>et al.</i> 2001
-7.7 aw	64.5°N, 17.5°E	low-sedge fen	Nilsson <i>et al.</i> 2001
-5.3 aw	64.5°N, 17.5°E	low-sedge fen	Nilsson <i>et al.</i> 2001
-10.2 aw	67°N, 20°E	low-sedge fen	Nilsson <i>et al.</i> 2001
-15.2 aw	67°N, 20°E	low-sedge fen	Nilsson <i>et al.</i> 2001
-7.5 aw	61°N, 15°E	tall-sedge fen	Nilsson <i>et al.</i> 2001
-34.9 aw	64.5°N, 17.5°E	tall-sedge fen	Nilsson <i>et al.</i> 2001
-8.4 aw	64.5°N, 17.5°E	tall-sedge fen	Nilsson <i>et al.</i> 2001
-13.0 aw	67°N, 20°E	tall-sedge fen	Nilsson <i>et al.</i> 2001
-9.4 aw	67°N, 20°E	tall-sedge fen	Nilsson <i>et al.</i> 2001
-19.4, -34.1 w	61°47'N, 24°18'E	tall-sedge fen (oligotrophic/oligo- mesotrophic)	Nykänen <i>et al.</i> 1998
-15.5, -4.6 w	61°47'N, 24°18'E	tall-sedge pine fen (oligotrophic/oligo- mesotrophic)	Nykänen <i>et al.</i> 1998
-41.0, -25.3 w	62°46'N, 29°50'E	lagg fen (oligotrophic/oligo- mesotrophic)	Nykänen <i>et al.</i> 1998
-11.2, -13.1 w	62°46'N, 29°50'E	herb-rich flark fen (mesotrophic)	Nykänen <i>et al.</i> 1998
-2.1 w	61°47'N, 24°18'E	herb-rich flark fen (mesotrophic)	Nykänen <i>et al.</i> 1998
-0.4, -0.4	55°45'N, 97°53'W	poor intermediate fen, hummocks, hollows	Potter <i>et al.</i> 2001
-22.1	62°47'N, 30°56'E	oligotrophic fen, hummocks, lawns, flarks	Saarnio <i>et al.</i> 1997
-13.3	47°32'N, 93°28'W	poor fen, hummocks, hollows	Shurpali <i>et al.</i> 1993
-19.2 w	53°57'N, 105°57'W	meso-eutrophic fen, strings, flarks	Suyker <i>et al.</i> 1996

w = winter release has been estimated to be 15% of the annual CH₄ or CO₂ release (respiration).

wg = winter release has been estimated to be 30 g C m⁻².

a = average of several sites.

p = assumed that 80% of the surface area represented hollow surface and the remaining 20% hummock surface.

rate for ombrotrophic and minerotrophic mires according to the practice of VTT (Savolainen *et al.* 1994, Kirkinen *et al.* 2007). Thus the average C gas fluxes, as well as the lifecycle analyses, are not site specific but, instead, represent the average of observed and published values for pristine ombrotrophic and minerotrophic mires in the whole boreal zone.

Both ombrotrophic and minerotrophic mires can be either net sinks or net sources of CO₂ at the annual level (Table 1). The great variation in the annual CO₂ balance is a consequence of spatial and, more importantly, interannual variation

in the hydrology and thermal conditions. Wet conditions favour CO₂ accumulation (Alm *et al.* 1997, Nykänen *et al.* 2003), whereas on drier sites or in drier years the direction of the net flux is from the ecosystem to the atmosphere (Alm *et al.* 1999b, Frolking *et al.* 2002). Exceptional dryness or wetness, however, decreases both the rate of photosynthesis and of decomposition (Bubier *et al.* 2003). Thus any change in the frequency of exceptional weather conditions may have a significant bearing on the CO₂ balance of boreal mires. The high proportion of negative years in the published values may indicate a skewed pub-

Table 2. Regression models, their coefficients of determination and parameter estimates (\pm standard error of mean).

Minerotrophic site

$$\text{Gross photosynthesis} = q \times \text{PAR} / (k + \text{PAR}) \times \text{GAlt} / (d + \text{GAlt}),$$

$$r^2 = 0.77, q = 2220 \pm 100, k = 276 \pm 28, d = 0.55 \pm 0.05$$

$$\text{Ecosystem respiration} = \exp(b \times t_2) \times c \times \text{WT} + d \times \text{GAlt},$$

$$r^2 = 0.64, b = 0.075 \pm 0.01, c = -2.45 \pm 0.30, d = 325 \pm 11$$

$$\text{Methane efflux} = \exp(b \times t_{40} + c \times \text{WT}) + d \times \text{GAla}, r^2 = 0.72, b = 0.11 \pm 0.01, c = 0.02 \pm <0.00, d = 4.3 \pm 0.42$$

Ombrotrophic site, hummock

$$\text{Gross photosynthesis} = q \times \text{PAR} \times \text{GAlt} / (k + \text{PAR}), r^2 = 0.74, q = 1724 \pm 85, k = 297 \pm 51$$

$$\text{Ecosystem respiration} = \exp(b \times t_{10}) \times c \times \text{WT} + d \times \text{GAlt},$$

$$r^2 = 0.63, b = 0.13 \pm 0.02, c = -0.74 \pm 0.38, d = 477 \pm 59$$

$$\text{Methane efflux} = \exp(b \times t_{40} + c \times \text{WT}) + d \times \text{GAla}, r^2 = 0.37, b = 0.09 \pm 0.02, c = 0.02 \pm 0.01, d = 2.7 \pm 1.7$$

Ombrotrophic site, hollow

$$\text{Gross photosynthesis} = q \times \text{PAR} / (k + \text{PAR}) \times \text{GAlt} / (d + \text{GAlt}),$$

$$r^2 = 0.80, q = 2005 \pm 149, k = 308 \pm 43, d = 0.51 \pm 0.06$$

$$\text{Ecosystem respiration} = \exp(b \times t_2) \times c \times \text{WT} + d \times \text{GAlt},$$

$$r^2 = 0.75, b = 0.12 \pm 0.01, c = -1.5 \pm 0.4, d = 370 \pm 19$$

$$\text{Methane efflux} = \exp(b \times t_{40}) \times c \times \exp\{-0.5 \times [(WT - x)/y]^2\} + d \times \text{GAla},$$

$$r^2 = 0.72, b = 0.10 \pm 0.03, c = 0.71 \pm 0.29, x = -6.1 \pm 0.5, y = -2.5 \pm 0.3, d = 6.8 \pm 1.1$$

GAlt = green area index of all vascular plants.

GAla = green area index of aerenchymal vascular plants.

PAR = photosynthetically active radiation.

WT = water table.

t_2, t_{10}, t_{40} = peat temperature at the depths of 2, 10 and 40 cm, respectively.

Table 3. Range of the modelled CO₂ and CH₄ flux rates (g C m⁻² a⁻¹) for the ombrotrophic and minerotrophic sites for 30 simulated years. The value for the whole ombrotrophic site ("whole") was calculated using the proportion of different microsites on the study site (for more details see Material and methods). Negative values indicate net C efflux from the ecosystem.

	Ombrotrophic			Minerotrophic
	hollow	hummock	"whole"	
Gross uptake	+166 to +184	+467 to +522	+333 to +372	+460 to +511
Respiration	-98 to -164	-477 to -684	-322 to -472	-378 to -474
Net CO ₂ flux	16 to 74	-162 to -1	-100 to +17	+36 to +91
CH ₄ efflux	-6 to -9	-7 to -10	-7 to -9	-17 to -19

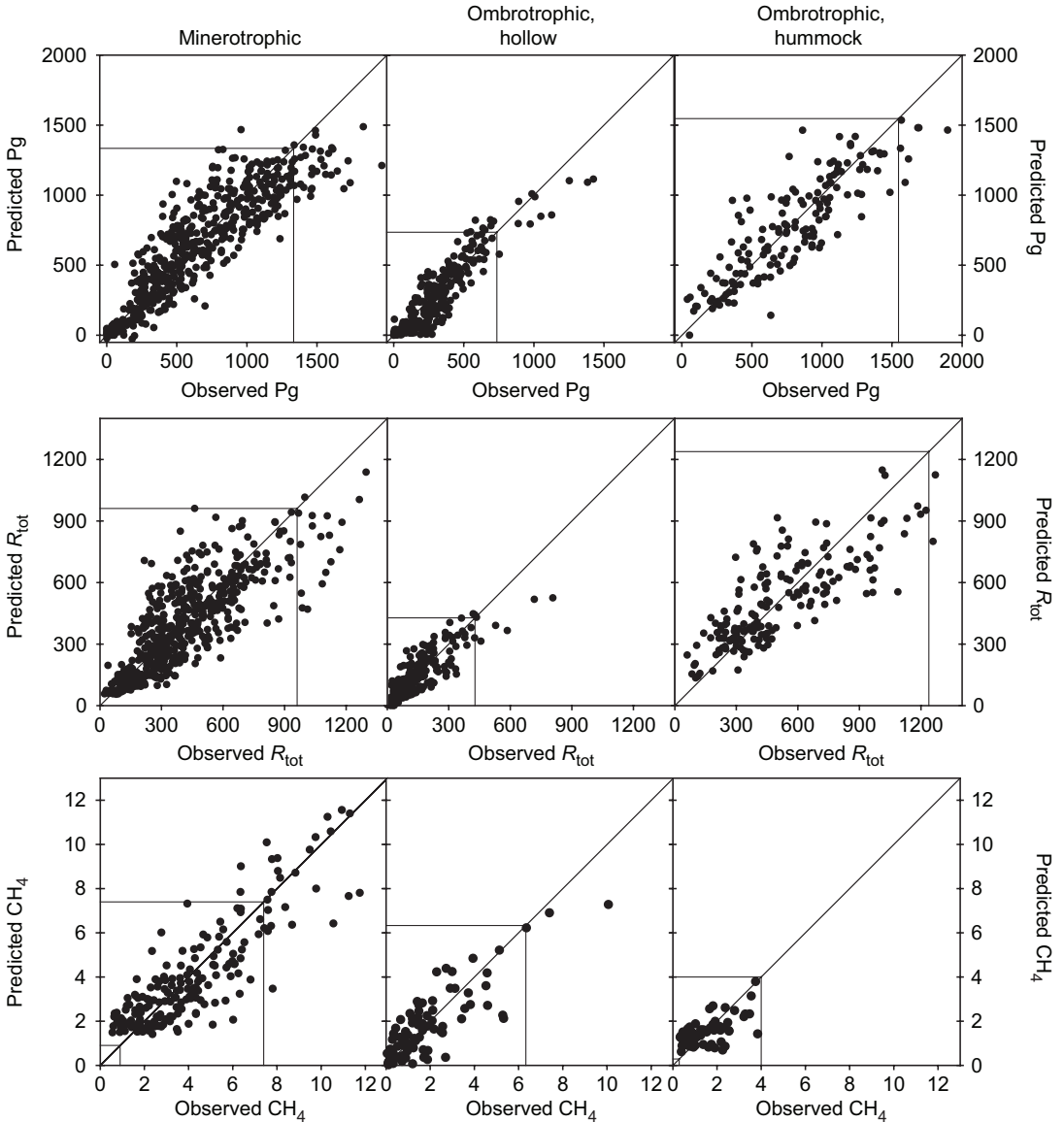


Fig. 1. Observed *versus* predicted rates of gross photosynthesis (Pg), respiration (R_{tot}) and methane (CH_4) release on minerotrophic site and ombrotrophic hollows and hummocks when the regression models were produced using field data from the years 2002–2004. The 1:1 line indicating perfect match is shown. The boxes inside individual figures indicate the range of hourly flux estimates calculated for 30 simulated years.

lication record, or that the rate of peat accumulation is becoming slower. The review also indicated higher net CO_2 uptake for minerotrophic than ombrotrophic mires, which is in conflict with the average rate of C accumulation for fens ($17 \text{ g C m}^{-2} \text{ a}^{-1}$) and bogs ($21 \text{ g C m}^{-2} \text{ a}^{-1}$) in Finland during the entire Holocene (Turunen *et al.* 2002). Due to the very limited number of pub-

lished annual CO_2 balances, further comparison is, however, fruitless before additional studies are carried out.

Studies on CH_4 release from mires are numerous and clearly show that minerotrophic mires release, on the average, more CH_4 annually than ombrotrophic mires (Table 1). The significantly different rate in the CH_4 efflux is considered to

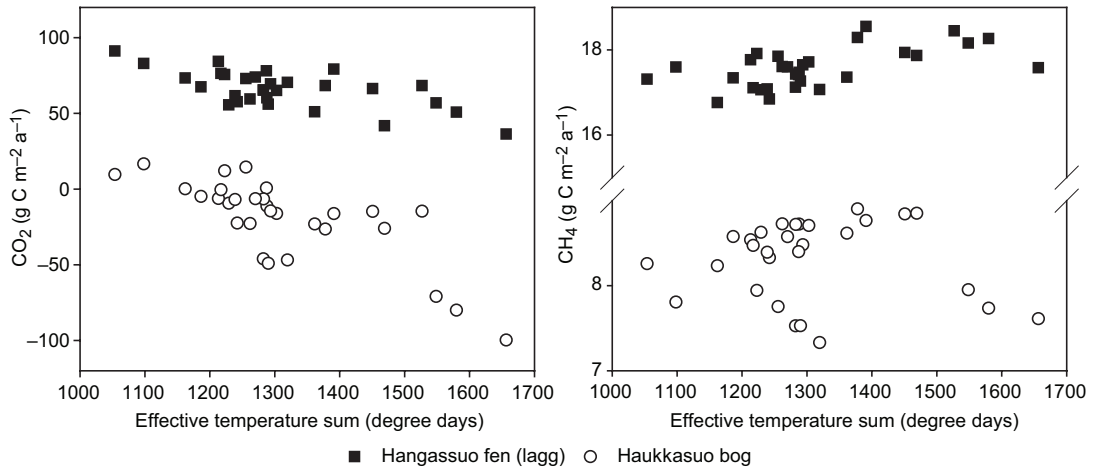


Fig. 2. Relationship between effective temperature sum (= accumulation of the daily mean air temperature exceeding 5 °C) and the simulated annual CO₂ and CH₄ balance on the ombrotrophic and minerotrophic study sites.

be caused by the differences in substrate supply (e.g. Chasar *et al.* 2000, Duddleston *et al.* 2002). The direct and higher allocation of fresh litter and exudates for the anaerobic decomposition chain on minerotrophic sedge-dominated mires supports the production of CH₄ from acetate, whereas in ombrotrophic mires or deeper layers of minerotrophic mires the main substrates are CO₂ and H₂ derived from the older recalcitrant litter. Interannual variability in the efflux rate can, however, be 2–3-fold both on ombrotrophic and minerotrophic mires. Unfortunately, the information in the reviewed publications did not support a more detailed analysis of the dependence of CH₄ release on different abiotic and biotic factors. In general, however, it is known that the spatial variation in hydrogeochemistry and consequent variation in vegetation cause great variation in the annual CH₄ balance of mires (e.g. Bubier and Moore 1994, Nykänen *et al.* 1998). Correspondingly, high annual CH₄ effluxes are favoured by the warm and wet conditions during the growing season (e.g. Saarnio *et al.* 2000, Granberg *et al.* 2001). As compared with the annual CO₂ balance, the CH₄ efflux from mires seems less sensitive to the interannual variation in weather conditions (Fig. 2 and Table 1), and thus the changes in CH₄ release at a given location require more permanent alterations in climate or other affecting factors.

The modelling of C gas fluxes still needs improvements

The estimated CO₂ and CH₄ fluxes for 30 simulated years were of the same magnitude as those observed in 2002–2004, but the highest rates were missing, except in the hummock surface of ombrotrophic site (Fig. 1). Field data for regression models seemed to be ideal as the data were gathered during three years with very different weather conditions from a large number of collars in both study sites. Thus, most of the ecological models fit relatively well in the data sets, and the variation in the simulated 30-year weather and environmental data set did not markedly exceed the variation in the observations in the field. In contrast, the variation in the water table and peat temperature often remained lower in the simulated data than in the observations in the field, thus diminishing the variation in the estimated annual fluxes, especially in the minerotrophic study site. Problems in the long-term estimations (1) encourage the use of process-based models that lack the equalising nature of regression models, (2) raise the need for the development of hydrological models that better take into account the long-term variation in the regional groundwater level affecting the water level in minerotrophic but also on ombrotrophic mires, (3) demonstrate the need for the modelling

of a dynamic green area index which depends on the annual growing conditions and is a strong regulator for photosynthesis and autotrophic respiration, and (4) emphasize the importance of long-term observation series of numerous abiotic and biotic factors from the same site for calibration and estimation purposes.

Despite the deficiencies in the modelling of CO₂ fluxes, the 30-year ranges of the CO₂ balance for the ombrotrophic and minerotrophic sites were of the same magnitude as the estimations of the annual net CO₂ exchange for other ombrotrophic and minerotrophic mires (Table 1). Our results support the conclusion based on continuous tower measurements that the annually assimilated amount of CO₂ at a given location is relatively constant, whereas greater variation in the rate of respiration governs the annual CO₂ balance (e.g. Shurpali *et al.* 1995, Vourlitis and Oechel 1999). In the modelled fluxes, the annual net CO₂ balances at both mire types decreased with the increasing annual effective temperature sum, i.e. the accumulation of the daily mean air temperature exceeding 5 °C (Fig. 2). This is in line with the studies concerning individual years at different study sites (e.g. Alm *et al.* 1999b, Frolking *et al.* 2002). A high temperature sum indicates less precipitation and increased evapotranspiration i.e. warmer and drier conditions favouring aerobic decomposition.

Our CH₄ release estimates systematically omit the CH₄ gas released through bubbling which, according to Christensen *et al.* (2003), can lead to 20%–50% underestimation of the total efflux during the active CH₄ production season. In general, eddy covariance CH₄ fluxes which include the CH₄ emitted through all possible pathways (Shurpali *et al.* 1993, Suyker *et al.* 1996) do not, however, systematically indicate higher CH₄ fluxes for mires than the current figures (Table 3) or other estimates based on chamber techniques (Saarnio *et al.* 1997, Huttunen *et al.* 2003, Nykänen *et al.* 2003, *see* Table 1). This is probably because the release of CH₄ through bubbling is concentrated in less-vegetated sub-sites like flarks, pools and ponds (Chanton and Dacey 1991, Dove *et al.* 1999). In practise, our 30-year ranges of the CH₄ efflux for both the minerotrophic and the ombrotrophic sites were in the middle of the range of earlier estimates

for other minerotrophic and ombrotrophic mires. However, the variation in the CH₄ efflux between the simulated years remained lower than that in the estimations of Granberg *et al.* (2001) for a nutrient-poor minerotrophic mire. The lower variation in the annual efflux rate is possibly true at ombrotrophic mires (e.g. Nykänen *et al.* 1998) but, in the case of the minerotrophic site, the partly unsuccessful simulation of the water level and peat temperature certainly reduced the variation in the annual CH₄ release.

Implications for life cycle analyses of peat energy

Continuous long-term measurements at several minerotrophic and ombrotrophic mires would be needed for the determination of the current net CO₂ balance in pristine boreal mires. Studies on the rate of CH₄ release are more numerous and probably represent the true range of CH₄ efflux rate from different types of mire. Simplification of mire ecosystems into two classes causes uncertainty for the lifecycle calculations, especially in the case of minerotrophic mires which form a more diverse group of mire ecosystems than ombrotrophic mires (Ruuhijärvi 1983). Even ombrotrophic mires do not form a homogenous group of mires because the proportion of wet and dry microsites varies between bog types. Finnish mires alone may be classified into 29 (Lappalainen *et al.* 1984), into 30 (Laine and Vasander 1996) or even over 100 site types (Ruuhijärvi 1983) on the basis of the variation in vegetation reflecting local hydrogeochemical conditions. Most of the peat harvesting areas (75%) were, however, established on sites unsuccessfully drained for forestry purposes and only less than 25% on natural mires (Selin 1999). Thus CO₂ and CH₄ fluxes from the energy use of peat should primarily be compared with such drained peatlands.

The natural C cycle in mires is not altering the living conditions for humans but, instead, the current function of pristine mires is likely to be affected by human-induced changes in the atmosphere and in land use forms, e.g. drainage around mires, increased atmospheric CO₂ concentration, UV-B radiation, deposition of dif-

ferent chemicals or elements and the O₃ concentration in the lower atmosphere. For example, the increasing atmospheric CO₂ concentration has been found to increase both the rate of CO₂ and CH₄ fluxes in northern mires (Saarnio *et al.* 2000, Saarnio *et al.* 2003). Thus, the current C gas flux estimates for natural or drained mires cannot be reliably projected very far into the future. The use of dynamic C gas fluxes based on the atmospheric change scenarios could improve the lifecycle calculations on the use of peat for energy.

In conclusion, naturally high spatial and interannual variation in C gas fluxes create a wide range for the background values used in the life cycle analyses of peat energy. The reduction of this uncertainty requires more detailed knowledge of the mire types used for peat harvesting and long-term field measurements combined with the developed process models and meteorological information. The natural C cycle of mire ecosystems is, however, not responsible for the current anthropogenic global warming, and annual CH₄ or CO₂ effluxes are therefore not reported in the national greenhouse gas inventories. This should be borne in mind when evaluating lifecycle analyses of peat energy. The current approach that the C fluxes in natural mire ecosystems are considered to be emissions or omissions in the lifecycle analyses is only one option. Another option could be to consider anthropogenic emissions from the use of peat energy as such.

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