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Methods for determining emission factors for the use of peat and peatlands — flux measurements and modelling

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The purpose of this paper is to introduce the gas exchange measurement and flux calculation methods commonly used in the projects of the programme “Greenhouse gas emissions from the use of peat and peatlands in Finland”. The methods include measurements of instantaneous fluxes of CO_2, CH_4 and N_2O made at the ecosystem–atmosphere boundary using closed chamber, and whole ecosystem fluxes of the gases using micrometeorological EC tower extending above the canopy, and the integration of seasonal and annual fluxes. In addition, tools developed for gap filling of missing weather records, and generating complete weather patterns for the key environmental controls of the gas fluxes are introduced. Derivation of emission factors from the collected gas fluxes, capable of reproducing the dynamic, climate dependent nature is outlined.

Introduction

Peatlands have been under significant land use in Finland. One third of the Finnish land area originally consisted of peatlands, and more than half of that has been taken in use. Peatlands have been drained for agriculture (Valmari 1982), and especially for forestry (Heikurainen 1982), but also for peat extraction purposes (Suoninen 1982). After abandonment from the original use, peatlands may be restored towards peat-forming ecosystems (Vasander *et al*. 2003, Tuittila *et al*. 2000) or even turned into other use (Selin 1999). The extent of Finnish peatland utilization brings about a substantial contribution to nation’s land-use-related greenhouse gas emissions (Lapveteläinen *et al*. 2007).

The purpose of this paper is to introduce the methods commonly used in all gas exchange data collecting projects within the programme “Greenhouse gas emissions from the use of peat and peatlands in Finland”. The programme aimed at improving the knowledge on the greenhouse gas emissions due to peatland drainage.

Many types of modified peatland ecosystems in Finland imply a broad palette of techniques to capture the changes in rates of organic matter decomposition and the carbon stores. The role of a terrestrial ecosystem as an organic carbon source or sink depends on the ratio of litter production and removal by decomposition. The largest part of matter fluxes in terrestrial ecosystems takes place in gaseous form: plants take CO_2 from the atmosphere in photosynthesis, and release much of it back in respiration. Drainage increases oxygen penetration in peat above the lowered water table, where heterotrophic respiration may mineralize peat organic matter releasing CO_2 (Silvola *et al*. 1996) but also other greenhouse gases such as N_2O. The changes in biological processes and the resulting gas fluxes are strongly time dependent. Organic carbon has certainly been lost from Finnish peatlands reclaimed for agriculture (Nykänen *et al*. 1995, Kasimir-Klemedtsson *et al*. 1997, Maljanen *et al*. 2001, Lohila *et al*. 2003, 2004, Maljanen *et al*. 2004), but in peatlands drained for forestry the changes in the C stock seem more ambiguous (Laiho 2006). Increased growth of trees and shrubs (Minkkinen & Laine 1998) has introduced a clear shift in growing stock and litter production, but estimation of the turnover rate of belowground litter is hard.

Carbon (C) stock changes due to peatland management may be relatively small as compared with the C stock and therefore direct measurement of the stock size is very difficult. Instead, gas fluxes are indicative of the stock changes. According to the internationally accepted guidance (Houghton *et al*. 1997, Penman *et al*. 2000, Penman *et al*. 2003) for reporting the greenhouse gas emissions and removals to the United Nations Framework Convention of Climate Change and the Kyoto Protocol, the gas fluxes from peat soils can be reported. Fluxes of CO_2 (Minkkinen *et al*. 2007a, Mäkiranta *et al*. 2007, Saarnio *et al*. 2007), and the non-CO_2 gases as indicated by the Climate Convention, such as CH_4 (Minkkinen *et al*. 2007b, Saarnio *et al*. 2007) and N_2O (Maljanen *et al*. 2007), were measured in the research programme using closed chamber techniques. The mere vertical distributions of live vegetation both above and below the peat surface level dictate how the gas exchange balances can be assessed. Closed chambers were employed at the soil-atmosphere boundary while the exchange rates for the whole ecosystem were monitored with a tower-based micrometeorological methods (Lohila *et al*. 2007). Partitioning of the sources for total soil CO_2 efflux is challenging in field conditions (Kozyakov 2006). As the gas fluxes continue through summer and winter (Alm *et al*. 1999), methods are presented for both conditions.

The principal methods for closed chamber and EC measurements are outlined below. The details may slightly differ by site, and those particular details are described in the specific papers for each land use category. Both field methods and the computation of the flux rates from the measurements of CO_2, CH_4 and N_2O are introduced. The methods should allow for compilation of emission factors for all land use types applied on peatlands in different regions in Finland, as described by Lapveteläinen at al. (2007). As the regional adaptation of emission factors depends on the models used for extrapolation, the shortage of regional test data restricted the validation of models. The actual emission factor coefficients are reported and their uncertainty discussed elsewhere in this issue (Alm *et al*. 2007).

Measuring the exchange rate of CO_2, CH_4 and N_2O

Gas exchange in forested peatland ecosystems

Net gas balance of an ecosystem is a result of input and outputs. The physical structure of the ecosystem restricts the methods available for studies on ecosystem–atmosphere gas exchange. A low or missing vegetation layer as in the case of the reference mires (Saarnio *et al*. 2007) or open agricultural peatlands (Maljanen *et al*. 2007) allows for the use of portable chambers, while the presence of even a modest tree layer exceeds the chamber headspace dimensions (Fig. 1). Micrometeorological eddy covariance method (Fig. 2) with towers reaching above the highest canopy are useful in treed sites (Lohila *et al*. 2007), but are burdened with high cost, low portability and low spatial resolution.

Our solution of assessing carbon balance in forested peatlands was to estimate the ecosystem inputs and outputs by combining multiple

Fig. 1. Closed (vented) chamber systems for measuring CO_2 exchange NEE between ground vegetation and the atmosphere. Left-hand side panel: the transparent chamber was thermostatically controlled to near ambient air temperature (photo by Miculáš Černota). Right-hand side panel: the opaque chamber was used for total ecosystem respiration R_{TOT}, and the fluxes of CH_4, and N_2O. R_{TOT} was measured with delay after NEE to allow for equilibration of soil CO_2 conditions (photo by Kees Blom).

sources of information (T. Penttilä unpubl. data). For input, data collected in Finnish National Forest Inventory (NFI; Tomppo *et al*. 1997) provides data on tree growth, collected on a regular basis. With the help of models and the NFI database, litter production and gaseous decomposition of the litter can be estimated. The application and details of biomass expansion factors and the decomposition models will be published later. In addition to the NFI compilation, an estimate of old peat matrix decomposition rate is needed. This was accomplished by separating the heterotrophic soil CO_2 release component from the total ecosystem respiration, excluding the rate of litter decomposition. Finally, an estimate of wintertime soil CO_2 release was added. Instantaneous emissions of non-CO_2 greenhouse gases (CH_4 and N_2O) were in most cases determined using closed chamber.

Fig. 2. Eddy covariance tower used to measure gas fluxes at a forested peatland site. Photo by Tuomas Laurila.

Soil CO_2 emission using closed chamber

In treed peatlands managed for forestry purposes (drained for forestry, afforested after agriculture, afforested after peat extraction) soil CO_2 effluxes were measured using a portable infra-red gas-analyser (IRGA; models EGM-3 and EGM-4) equipped with a modified version (d = 31.5 cm, h = 15 or 17 cm) of an automatic soil respiration chamber (SRC-1, PPsystems Inc.). EGM + SRC is a closed chamber system in which the air circulates between chamber headspace and IRGA. In the IRGA the CO_2 concentration of sample gas is measured and results are saved in the internal memory every 4.8/8 seconds (EGM4/3). CO_2

Fig. 3. Partitioning soil CO_2 emission sources with different collar setups. Aboveground parts of vegetation were removed from each collar. The left-hand side collar extended below the rooting depth, and was used for eliminating the root respiration nearby. Entry of litter was eliminated from the left- and right-hand side collars. Photo by Kari Minkkinen.

flux is automatically calculated from the linear change of CO_2 concentration in chamber headspace in time as a function of chamber volume, air temperature, and air pressure according to the ideal gas law.

Soil respiration was always measured after removal of the living above-ground vegetation. The sites were kept vegetation free by regular cutting. Different types of collars were set up to separate soil C efflux into heterotrophic (old peat and litter decomposition) and autotrophic (root respiration) components (Fig. 3). Spots with a plain groove for air-tight water sealing in the soil surface were used to measure the total soil respiration. Autotrophic root respiration was excluded from some spots by inserting collars, with the grooves on top, 30 cm deep down to the peat. Data from these plots were used starting from the second year after cutting the roots, when they presumably were dead. The impact of new litter decomposition was studied by removing all litter from some spots and removing new litter regularly with mosquito nets inserted inside the collars. The partitioning of CO_2 emission sources was done by pairwise comparisons of the collar setups.

For the flux measurement, the chamber was inserted on the groove for a 80 to 120 second period (up to 240 seconds in winter). Sufficient sealing was ensured with a rubber seal between the chamber and the groove. Initial CO_2 concentration was observed and if it clearly exceeded the concentration in ambient air (due to accidentally poor flushing of tubings) the measurement was restarted. Simultaneously with flux measurements, soil temperature (5 cm) and distance to water table were measured. All spots were visited 2–4 times a month during the warm season, and once a month in winter. In winter, fluxes were measured from the top of the snow at some selected spots at each site. A 10-cm-deep collar equipped with a supporting "snowshoe" plate was inserted in the snow and a measurement was done as that in the summer, except that measurement time was 240 seconds due to very low wintertime fluxes.

The automatically saved CO_2 concentration data were carefully inspected and serious deviations from linearity were corrected either by removing bad data points and calculating the flux manually, or deleting the whole measurement. Data quality was on average very good; only a few measurements were deleted and less than 1% of summertime fluxes needed any correction. Low winter fluxes were mostly calculated manually, to increase the accuracy of the close-to-zero flux estimates.

All automatically calculated fluxes were manually corrected for air temperature and spot-specific chamber headspace volume. Chamber headspace volume varies between spots and may change in time within the spots, since the height of the headspace changes when mosses inside the collar grow or when old peat decomposes and the surface therefore subsides. The mean height was measured using a cylinder equipped with a systematically perforated lid. The cylinder was placed on the groove, a measuring rod was dropped through the lid-holes down to soil surface and the distances from lid to the soil surface were recorded. EGM-4 makes automatic corrections for water vapour and atmospheric pressure, while EGM-3 does not. These corrections are, however, small and EGM-3 results were left uncorrected.

For treeless land use types (natural mires, peatlands reclaimed for agriculture, abandoned after agriculture, abandoned cutaways, and rewetted cutaways), respiration was measured as a part of plant community net flux measurements, using larger 60 × 60 cm collars, a dark chamber and manual data recording.

Fluxes of CH_4, N_2O and wintertime CO_2

Closed vented static chambers were employed in summer soil CH_4 and N_2O exchange measurements at treeless sites, and throughout the year in treed sites. In winter, when the snow depth was less than ca. 30 cm, the following procedure was also applied for measuring the CO_2 emission when the IR analyser could not be used on site. A permanent 60 × 60 cm or a round (d = 31.5 cm) collar with a groove for water sealing was installed in soil. The sleeve of the collar extended 20–60 cm in soil, which is usually below the rooting zone (Laiho & Finér 1996). Ground vegetation within the collar was left intact. For the gas sampling, an opaque aluminium chamber (h = 30 cm) was placed upon the collar air-tightly due to water added in the groove. Four 30–50 ml air samples were drawn in syringes from the large (> 100 dm^3) chamber headspace at known intervals over 15–60 min closure of the chamber. In winter, when the soil surface temperature was close to 0 °C the chamber was closed for 40–60 min, and in summer for 15–20 min. Each collar was visited 2–4 times a month in summer, and once a month in winter.

The gas samples were analysed within 24 hours using gas cromatograph equipped with packed column, FID, ECD and TCD (for exact configurations, *see* Saarnio *et al*. 2007, Maljanen *et al*. 2007, Mäkiranta *et al*. 2007, Yli-Petäys *et al*. 2007). Compressed air, analysed against known concentration of the gases, was used as a standard. The standard gas was analysed in accordance with the samples in order to monitor the performance of the GC.

For closed chamber data the flux rates of CH_4 and N_2O were calculated from the analysed chamber headspace samples as follows: A linear regression slope was calculated from the four sequential sub-samples over the exact sampling time of each syringe (minutes). The slope indicating the flux rate at the collar area was extrapolated over time and area into a flux estimate of mg CH_4 m^{-2} h^{-1} or μg N_2O m^{-2} h^{-1}. If the flux rates are expressed as daily values, they originate from hourly fluxes multiplied by 24. Coefficient of determination R^2 calculated for the individual sample set regressions were used, together with the diagram of sub-sample concentrations against sampling time, to evaluate the correctness of the sample. If the initial headspace gas concentration estimated with the graph was overly high as compared with the ambient air concentration (ca. 1.8 ppm for CH_4 and 311 ppb for N_2O), the sample was discarded due to probable ebullition due to disturbance in placing the chamber. Similarly, other unexplained changes in the measured headspace concentrations and a low R^2 (< 0.9) could lead to discarding of the sample. However, in cases of close to zero fluxes the R^2 is always low and was not used as a criteria for flux disqualification.

When the soil was covered by at least 30 cm of snow, the snow gas gradient method was used (Fig. 4). In the gradient flux calculation, the snow was assumed a homogenous porous media, and the flux rate for each gas F_g was calculated using Fick's first order diffusion formula (Sommerfeld *et al*. 1993, Alm *et al*. 1999):

$$F_g = D_g(dC_g/dz)f. \qquad (1)$$

Concentration gradient dC_g was measured as difference between the gas concentration below and above the snow layer. Diffusion coefficient

Fig. 4. Gas sampling in snow gradient flux method. A gas sample is taken into a syringe from beneath a known depth in the snow pit, and the gas concentration is compared with that from ambient air above the snow. Snow porosity is measured from a volumetric sample with help of solid ice density. Photo by Markku Parhiala.

(D_g) of 0.139 cm^2 s^{-1} was used for CO_2 and N_2O, and 0.22 cm^2 s^{-1} for CH_4, respectively. Snow porosity f was estimated on the basis of density ϱ measured during each measurement campaign by weighing volumetric snow samples taken through the known depth z of the snow layer:

$$f = 1 - (\varrho/0.9168 \text{ g cm}^{-3}),$$
$$\text{where } 0.9168 \text{ g cm}^{-3} = \text{the density of ice.} \quad (2)$$

In treed sites, wintertime fluxes were measured with chambers from the top of the snowpack. A 10-cm-deep collar equipped with a "snowshoe" was inserted on the snowpack and measurement was done as usual in summer, except that closure time was longer (up to 60 min.).

Soil/plant-atmosphere CO_2 exchange using closed chamber

Instantaneous net ecosystem CO_2 exchange (NEE) measured with a transparent chamber is a balance between the simultaneous CO_2 fixation of ground vegetation and CO_2 release from the system in the respiration of plants and heterotrophes. A polycarbonate static chamber with dimensions of 60 × 60 × 30 cm and total volume of 111.5 dm^3 including the cooler unit was used. The chamber was equipped with a battery-operated fan to mix the chamber headspace air, temperature controlled with a radiator cooling system (volume 3.5 dm^3) within 1–5 °C of the ambient temperature. The same 60 × 60 cm collars were used during the growing season for NEE, CH_4 and N_2O measurements.

For each collar a series of measurements were done, the first in prevailing light conditions, and the following ones with progressive shading in the cropland sites (Maljanen *et al.* 2007) and restored cutaways (Yli-Petäys *et al.* 2007). Artificial shades were applied to obtain NEE rates under a wider range in photosynthetic photon flux densities (PPFD) in order to better establish a relationship between photosynthesis and PPFD. Finally, NEE was measured either with an opaque chamber, or the transparent chamber was covered with an opaque shroud for an estimate of instantaneous total respiration rate (R_{TOT}). At the beginning of each measurement the chamber was placed into the groove of the collar and water was added to provide an airtight seal. The CO_2 mixing ratio in the chamber headspace was measured with a portable infrared gas analyzer. After each measurement the chamber was removed for a while to allow stabilization of the gas concentration in the sample plot and in the chamber to the ambient level. The analyzer readings in ppm were monitored after closing the chamber. The NEE measurement period lasted for 45–240 seconds. CO_2 exchange rate (mg CO_2 m^{-2} h^{-1}) was calculated from the linear change of gas concentration as a function of time, chamber volume, and temperature in the headspace. Positive sign for instantaneous NEE was used when net consumption of CO_2 from the chamber headspace was observed.

Special care was taken that the irradiation level did not vary during the accepted measurement period. In case of e.g. a cloud shading the chamber, the measurement was interrupted. The length of the measurement period was regulated based on the change in gas concentration: Measurement was carried out over a longer period (135–240 s) if the rate of change was low and especially in the cases where the small changes in concentration were fluctuating up and down. These cases were typical to peat surfaces with very sparse vegetation. In fully closed vegetation a shorter period of 45–120 s was considered appropriate when the change in consecutive CO_2 concentrations was even.

Air temperature inside the chamber (°C), water level relative to soil surface in a tube next to the sample spot (cm), and temperature in peat at 5, 10, 15, and 20 cm depth (°C) were measured concurrently with NEE in order to relate the CO_2 fluxes to prevailing environmental conditions. Photosynthetic photon flux density (PPFD, (μmol m^{-2} s^{-1}) was measured every 15 seconds with a quantum sensor (PAR-1. PP Systems, UK) located at the top of the chamber during NEE measurements in light.

Whole ecosystem exchange of CO_2, CH_4 and N_2O using eddy covariance

Micrometeorological eddy-covariance method (Baldocchi 2003) is based on sensing turbulent wind field, temperature, and gas concentrations at high frequency and calculation of covariance between the vertical wind component and the respective scalar variable. The sensors are attached to a mast extending above the ecosystem. Turbulent flux rates are calculated on the basis of the covariances. The area corresponding to the average fluxes extends to several hundreds of metres upwind from the measurement mast. Data collected in turbulent weather conditions were sampled at 10 Hz and the fluxes calculated as 30-min averages. A three-axis sonic anemometer SATI-3SX (Applied Technologies, Inc.) was installed on the top of the tower. Air was sucked at high flow rate of 6 l min^{-1} through a heated inlet tube to the CO_2/H_2O analyzer LI-7000 (Li-Cor, Inc.) for the analysis of the gas concentrations. This instrument and a data logging computer were located on a scaffold below the tower and calibrated monthly using zero and span (391 or 276 ppm) gases in synthetic air.

Air temperature and humidity (Vaisala HMP230) was measured at two elevations, at the top of the tower and at 3 m. Net irradiation (K&Z NR-LITE), global irradiation and reflected irradiation (LI200SZ), photosynthetic photon flux density (PPFD) and reflected PPFD (LI-190SZ) were measured at the top of the mast. We also measured soil temperatures (Pt100), moistures (ThetaProbe ML2x/w) and heat flux (HFP05). These and some other temperature and radiation data close to the ground were read using Vaisala QLI50 sensor collector and stored on a computer.

Nitrous oxide and methane fluxes using eddy-covariance method were measured at Alkkia for short periods of time between August 2003 and June 2004. The high-frequency gas concentrations of N_2O and CH_4 concentrations were observed by a Tunable Diode Laser gas analyser (TGA100, Campbell Scientific).

Calculation of eddy covariance flux rates

The high-frequency data were collected and processed by a LabView based program BARFLUX. The coordinate system was double rotated to yield vanishing average vertical wind speed during each averaging period (Kaimal and Finnigan 1994). For determining the fluctuating components of signals, autoregressive filtering with a running mean time constant of 200 s was applied. The time shifts between the signals from the anemometer and each gas analyzer were determined on-line for each averaging period by maximizing the absolute value of the covariance in question. The corrections for high-frequency flux loss (Moore 1986) and density fluctuations due to H_2O (Webb *et al.* 1980) were calculated as part of the post-processing procedures. Flux observations with abnormal spikes or excessive sensor variance or when turbulence was insufficient (friction velocity smaller than 0.2 m s^{-1}) were deleted.

Uncertainty in fluxes due to measurement techniques

Calibration of flux chambers

CO_2 chamber systems (EGM-4 + modified SRC-1) used in the drained treed sites were tested in Hyytiälä (Finland) in 2003–2004 using a chamber calibration tank (Pumpanen *et al.* 2004). Overall, the 12 tested similar static chamber systems (with air circulating between chamber headspace and analyser, i.e. "*non-steady-state through-flow systems*"), gave fluxes which were between 79% and 133% of the theoretical ("correct") flux given by the calibration tank. On average, however, deviation from the tank flux was only 4%. Differences between systems were mainly caused by different chamber size/fan size combinations, which create different strength of air mixing and turbulence inside the chamber. Our system gave on average similar flux (100%) as the calibration tank when coarse dry sand was used as the soil material, but lower fluxes than the tank with fine dry and fine wet sand (85%–87%). Thus, soil particle size seemed to affect our results whereas soil moisture did not. Similar results were seen with other "*non-steady-state non-flow-through-flow*" chamber systems that were tested (Pumpanen *et al.* 2004).

The chamber specific fluxes could be calibrated using the correction formulas given in Pumpanen *et al.* (2004). However, since the test did not include organic soils which typically have very heterogenous particle size and moisture distribution, the calibration may not be meaningful in our case. Thus, although the possibility of such errors is recognised, no corrections were applied.

Biological and physical disturbances by chamber

Measurements of soil–atmosphere gas exchange with static flux chambers may introduce errors associated with disturbance of ecosystem functions (e.g. clipping of aboveground vegetation or shading by shrouds), and disturbance of the gas concentration gradient or soil properties at the boundary layer. The benefits of chambers over EC tower measurements arise from the fact that while EC methods average the fluxes over a rather large footprint area, and may serve as a valuable ecosystem level reference, the large spatial variability in the fluxes, and the factors behind that variability at the microsite level, can only be assessed by chambers. Regarding the problems and solutions concerning chamber (Knapp & Yawitt 1992, Longdoz *et al.* 2000, Hutchinson & Livingston 2001, Davidson *et al.* 2002, Hirsch *et al.* 2004, Pumpanen *et al.* 2004, Burrows *et al.* 2005, Kuzyakov 2006) and EC techniques (Massman & Lee 2002, Pihlatie *et al.* 2005, Laine *et al.* 2006, Papale *et al.* 2006), we point out only those most specific to the methods applied in this research programme.

Disturbance of ecosystems functions was evident in partitioning heterotrophic (catabolic) soil respiration from the belowground growth and maintenance (anabolic) respiration. Especially in forest soil conditions, with abundand mycorrhizae and different turnover rates the partitioning of the various soil organic matter (SOM) fractions without intervention is very difficult. Kuzyakov (2006) reviewed a wealth of techniques used in separation of plant-derived and SOM-derived CO_2 effluxes and analysed their shortcomings. In the review, root-exclusion techniques were considered reaching only a crude estimate of SOM-derived CO_2, and being sensitive to the initial disturbance. However, we used the data only of one season after the roots were killed. Our version of the root-exclusion technique with 30-cm-deep collars and clippings was not able to distinguish the share of decomposition of the dead roots from the total heterotrophic CO_2 (Minkkinen *et al.* 2007), but according to Laiho *et al.* (2004), 20%–40% of Scots pine fine and small root litter can decay in the 0–20 cm layer during a year. The collars penetrated well the shallow rooting zone, typically ca. 20 cm in drained peatlands (e.g., Laiho and Finér 1996), thereby avoiding errors from underlying live roots or potential lateral diffusion below the collar (Hutchinson & Livingston 2001). Nevertheless, the comparison of rooted and non-rooted plots revealed that the rate of decomposition seemed not to be greatly affected by disturbances in soil moisture even under conditions of very low water table below the collars (Minkkinen *et al.* 2007a), since the high water retention capacity of organic soil seemed still to support the heterotrophic decomposition similarly within and without the exclusion collar.

The time of employment of a chamber has several impacts on the gas fluxes. Initial placement of the chamber causes a pressure artefact visible in the headspace gas concentration (Davidson *et al.* 2002) that may last almost a minute. This period of time is relevant in CO_2 exchange studies where the mixing ratio is followed in real time with IRGA. We waited until the change (or no change) in the headspace concentration became stabilized for the measurement of NEE. Further, the headspace may become saturated of CO_2 during net respiration conditions, the chambers may leak or become depleted during net assimilation if the chamber is employed over longer periods of time (e.g. Burrows *et al.* 2005). Both conditions would lead to a nonlinear change in the concentration over time. As we assumed a linear change in our flux calculations, the logging was started after and chamber employment stopped before any apparent nonlinearity was observed, typically after a maximum of 120 s (or 240 s in winter). However, while the large chambers with basal area of 60 × 60 cm were used in winter with closure times reaching 60 min, the headspace concentration was not saturated enough for the nonlinearity due to the low flux rates at low soil temperatures.

Transparent chambers act like greenhouses and may be heated by sun during the employment and, according to our trials, the relative headspace humidity may rise to 100% almost immediately. Application of shrouds may create unrealistic temperature conditions especially for the estimation of R_{TOT} at night when using the daytime data (Burrows *et al.* 2005) for temperate climate. Adjustment for temperature may be needed in order to avoid underestimation of NEE in low, or overestimation in high irradiation conditions. These factors would certainly affect the plant activities and NEE. Our chambers were automatically thermostatically regulated (Alm *et al.* 1997) to decrease impacts of excess temperature, but no temperature corrections were applied. As the measurements with shrouds continued from spring to late autumn (Maljanen *et al.* 2007, Yli-Petäys *et al.* 2007), our data in part consist of measurements made at low temperatures, which prevents extrapolations of the responses to nighttime temperatures.

In CH_4 and N_2O measurements, lasting for 15–60 min, reaching overly saturating mixing ratios is hardly possible through a diffusive flux from soil to the chamber. Aluminium chambers get less heated in direct sunlight even without a thermal control, but the chamber fan could perturb the gas concentration in the soil surface layer especially in highly porous litter or moss layer. While the fan perturbation may be significant in measuring the CO_2 exchange, it may not be so important for CH_4 or N_2O when they originate in deeper layers.

Uncertainties in EC measurements

EC measurements have several potential error sources, among them topographic effects with night-time gravitational or drainage flows on uneven ground, terrain obstacles can generate a bluff body effect, or the surface source strength may not be uniform (Massman and Lee 2002). Incomplete data sets typically require gap filling in order to get estimate of annual flux dynamics, and these procedures introduce additional errors. The terrain in our study site at Alkkia was even and without major obstacles (Lohila *et al.* 2007) within the wind sector of 225° (270° through N to 135°) that was used in the EC measurements. The incomplete sector and especially low wind speeds at nighttime caused a need for gap filling, here performed for wintertime using the procedure of Lloyd and Taylor (1994), and for summertime with help of phytomass index (Aurela *et al.* 2001). The final uncertainty in annual CO_2 balance was roughly estimated to cover a range of –163 to 154 g CO_2 m^{-2} a^{-1} (Lohila *et al.* 2007). Standardization of and uncertainty due to gap filling procedures are discussed by Papale *et al.* (2006).

Collection and simulation of environmental data

Measurements

All the sites were equipped with temperature logging devices, measuring continuously (in 1–4 hour intervals) air and soil temperatures at several depths. For diurnal and seasonal integration of chamber NEE measurements solar irradiation (PAR) above the canopy was recorded using quantum sensors (μmol m^{-2} s^{-1}). Distance to the water table (WT) was measured at all sites in water wells (perforated plastic pipes) usually during the flux measurements. In order to reach continuous WT-records, the missing days were linearly interpolated from the data.

Gap filling of missing environmental data

Circumstances unavoidably arise when instrument or infrastructural failures create gaps in the temporal stream of environmental measurements. In the following we describe the computational methods devised for various gap filling situations. Most gaps are short in duration and affect only one or few related parameters. However, some failures, such as wide-area power outages or storms, occasionally affect nearly all recorded parameters at a given measurement facility. Moreover, the instruments and sensors may themselves become unstable or defective. Effort invested in filling gaps must be justified by evaluating whether carbon models are sensitive to or benefit from marginal improvements provided by more advanced gap filling methods.

Some of the peatland carbon exchange and hydrology modelling tools such as PCARS (Frolking *et al.* 2002) and water table and soil temperature models employed in this study require climatic data on an hourly temporal scale, while others such as DNDC (Zhang *et al.* 2002) need data on a daily scale and models such as COUP (*see* Jansson and Karlberg 2004) operate on both daily and hourly time scales. A data gap was considered SHORT if the data were missing for 1 to 6 hours, MEDIUM if the data were missing for more than 6 hours, but less than 24 hours and LONG if the data gap was more than 24 hours. Short data gaps were filled using simple linear interpolation methods such as the one described in Akima (1970) and IMSL (1989). Medium gaps were filled with available data from climatically similar neighbouring periods. Data gaps longer than 3 days required advanced gap filling techniques such as mechanistic, physically based models that describe the behaviour of the environmental parameter in time and space. In the following, we discuss the procedure we have adopted in filling data gaps for longer periods of time (data requirements ranging from a single growing season to several years worth of climatic data).

Simulation of weather patterns

A stochastic weather generator is a useful tool for calculating time series of weather data of unlimited length. Models for generating stochastic weather data are generally developed to meet the requirements of long time series of daily weather, which are not available from observational records, gridded weather data for spatio-temporal analysis or the ability to investigate changes in both the mean climate and its diurnal and interannual variability. With this in view, we have adopted and modified a weather generator originally developed at the University of Joensuu as a part of FINNFOR, a model used to assess the response of boreal forest ecosystem to climate change (for further details *see* Kellomäki *et al.* 1993, Strandman *et al.* 1993). The weather simulator generates weather series at hourly and daily time resolutions at a given location by spatially weighting the observed, long term monthly statistics from all measurement locations situated within the 180 km radius from the location of interest.

Here we used monthly average air temperatures and precipitation for 1961–1990 (published by Finnish Meteorological Institute). This period was used for obtaining a more conservative distribution of temperatures than would have been the case had the recently observed exceptionally warm years been included. This allowed for evaluation of validity of the emission factors under changed climate conditions, but did not overestimate the emissions at the start of the reporting period 1990. In the weather simulator, the air temperature pattern is calculated as a stochastic process and it forms the basis for the calculation of other climatic variables in the model. Thereby the occurrence of clouds is modelled as a random process modified by the temperature pattern. The presence of clouds is always required for precipitation. The precipitation amount is related to the degree of cloudiness. For estimating dynamic emission factors, we employed 30 years worth of climatic variables such as air temperature, rainfall, and incident solar radiation, relative humidity generated by the weather simulator for several locations in Finland and at hourly and daily time scales as relevant to our research objectives.

Simulation of WT levels and soil temperatures

In addition to climatic variables, soil temperature profile and WT form an important set of driving variables in both statistical and process-oriented biogeochemical models. As these data are not routinely measured in peatlands and a continuous record of these variables is crucial in using the models, we have adopted models based on the closure of the water balance and soil heat exchange on an hourly to daily time scale. For WT and soil temperature in udrained sites we employed the mixed mire heat model of Granberg *et al*. (1999) that takes into account the snow processes, and for drained sites soil temperatures were simulated using the COUP model (Jansson & Karlberg 2004). The water retention characteristics, varying among different peat types, are described in the model following Weiss *et al*. (1998). The models utilize weather data on standard climatic variables such as air temperature, relative humidity and precipitation as driving variables, and peat quality and vegetation characteristics as input parameters.

Calculation of weather-dependent emission factors

Annual fluxes of NEE, CH_4 and N_2O

Regression-based transfer functions (Silvola *et al*. 1996, Saarnio *et al*. 1997, Alm *et al*. 1997) were applied when the instantaneous flux estimates were integrated into seasonal fluxes. Although the uncertainty of single hourly estimates can be large (Bubier *et al*. 1999), the averaging nature of regression functions was assumed to produce stable seasonal estimates with the data collection frequency applied in the field (Kettunen 2000, Kettunen *et al*. 2000). For the integration of the instantaneous NEE data over the season and longer periods of time, statistical but physiologically based response models were built.

Instead of directly modelling NEE, the two components, gross photosynthesis P_G and total respiration R_{TOT} were separately related to variation in controlling factors following the ecological interpretation of Tuittila *et al*. (2004). The model for P_G was based on Michaelis-Menten relationship for light dependence of photosynthesis rate:

$$P_G = P_{MAX(PPFD)} \times PPFD/(k + PPFD) \quad (3)$$

where the parameter $P_{MAX(PPFD)}$ is the maximal, light saturated photosynthesis rate and the parameter k is equal to the PPFD at which photosynthesis rate is half of its maximum. Irradiation dependent P_G rate was related to the photosynthetic activity controlled by temperature (T), WT and the amount of photosynthesizing material (Green Area of vascular plants, GA) using a multiplicative model form. The other factors control how large proportion of the potential maximal light saturated photosynthesis is reached in various situations.

Total respiration of samples with living vegetation has two components: CO_2 released in decomposition of organic matter (R_D) and CO_2 released in plant respiration (R_P).

$$R_{TOT} = R_D + R_P \quad (4)$$

In the model for R_{TOT} these two components were independently described. Yli-Petäys *et al.* (2007) described the dependence of R_D on WT as a sigmoid. Here, we elaborate the approach as an example, although other measurement projects (Saarnio *et al.* 2007, Maljanen *et al.* 1007) have used different variants of the response functions. In the sigmoidal model the decomposition rate is limited by lack of oxygen while the WT is close to soil surface. Further, when the WT drops below a certain threshold, dryness of the surface peat starts to limit microbial activity and the peat respiration rate becomes saturated.

$$R_D = \left[\frac{mR_{D(WT)}}{1+\exp\left(\frac{WT-b_1}{-b_2}\right)}\right]\exp\left(b_3 T\right), \quad (5)$$

where the parameter $mR_{D(WT)}$ is the maximal respiration at conditions in which water level does not constrain respiration, b_1 determines the speed and direction of change in R_D along the WT gradient, b_2 the center of the fastest change along the water level gradient and b_3 determines the rate and direction of the change in R_P along the temperature range.

Plant respiration was added to the model of R_{TOT} using a linear dependence of the respiration rate on the Vascular Green Area (VGA, Wilson *et al.* 2007). The VGA, sum of the species specific Green Area Indices (GAI's), was used to describe the amount of living, metabolically active plant material. The use of VGA relies on the assumption that the ratio between above-ground and below-ground parts is similar over the growing season and over all sample plots used in the model estimation.

The response functions estimated for P_G and R_{TOT} were used for the seasonal reconstruction of NEE. The functions transferred the logged hourly time series of solar irradiation, air temperature, and WT into separate estimates of P_G and R_{TOT}, which resulted in NEE = $P_G - R_{TOT}$. The hourly values of NEE were then summed over the season. In the calculations for drained peatlands, the length of the season was assumed to extend from 1 May to 31 October. The wintertime emissions were added to the growing season NEE using daily averages of wintertime flux data weighted by the number of days with permanent snow cover in the pristine mire sites in southern Finland (Saarnio *et al.* 2007), or the period or 1 November–30 April in drained peatlands.

The transfer functions used for the components of soil CO_2 release (Minkkinen *et al.* 2007a, Mäkiranta *et al.* 2007) were simple exponential models accounting for temperature dependence only. Moreover, the WT dynamics are not frequently monitored in drained peatlands. For this reason the extrapolation of fluxes were not based on all possible predictors for the gas fluxes (Moore & Knowles 1989, Silvola *et al.* 1985, Silvola *et al.* 1996). It was assumed that drainage kept the WT low, with little contribution to soil respiration dynamics.

Fluxes of CH_4 from the pristine mires were integrated using corresponding regression transfer function techniques (*see* Saarnio *et al.* 2007). However, since the net fluxes were either close to zero or showed emission pulses not related directly to the measured environmental variables (N_2O), the seasonal flux estimates for both CH_4 and N_2O at the drained sites were obtained using average measured rates weighted by number of days in the season. In such conditions, the environmental controls for the microbiological processes are complicated, and simple regression models do not adequately describe the fluxes. Wintertime fluxes of CH_4 and N_2O, measured outside the growing season, were also averaged, weighted by the length of winter in days, and added to the seasonal estimate for both gas species.

Annual fluxes from micrometeorological measurements

For the calculation of average CO_2 balances the data gaps were filled because substantial part of the flux data is typically lost due to technical problems, insufficient turbulence conditions or other reasons. Data points originating from the southerly sector of the source area at Alkkia were deleted because the area was considered unrepresentative for the study site. Simple regression models of R_{TOT} and P_G (Aurela *et al.* 2002) were constructed and seasonally fitted to the NEE. The equation for R_{TOT} was adopted from Lloyd and Taylor (1994) who assumed exponential dependence on temperature. We used the air temperature because of its better availability and because regression models based on the air temperature are nearly as good as those based on the soil temperature. During the growing season when photosynthesis was observed, in order to solve the apparent quantum yield (α) and the light saturated gross production (P_{Gmax}), a rectangular hyperbola function between PPFD and NEE was applied after subtracting the corresponding R_{TOT}. Seasonally varying leaf area was taken into account by calculating effective phytomass index as described in Aurela *et al.* (2001). After constructing the continuous time-series, daily, seasonal and annual CO_2 balances were calculated.

Weather dependent emission estimates

Scales of temporal and spatial variability must be accounted for when emission factors are generalized: (1) inter-annual variations in weather or climate, and (2) regional variation in the distribution of peatlands over the region of assessment. Measurement of temporal variation is seldom possible; most of flux observation data are confined to a couple or few years only. The observed inter-annual changes most probably do not reflect the complete range of the possible annual gas exchange rates. Using the flux rates and the values measured for controlling environmental factors, the relationship of instantaneous flux rates and the factors can be statistically evaluated. Within the range of covariation observed in fluxes and the controls, annual emissions can be predicted for periods when the seasonal controlling factors are recorded. If the regional coverage of gas flux and environmental measurements is adequate, suitable regression models could be estimated for climatically different regions. The weather simulator and the underlying weather statistics would support such a regional assessment. Extrapolation of the regression predictions is principally not allowed in conditions that exceed the range in observations.

We have so far employed the weather simulator and soil models for estimating the possible contribution of inter-annual variability in weather to the gas fluxes (Minkkinen *et al.* 2007a, Mäkiranta *et al.* 2007, Saarnio *et al.* 2007). As measured data of solar irradiation and peat soil moisture (or WT) are not commonly available, such data were generated by means of a weather simulator. A chain of models were applied to simulate peat moisture, depth of the water table and peat temperature with input from hourly weather parameters, as described above. Transfer functions for NEE and CH_4 were guided by the thirty year time series of simulated hourly weather patterns, and the variation in the respective gas flux estimates was used to illustrate the potential long-term weather-dependency of emission factors (Minkkinen *et al.* 2007a, Mäkiranta *et al.* 2007, Saarnio *et al.* 2007). The description of current vegetation, in terms of VGA, was used in order to achieve dynamic NEE for the pristine peatlands. It is likely that the artificial weather data includes such combinations of environmental factors which our measurements do not cover. It was assumed that over the season, the averaging properties of regression transfer functions tended to compensate for the possible few extrapolated values.

Inter-annual variability in the greenhouse gas fluxes, as such, is not directly usable as an error estimate in the land use related gas emission inventories. However, much of the uncertainty in the emission factors is due to the variation observed during the necessarily short study periods possible at each land use category. There the simulation tools may provide insight to the climatic responses of and feedbacks from the ecosystems under both management and environmental changes. In this respect, weaknesses carried by statistical transfer functions can hopefully soon be overcome when process models are improved to make use of the collected new flux data and the better quantified process controls.

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References

Akima H. 1970. A new method of interpolation and smooth curve fitting based on local procedures. *Journal of the ACM* 17: 589–602.

Alm J., Talanov A., Saarnio S., Silvola J., Ikkonen E., Aaltonen H., Nykänen H. & Martikainen P.J. 1997. Reconstruction of the carbon balance for microsites in a boreal oligotrophic pine fen, Finland. *Oecologia* 110: 423–431.

Alm J., Saarnio S., Nykänen H., Silvola J. & Martikainen P.J. 1999. Winter CO_2, CH_4 and N_2O fluxes on some boreal natural and drained peatlands. *Biogeochemistry* 44: 163–186.

Alm J., Shurpali N.J., Minkkinen K., Aro L., Hytönen J., Laurila T., Lohila A., Maljanen M., Martikainen P.J., Mäkiranta P., Penttilä T., Saarnio S., Silvan N., Tuittila E.-S. & Laine J. 2007. Emission factors and their uncertainty for the exchange of CO_2, CH_4 and N_2O in Finnish managed peatlands. *Boreal Env. Res.* 12: 191–209.

Aurela M., Laurila T. & Tuovinen J.-P. 2001. Seasonal CO_2 budgets on a subarctic mire. *Journal of Geophysical Research* 106: 1623–1637.

Aurela M., Laurila T. & Tuovinen J.-P. 2002. Annual CO_2 balance of a subarctic fen in northern Europe: The importance of the wintertime efflux. *Journal of Geophysical Research* 107(D21), doi:10.1029/2002JD002055.

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

Bubier J.L., Frolking S., Crill P.M. & Linder E. 1999. Net ecosystem productivity and its uncertainty in a diverse boreal peatland. *Journal of Geophysical Research* 104: 27683–27692.

Burrows E.H., Bubier J.L., Mosedale A., Cobb G.W. & Crill P.M. 2005. Net ecosystem exchange of carbon dioxide in a temperate poor fen: a comparison of automated and manual chamber techniques. *Biogeochemistry* 76: 21–45.

Davidson E.A., Savage K., Verchot L.V. & Navarro R. 2002. Minimizing artifacts and biases in chamber-based measurements of soil respiration. *Agricultural and Forest Meteorology* 113: 21–37.

Frolking S., Roulet, N.T., Moore T.R., Lafleur P.M., Bubier J.L. & Crill P.M. 2002. Modelling seasonal to annual carbon balance of Mer Bleue Bog, Ontario, Canada. *Global Biogeochemical Cycles* 16, doi 10.1029/2001GB0011457.

Granberg G., Grip H., Ottoson-Löfvenius M., Sundh I., Svensson B. & Nilsson M. 1999. A simple model for simulation of water content, soil frost, and soil temperatures in boreal mixed mires. *Water Resources Research* 35: 3771–3782.

Heikurainen L. 1982. Peatland forestry. In: Heikurainen L., Kurki M., Paavilainen E., Suoninen A., Tolonen K. & Laine J. (eds.), *Peatlands and their utilization in Finland*, Finnish Peatland Society, Finnish National Committee of the International Peat Society, Helsinki, pp. 53–61.

Hirsch A.I., Trumbore S.E. & Goulden M.L. 2004. The surface CO_2 gradient and pore-space storage flux in a high-porosity litter layer. *Tellus* 56B: 312–321.

Houghton J.T., Meira Filho L.G., Treanton K., Mamaty I., Bonduki Y., Griggs D.J. & Callander B.A. (eds.) 1997. *Revised 1996 IPCC Guidelines for National Greenhouse Inventories*. IPCC/OECD/IEA, Paris, France.

Hutchinson G.L. & Livingston G.P. 2001. Vents and seals in non-steady-state chambers used for measuring gas exchange between soil and the atmosphere. *European Journal of Soil Science* 52: 675–682.

IMSL 1989. *Math/Library*, *FORTRAN subroutines for mathematical applications*, ver. 1.1, IMSL Houston, Texas, USA, pp. 399–560.

Jansson P.-E. & Karlberg L. 2004. *Coupled heat and mass transfer model for soil-plant-atmosphere systems*. Royal Institute of Technology, Dept. of Civil and Environmental Engineering, Stockholm.

Kaimal J.C. & Finnigan J.J. 1994. *Atmospheric boundary layer flows: their structure and measurement*. Oxford University Press, New York.

Kasimir-Klemedtsson Å., Klemedtsson L., Berglund K., Martikainen P.J., Silvola J. & Oenema O. 1997. Greenhouse gas emissions from farmed organic soils: a review. *Soil Use and Management* 13: 245–250.

Kellomäki S., Väisänen H. & Strandman H. 1993. Finnfor: *A model for calculating the response of boreal forest ecosystem to climate change*. Research Notes 6, Faculty of Forestry, University of Joensuu.

Kettunen A. 2000. Short-term carbon dioxide exchange and environmental factors in a boreal fen. *Verh. Internat. Verein. Limnol*. 27: 1–5.

Kettunen A., Kaitala V., Alm J., Silvola J., Nykänen H. & Martikainen P.J. 2000. Predicting variations in methane emissions from boreal peatlands through regression models. *Boreal Environment Research* 5: 115–131.

Knapp A.K. & Yavitt J.B. 1992. Evaluation of a closed-chamber method for estimating methane emissions from aquatic plants. *Tellus* 44B: 63–71.

Kuzyakov Y. 2006. Sources of CO_2 efflux from soil and review of partitioning methods. *Soil Biology and Biochemistry* 38: 425–448.

Laiho R. 2006. Decomposition in peatlands: Reconciling seemingly contrasting results on the impacts of lowered water levels. *Soil Biology and Biochemistry* 38: 2011–2024.

Laiho R. & Finér L. 1996. Changes in root biomass after waterlevel drawdown on pine mires in southern Finland. *Scandinavian Journal of Forest Research* 11: 251–260.

Laiho R., Laine J., Trettin C.C. & Finér L. 2004. Scots pine litter decomposition along drainage succession and soil nutrient gradients in peatland forests, and the effects of inter-annual weather variation. *Soil Biology and Biochemistry* 36: 1095–1109.

Laine A., Sottocornola M., Kiely G., Byrne K.A., Wilson D. & Tuittila E.-S. 2006. Estimating net ecosystem exchange in a patterned ecosystem: Example from blanket bog. *Agricultural and Forest Meteorology* 138: 231–242.

Lapveteläinen T., Regina K. & Perälä P. 2007. Peat-based emissions in Finland's national greenhouse gas inventory. *Boreal Env. Res.* 12: 225–236.

Lloyd J. & Taylor J.A. 1994. On the temperature dependence of soil respiration. *Functional Ecology* 8: 315–323.

Lohila A., Aurela M., Regina K. & Laurila T. 2003. Soil and total ecosystem respiration in agricultural fields: effect of soil and crop type. *Plant and Soil* 251: 303–317.

Lohila A., Aurela M., Tuovinen J.-P. & Laurila T. 2004. Annual CO_2 exchange of a peat field growing spring barley or perennial forage grass. *Journal of Geophysical Research* 109(D18116), doi:10.1029/2004JD004715.

Lohila A., Laurila T., Aro L., Aurela M., Tuovinen J.-P., Laine J., Kolari P. & Minkkinen K. 2007. Carbon dioxide exchange above a 30-year-old Scots pine plantation established on organic-soil cropland. *Boreal Env. Res.* 12: 141–157.

Longdoz B., Yernaux M. & Aubinet M. 2000. Soil CO_2 efflux measurements in a mixed forest: impact of chamber disturbances, spatial variability and seasonal evolution. *Global Change Biology* 6: 907–917.

Mäkiranta P., Hytönen J., Aro L., Maljanen M., Pihlatie M., Potila H., Shurpali N.J., Laine J., Lohila A., Martikainen P. J. & Minkkinen K. 2007. Soil greenhouse gas emissions from afforested organic soil croplands and cutaway peatlands. *Boreal Env. Res.* 12: 159–175.

Maljanen M., Hytönen J. & Martikainen P.J. 2001. Fluxes of N_2O, CH_4 and CO_2 on afforested boreal agricultural soils. *Plant and Soil* 231: 113–121.

Maljanen M., Komulainen V.-M., Hytönen J., Martikainen P.J. & Laine J. 2004. Carbon dioxide, nitrous oxide and methane dynamics in boreal organic agricultural soils with different soil management. *Soil Biology and Biochemistry* 36: 1801–1808.

Maljanen M., Hytönen J., Mäkiranta P., Alm J., Minkkinen K., Laine J. & Martikainen P. J. 2007. Greenhouse gas emissions from cultivated and abandoned organic croplands in Finland. *Boreal Env. Res.* 12: 133–140.

Massman W.J. & Lee X. 2002. Eddy covariance flux corrections and uncertainties in long-term studies of carbon and energy exchanges. *Agricultural and Forest Meteorology* 113: 121–144.

Minkkinen K. & Laine J. 1998. Long-term effect of forest drainage on the peat carbon stores of pine mires in Finland. *Canadian Journal of Forest Research* 28: 1267–1275.

Minkkinen K., Laine J., Shurpali N.J., Mäkiranta P., Alm J. & Penttilä T. 2007a. Heterotrophic soil respiration in forestry-drained peatlands. *Boreal Env. Res.* 12: 115–126.

Minkkinen K., Penttilä T. & Laine J. 2007b. Tree stand volume as a scalar for methane fluxes in forestry-drained peatlands in Finland. *Boreal Env. Res.* 12: 127–132.

Moore C. J. 1986 Frequency response correction for eddy correlation systems. *Boundary Layer Meteorology* 37: 17–35.

Moore T.R. & Knowles R. 1989. The influence of water table levels on methane and carbon dioxide emissions from peatland soils. *Canadian Journal of Soil Science* 69: 33–38.

Nykänen H., Alm J., Lång K., Silvola J. & Martikainen P.J. 1995. Emissions of CH_4, N_2O and CO_2 from a virgin fen and a fen drained for grassland in Finland. *Journal of Biogeography* 22: 1149–1155.

Papale D., Reichstein M., Aubinet M., Canfora E., Bernhofer C., Kutsch W., Longdoz B, Rambal S. Valentini R., Vesala T. & Yakir D. 2006. Towards a standardized processing of Net Ecosystem Exchange measured with eddy covariance technique: algorithms and uncertainty estimation. *Biogeosciences* 3: 571–583.

Penman J., Gytarsky M., Hiraishi T., Krug T., Kruger D., Pipatti R., Buendia L., Miwa K., Ngara T., Tanabe K. & Wagner F. (eds.) 2003. *Good practice guidance for land use, land-use change and forestry*. Published for the IPCC by the Institute for Global Environmental Strategies, Hayama, Japan.

Penman J., Kruger D., Galbally I., Hiraishi T., Nyenzi B., Emmanuel S., Buendia L., Martinsen T., Meijer J., Miwa K. & Tanabe K. (eds.) 2000. *Good practice guidance management in national greenhouse gas inventories*. Published for the IPCC by the Institute for Global Environmental Strategies, Hayama, Japan.

Pihlatie M., Rinne, J., Ambus P., Pilegaard K., Dorsey J.R., Rannik Ü, Markkanen T., Launiainen S. & Vesala T. 2005. Nitrous oxide emissions from a beech forest floor measured by eddy covariance and soil enclosure techniques. *Biogeosciences* 2: 377–387.

Pumpanen J., Kolari P., Ilvesniemi H., Minkkinen K., Vesala T., Niinistö S., Lohila A., Larmola T., Morero M., Pihlatie M., Janssens I., Curiel Yuste J., Grünzweig J. M., Reth S., Subke J.-A., Savage K., Kutsch W., Østreng G., Ziegler W., Anthoni P., Lindroth A. & Hari P. 2004. Comparison of different chamber techniques for measuring soil CO_2 efflux. *Agricultural and Forest Meteorology* 123: 159–176.

Saarnio S., Alm J., Silvola J., Lohila A., Nykänen H. & Martikainen P.J. 1997. Seasonal variation in CH_4 emission and production and oxidation potentials in microsites of an oligotrophic pine fen. *Oecologia* 111: 414–422.

Saarnio S., Morero M., Shurpali N.J., Tuittila E.-S., Mäkilä M. & Alm J. 2007. Annual CO_2 and CH_4 fluxes of pristine boreal mires as a background for the lifecycle analyses of peat energy. *Boreal Env. Res.* 12: 101–113.

Selin P. 1999. *Turvevarojen teollinen käyttö ja suopohjien hyödyntäminen Suomessa*. Jyväskylä Studies in Biological and Environmental Science 79, Jyväskylän yliopisto, Jyväskylä.

Silvola J. 1985. CO_2 dependence of photosynthesis in certain forest and peat mosses and simulated photosynthesis at various actual and hypothetical CO_2 concentrations. *Lindbergia* 11: 86–93.

Silvola J., Alm J., Ahlholm U., Nykänen H. & Martikainen P.J. 1996. CO_2 fluxes from peat in boreal mires under varying temperature and moisture conditions. *Journal of Ecology* 84: 219–228.

Sommerfeld R.A., Mosier A.R. & Musselman R.C. 1993. CO_2, CH_4 and N_2O flux through a Wyoming snowpack and implications for global budgets. *Nature* 361: 140–142.

Suoninen A. 1982. Peat production. In: Heikurainen L., Kurki M., Paavilainen E., Suoninen A., Tolonen K. & Laine J. (eds.) *Peatlands and their utilization in Finland*, Finnish Peatland Society, Finnish National Committee of the International Peat Society, Helsinki, pp. 67–97.

Strandman S., Väisänen H. & Kellomäki S. 1993. A procedure for generating synthetic weather records in conjunction of climatic scenario for modelling of ecological impacts of changing climate in boreal conditions. *Ecological Modelling* 80: 237–250.

Tomppo E., Varjo J., Korhonen K., Ahola A., Ihalainen A., Heikkinen J., Hirvelä H., Mikkelä H., Mikkola E., Salminen S. & Tuomainen T. 1997. Country report for Finland. In: *Reports on forestry inventory and survey*

systems, vol. 1, European Commission, pp. 145–226.
Tuittila E.-S., Komulainen V-M., Vasander H., Nykänen H., Martikainen P.J. & Laine J. 2000. Methane dynamics of a restored cut-away peatland. *Global Change Biology* 6: 569–581.
Tuittila E.-S., Vasander H. & Laine J. 2004: Sensitivity of C sequestration in reintroduced *Sphagnum* to water-level variation in a cut-away peatland. *Restoration Ecology* 12: 482–492.
Valmari A. 1982. Agricultural utilization of peatlands. In: Heikurainen L., Kurki M., Paavilainen E., Suoninen A., Tolonen K. & Laine J. (eds.), *Peatlands and their utilization in Finland*, Finnish Peatland Society, Finnish National Committee of the International Peat Society, Helsinki, pp. 42–48.
Vasander H., Tuittila E.-S., Lode E., Lundin L. Ilomets M., Sallantaus T., Heikkilä R., Pitkänen M.-L. & Laine J. 2003. Status and restoration of peatlands in Northern Europe. *Wetlands Ecology and Management* 11: 51–63.
Webb E.K., Pearman G.I. & Leuning R. 1980. Correction of flux measurements for density effects due to heat and vapour transfer, *Quarterly Journal of the Royal Meteorological Society* 106: 85–100.
Weiss R., Alm J., Laiho R. & Laine J. 1998. Modelling moisture retention in peat soils. *Soil Science Society of America Journal* 62: 305–313.
Wilson D., Alm J., Riutta T., Laine J., Byrne K.A., Farrell E.P. & Tuittila E.-S. 2007. A high resolution green-area index for modelling the seasonal dynamics of CO_2 exchange in vascular plant peatland communities. *Plant Ecol.* 190: 37–51.
Yli-Petäys M., Laine J., Vasander H. & Tuittila E.-S. 2007. Carbon gas exchange of a re-vegetated cut-away peatland five decades after abandonment. *Boreal Env. Res.* 12: 177–190.
Zhang Y., Li C., Trettin C., Li H. & Sun G. 2002. An integrated model of soil, hydrology, and vegetation for carbon dynamics in wetland ecosystems. *Global Biogeochemical Cycles* 16(4), 1061, doi:10.1029/2001GB001838.