BOREAL ENVIRONMENT RESEARCH 12: 191–209
Helsinki 11 May 2007
ISSN 1239-6095

Emission factors and their uncertainty for the exchange of CO_2, CH_4 and N_2O in Finnish managed peatlands

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Received 9 Jan. 2007, accepted 20 Mar. 2007 (Editor in charge of this article: Raija Laiho)

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.

This paper summarises the results of several research groups participating in the research programme "Greenhouse Impacts of the use of Peat and Peatlands in Finland", and presents emission factors for peat–atmosphere fluxes of CO_2, CH_4, and N_2O, filling gaps in knowledge concerning the afforestation of organic croplands and cutaways, and improves the emission assessment of peatlands drained for forestry. Forest drainage may result in net binding of soil carbon or net release, depending on site characteristics and the tree stand. Use of peatlands for agriculture (48–4821 g CO_2-eq. m^{-2} a^{-1}), even after the cultivation has ceased, or for milled peat harvesting (1948–2478 g CO_2-eq. m^{-2} a^{-1}) can cause the highest overall emissions. Extremely high CO_2 emissions are possible from peat harvesting areas during wet and warm summers. Afforestation of those peatlands abandoned from cultivation or peat harvesting can reduce the warming impact at least during the first tree generation. Heterotrophic soil respiration may have a systematic south–north difference in temperature response. More data must be collected before the information on peatland forest soil CO_2 emissions can be adapted for different climatic regions in Finland. A test of the model DNDC against measured data showed that DNDC has to be developed further before it can be used in estimating N_2O emissions from boreal peatlands.

Introduction

Energy and food production, waste management and land use changes all contribute to an increase in greenhouse gas (GHG) emissions to the atmosphere. Climate warming, in part caused by the emissions from land use (Watson *et al.* 2001), may increase the risks of serious environmental hazards. For nations, mitigation of such risks will require significant reductions in the anthropogenic GHG emissions. As a starting point for international collaboration in the mitigation activities, reliable inventories of emissions were agreed in the United Nations Framework Convention of Climate Change (UNFCCC) in 1992, and in the Kyoto Protocol thereafter (1997). The inventories should follow internationally accepted guidance (Houghton *et al.* 1997, Penman *et al.* 2000, Penman *et al.* 2003) by International Panel on Climate Change (IPCC). While the emissions from fossil fuel combustion for energy production can be calculated with reasonable accuracy, estimation of emissions originating from biogeochemical cycles, disturbed by land use is more challenging. The IPCC Good Practice Guidance reports (Penman *et al.* 2000, 2003) have suggested three methodological tier levels for estimating emissions and removals. For land use based estimates Tier 1 employs IPCC default emission factors per area and usually activity data that are spatially coarse, while Tier 2 uses the same methodological approach as Tier 1 but emission factors are country-specific and high resolution land area data are used. Tier 3 uses higher order methods including models and inventory measurement systems, and high resolution activity data. Countries are encouraged to use the two higher tiers in their inventories, whenever possible.

In Finland, peat comprises the largest soil carbon (C) store, containing ca. 5.5 Pg C (Minkkinen *et al.* 2002) as compared with the ca. 1.1–1.3 Pg C in mineral soils (Liski and Westman 1997). Mire vegetation binds atmospheric carbon dioxide (CO_2) in biomass. As the plants die, a part of carbon (and nitrogen) in organic litter gets deposited in waterlogged conditions as peat, thereby removing CO_2 from the atmosphere. On the other hand, slow decomposition of anoxic peat produces methane (CH_4), another greenhouse gas warming the atmosphere. Mires thus maintain, in part, the natural atmospheric greenhouse gas mixing ratio. Gas fluxes from natural ecosystems are not reported to the UNFCCC or the Kyoto Protocol.

Mires have been drained for various land uses, and the consequent lowering of the water tables changes the conditions for plants and soil organisms. The primary change is an increase in the aerated soil volume which changes the decomposition process and hence the greenhouse gas fluxes (Trettin *et al.* 2006). In this document, term “mire” is used for pristine ecosystems, and “peatland” for drained ones. Drained peatlands tend to emit more CO_2, but less CH_4 than undrained mires do (Moore and Knowles 1989, Silvola *et al.* 1996a, Nykänen *et al.* 1998). On the other hand, more biomass can be stored in forestry drained peatlands during the forest succession (e.g. Minkkinen *et al.* 1999), but the question of net carbon sink or source is more cumbersome (Laiho 2006). Further, mineralization of organic matter may stimulate emissions of nitrous oxide (N_2O) from drained nutrient rich peatlands as demonstrated by Martikainen *et al.* (1993).

A major proportion — 5.4–5.7 Mha of the originally ca. 10.4 Mha — of Finnish mires have been drained for forestry (Päivänen and Paavilainen 1996, Minkkinen 1999) and 0.7–1.0 Mha for agriculture (Myllys 1996, Myllys and Sinkkonen 2004), leaving ca. 40% (4.1 Mha, Finnish Forest Research Institute 2005) undrained. Some of the current peat extraction area (0.06 Mha) has been established on peatlands, previously drained for forestry, but pristine mires have also been reclaimed. Cutaway peatlands, abandoned from industrial peat extraction, have mostly been prepared for afforestation, for special agriculture and energy crops, or returned as waterlogged wetlands through restoration measures (Selin 1999).

Much data on peatland gas fluxes have been collected in two Finnish research programs, both consisting of research groups from several universities and research institutes, working under a common umbrella: The Finnish Programme on Climate Change (SILMU) funded by the Academy of Finland in 1990–1996, and the programme Greenhouse Impacts of the Use of Peat and Peatlands in Finland in 2001–2005. In addition, fluxes in peatlands under agriculture and forestry have been studied in projects funded by European Union and the Academy of Finland, and the Ministry of Agriculture and Forestry (conducted by Finnish Forest Research Institute). Because of these research efforts, many of the Tier 1 default values in the IPCC Good Practice Guidance for Land Use, Land Use Change and Forestry (Penman *et al*. 2003) for peatlands derive from Finnish research.

In this paper, Tier 2 and Tier 3 level emission factors usable in Finnish GHG inventories are reviewed, and the sources of uncertainty are discussed. We have collected published data on the emissions of CO_2, CH_4, and N_2O for the various categories of peatland use in Finland. Both new and previously measured data from peat extraction areas (Ahlholm and Silvola 1990, Nykänen *et al*. 1996) are combined here in order to obtain a more comprehensive understanding on emissions from this land-use category. The methodology used here is mostly similar to that in previous research in Finland by the same research groups, ensuring a reasonable comparability of the results.

For the terminology of mires and peatlands, please refer to e.g., Joosten and Clarke (2002). The sign convention for the emission factors in this paper is as follows: The gas emissions and their combination in CO_2 equivalents, using the gas specific GWP coefficients, are shown as positive values, and removals from the atmosphere as negative values. The ecosystem's carbon balance is referred to as negative when the C store is decreasing, and positive when it is increasing.

Where the data allows, the role of interannual weather variability in the uncertainty of the emissions is evaluated using weather simulation tools (Alm *et al*. 2007). Regional coverage of the emission factors is discussed. In addition, the applicability of a process model DNDC to Tier 3 is examined with test data.

Data from peatland categories

Fluxes of CO_2 and CH_4 in pristine mires

The majority of the C balance in pristine mires comprises of the exchange of CO_2 and CH_4 between the ecosystem and the atmosphere. The rates of gas exchange are sensitive to variations in weather, responding immediately to changes in irradiation and with varying lags to those in air and soil temperature and precipitation (Alm *et al*. 1997, 1999a, Saarnio *et al*. 1997, Kettunen *et al*. 2000). Average long term rate of C accumulation in Finnish minerotrophic fens during the Holocene was ca. 17 g C m^{-2} a^{-1}, and in ombrotrophic bogs ca. 21 g C m^{-2} a^{-1}, corresponding to sequestration rate of –62 g and –77 g CO_2 m^{-2} a^{-1}, respectively. Those figures have been obtained using geological cores and ^{14}C dating (Turunen *et al*. 2002), and carry the possible impact of past fires that may locally deplete a considerable part of peat reserves over the millennia (Pitkänen *et al*. 1999). Gas exchange measurements give information of C exchange in terms of CO_2 and CH_4 balances, which in turn can be used in estimation of the present-day C accumulation rate (Alm *et al*. 1997, Saarnio *et al*. 1997, Saarnio *et al*. 2007). The very different time scales of geologically determined peat accumulation rates and the annual C exchange rates estimated from gas exchange make the comparison difficult.

On an annual basis, both CO_2 and CH_4 exchange show great variability, which is related to local annual temperature sum and precipitation. There are differences between minerotrophic and ombrotrophic mires. According to the review by Saarnio *et al*. (2007), CO_2 balances from a net loss of –370 g CO_2 m^{-2} a^{-1} to a net gain of +359 g CO_2 m^{-2} a^{-1} have been reported in minerotrophic mires and from –312 to 246 g CO_2 m^{-2} a^{-1} in ombrotrophic mires, respectively. Similarly, the range of C loss in CH_4 emission in the minerotrophic mires has been 1–56 g CH_4 m^{-2} a^{-1}, and < 1–21 g CH_4 m^{-2} a^{-1} in the ombrotrophic ones. Because the gas fluxes from pristine mires are considered as zero and are not reported to the UNFCCC or the Kyoto Protocol, their gas balances are not tabulated with those from drained peatlands. The wide range of annual CO_2 or CH_4 balances in natural mires illustrates the uncertainties in estimates of the present C accumulation rate. Since peat surface layers are loaded with easily decomposable organic matter, a temporary lowering of the water table may cause rapid C losses through oxidation, and control the quality of organic matter entering permanently water saturated conditions. Decomposition of peat and litter constitutes the largest part of carbon output as CO_2, other losses occur in the form of dissolved organic matter, which has been estimated at 5–10 g C m^{-2} annually (Sallantaus 1992, Kortelainen and Saukkonen 1994), in possible forest fires (Pitkänen *et al.* 1999), and in erosion. The carbon leached from peatlands may be released as CO_2 and CH_4 within the receiving watercourses (Huttunen *et al.* 2003, Kortelainen *et al.* 2006).

The key to present and future rates of peat accumulation is hidden in the variation of annual scale responses of the mire ecosystems to climatic forcing. Biomass productivity, in that respect, seems more stable than decomposition of fresh organic litter (Shurpali *et al.* 1995, Vourlitis and Oechel 1999) as long as the vegetation type remains unchanged. Thus, the immediate dynamics of decomposition amplify the variation of net C exchange in mires. Young mires (Clymo *et al.* 1998) or restored peatlands (Tuittila 2000), if genuinely waterlogged, may initially accumulate organic matter with rates far greater than what will take place at later ages. Dynamics of mire plant communities guide the rate of ecosystem CO_2 assimilation (Riutta *et al.* 2006). A more frequent occurrence of droughts and simultaneous high temperatures could enhance the decay of the fresh litter "reserves" in the topmost peat layers (Alm *et al.* 1999a). A sound prediction of present rate of C accumulation in peat calls for new data and improved biogeochemical models (Frolking *et al.* 2002), that would combine the processes of auto- and allogenic vegetation succession and litter decay to climatic forcing through irradiation, temperature and hydrology (Kettunen 2000, Weiss *et al.* 2006).

Peatlands drained for forestry

Depending on peatland forest, 160–500 g C m^{-2} a^{-1} of the peat substrate (> 1-year-old organic matter) is oxidized (Minkkinen *et al.* 2007a). These figures exclude the contribution of root associated respiration (e.g. Silvola *et al.* 1996b). The soil losses of CO_2 are greatest at fertile site types such as the drained herb-rich type, and lowest at less fertile sites, e.g. dwarf-shrub or *Vaccinium vitis-idaea* type (Silvola *et al.* 1996a, Minkkinen *et al.* 2007a). With a help of 30 year weather simulations in Finnish conditions, the average modelled annual soil CO_2 release falls between 880–1713 g m^{-2} (Minkkinen *et al.* 2007a) from Vatkg (dwarf-shrub) to Rhtkg (herb-rich) types, respectively (Table 1). The simulated averages can be used as best estimates of soil respiration for the respective site quality classes of peatland forests in the Finnish GHG inventory. Litter from trees and ground vegetation adds new organic matter in the rooting zone and on the soil surface (Laiho *et al.* 2003). Part of this litter is quickly decomposed and returned to the atmosphere as CO_2, but a more recalcitrant fraction can remain in the soil for longer periods of time (Minkkinen and Laine 1998).

Methane is formed and oxidized in peatland forest soils, but the net CH_4 release rate is less than 4 g m^{-2} a^{-1} even in high water table conditions on less fertile drained peatlands. In successfully forested peatlands, where effective drainage and evapotranspiration keep the water level low, net CH_4 consumption rates up to –1 g m^{-2} a^{-1} have been measured (Minkkinen *et al.* 2007b). However, Minkkinen and Laine (2006) have estimated that the CH_4 emitted from the ditches compensates for or even exceeds the observed maximum rate of CH_4 consumption –0.82 g m^{-2} a^{-1} (Table 1) from within the forested strips. Thus even though drainage greatly diminishes CH_4 emissions, most drained peatlands remain as small sources of CH_4 when emissions from ditches are included (Table 1).

Drainage for forestry can stimulate N_2O emissions only on fertile or fertilized sites (Martikainen *et al.* 1993, Regina *et al.* 1996), but very little data are available from Finnish conditions. In nutrient-poor bogs N_2O effluxes remain very small (Regina *et al.* 1996, 1998) whereas in the most fertile drained pine fens and spruce mires emissions may rise close to 1 g N_2O m^{-2} a^{-1} (K. Minkkinen unpubl. data). According to Martikainen *et al.* (1993), drained mesotrophic peatlands, comparable to *Vaccinium myrtillus* type and herb-rich type, released 0.08 to 0.22 g N_2O m^{-2} a^{-1}, respectively. Klemedtsson *et al.* (2005) showed that the annual release of N_2O from drained Swedish, Finnish and German peatlands has an inverse, nonlinear correlation with peat C:N ratio. This method would give means for regional estimation of N_2O emissions if peat C:N ratios were known. A regional sampling for peatland sites in Finland was performed in 2001–2002 by the Finnish Forest Research Institute (Laiho *et al.* 2005). The C:N ratios derived from that database, and the actual N_2O measurements available from peatland forests were used in estimating the potential N_2O emissions from forestry drained peatlands (K. Minkkinen unpubl. data). The tested C:N ratio to N_2O relationships were comparable to those of Klemedtsson *et al.* (2005). Applying the different models and regional distribution of forested peatland site types in Finland from the 10th National Forest Inventory, the emission estimates fell between 8.5–15.3 Gg N_2O a^{-1}, i.e. 0.17–0.31 g N_2O m^{-2} a^{-1}. Half of this amount was emitted from the nutrient rich spruce sites, although the majority of drained peatlands are originally relatively nutrient-poor pine mires (Keltikangas *et al.* 1986).

Peatlands used for agriculture

Agricultural use of peatland reduces the natural release of CH_4 (Nykänen *et al.* 1995), but induces considerable and long-lasting emissions of CO_2 and N_2O. Repeated soil tillage keeps the topsoil layers in oxic conditions, and enhances heterotrophic decomposition and high CO_2 release rates (Nykänen *et al.* 1995, Maljanen 2003a, Maljanen *et al.* 2007). A reason for large N_2O emissions is nitrogen fertilization, being decisive in mineral soils, but in organic croplands nitrification and denitrification are mostly supported by the naturally high peat N content. Fertilization may enhance the release of N_2O from organic soils (Augustin *et al.* 1998), and denitrification reactions may benefit from organic substrates as their energy supply (Maljanen 2003b). The C:N ratio is low in agricultural peatlands (Regina *et al.* 2004, Klemedtsson *et al.* 2005, Lohila *et al.* 2007) due to conditions promoting the decomposition of organic matter. Even though the flux of N_2O shows great sensitivity to weather events, especially rain showers, the prediction of N_2O emissions on the basis of weather records alone

Table 1. Greenhouse gas emissions with ranges of 30-year simulated (CO_2) or annually-integrated observed emissions (CH_4 and N_2O) from organic soils drained for forestry. The CO_2 emissions consist of heterotrophic decomposition of peat and > 1-year-old litter. The site types represent different site quality characteristics from poor (dwarf-shrub) to fertile (herb-rich) types. The regions South and North refer to long-term regions of effective temperature sum below and above 950 dd in Finland (Fig. 1). N.D. = Not defined. Total CO_2 equivalent is calculated using conversion over a 100 year time span (GWP[CH_4] = 23; GWP[N_2O] = 296, Watson *et al.* 2001). [1)] Total CH_4 fluxes including estimated ditch emissions (Minkkinen *et al.* 1997, Minkkinen and Laine 2006) are shown in brackets after the average fluxes from drained strips.

GHG species	Dwarf-shrub type (Vatkg)	*Vaccinium vitis-idaea* type (Ptkg)	*Vaccinium myrtillus* type (Mtkg)	Herb-rich type (Rhtkg)	References
CO_2 (g m^{-2} a^{-1})					Minkkinen *et al.* (2007a)
South avg. (min–max)	880 (719–1001)	975 (810–1096)	1250 (1045–1404)	1713 (1437–1911)	
North avg. (min–max)	N.D.	N.D.	1749 (1555–2035)	N.D.	
CH_4 (g m^{-2} a^{-1}) avg. (min–max)	1.9 [2.1][1] (–0.3–3.5)	–0.27 [0.1][1] (–0.82–0.28)	0.21 [0.6][1] (–0.20–0.87)	–0.58 [–0.2][1] (–0.73–0.39)	Minkkinen *et al.* (2007b), Minkkinen & Laine 2006, Minkkinen *et al.* 1997
N_2O (g m^{-2} a^{-1}) avg. (min–max)	0.009 (0–0.018)	0.13 (0.06–0.21)	0.37 (0.17–0.82)	0.56 (0.30–0.81)	Martikainen *et al.* (1993) K. Minkkinen unpubl. data
Total CO_2-eq.	926	1007	1614	1865	

is difficult. Drainage for agriculture is generally effective enough to keep CH_4 emissions low (Table 2), and low temporary emissions or much more often net consumption from –0.5 to +4 g CH_4 m^{-2} a^{-1} continues even after abandonment of the cropland (Regina *et al*. 2004, Maljanen *et al*. 2001, 2003a, 2004, 2007, Lohila *et al*. 2004).

Both fallow and cultivated croplands give rise to CO_2 emissions of similar magnitude (Table 2), the range of net release rates observed being 2167–4033 g CO_2 m^{-2} a^{-1} from fallow, 290–2750 g CO_2 m^{-2} a^{-1} from grass, and 770–3043 g CO_2 m^{-2} a^{-1} from cereals (Maljanen *et al*. 2007). The respective N_2O emissions from fallow areas were 0.6–5.8 g N_2O m^{-2} a^{-1} , typically higher than those from vegetated areas, 0.2–3.8 g N_2O m^{-2} a^{-1}. New results have shown that in Finnish conditions as much as 25%–60% of N_2O emissions can occur in winter (Maljanen *et al*. 2007). This has important implications in developing process models suitable for boreal conditions. It is also worth noting that as part of the life cycle, the crops will be consumed by man or as animal fodder, and respired back to the atmosphere as CO_2 or partly as CH_4 by ruminants or at the landfills. Reporting of these emissions to the UNFCCC takes place in separate categories.

Former agricultural peatlands abandoned or afforested

Afforestation or abandonment of croplands is expected to reduce the greenhouse gas emissions. That may occur through an increase in C stock as accumulation of above ground wood biomass and through the cessation of tillage and fertilization that favor organic matter oxidation and N_2O emissions. However, strong emissions of CO_2 and N_2O may continue for several decades after the cultivation has ceased (Maljanen *et al*. 2001, Maljanen *et al*. 2007, Mäkiranta *et al*. 2007).

Although Maljanen *et al*. (2007) reported net annual accumulation of up to –330 g CO_2 m^{-2} in some cases, the average net emission value of the five study sites, 1188 g CO_2 m^{-2} a^{-1}, indicates a high loss of C from abandoned agricultural peatland sites (Table 2). At these sites, especially

Table 2. Annual greenhouse gas balances at organic croplands. Average gas exchange and range of reported fluxes are shown. Cultivated land class gives an average from different cultivation activities: grass, cereals, and fallow. Total CO_2 equivalent is calculated using the 100 yr GWP conversion with CO_2-eq. coefficients of 23 and 196 for CH_4 and N_2O, respectively (Watson *et al.* 2001).

GHG species	Average cultivated land	Grass	Cereals	Fallow	Abandoned	References
CO_2 (g m^{-2} a^{-1}) avg. (min–max)	2072 (290–4033)	1485	1760	2971 (2167–4033)	1188 (−330–3300)	Maljanen *et al.* (2007)
CH_4 (g m^{-2} a^{-1}) avg. (min–max)	0.42 (−0.49–0.91)	1.27 (0.11–0.91)	−0.43 (−0.49–0.51)	0.41 (−0.35–4.00)	−0.22	
N_2O (g m^{-2} a^{-1}) avg. (min–max)	1.74 (0.17–5.81)	0.85 (0.17–1.56)	1.74 (0.85–3.79)	2.63 (0.60–5.81)	1.29	
Total CO_2-eq.	2597	1766	2265	3759	1565	

the wintertime N_2O emissions remained high, contributing on average 50% of the annual emission of 1.3 g N_2O m^{-2} a^{-1}. However, there was a high interannual variation in the emissions, especially in the wintertime emissions. The annual N_2O emissions from abandoned croplands were similar to those obtained from organic croplands under active cultivation. The soils retain a low average CH_4 sink rate after the abandonment, –0.22 g CH_4 m^{-2} a^{-1}. Soil properties and hydrology, changed during the cultivation in favor of high organic matter turnover rates, seem to persist even after regular tillage or other amelioration measures have ceased.

Stand age on the afforested croplands, which were planted typically with birch or pine in the Finnish conditions, varied in our studies from 10 to 35 years (Mäkiranta *et al*. 2007), and stand volumes ranged from 2 to 193 m^3 ha^{-1}. However, no conclusions on the contribution of tree stand, original peat properties and differences in soil management could be made with the limited dataset.

The heterotrophic emissions of CO_2 from afforested organic croplands seem somewhat higher than those from forestry drained peatlands (Tables 1 and 3). When the amount of carbon bound annually in the new biomass, assumed as 169–1206 g CO_2 m^{-2} a^{-1} in the different tree stands, is subtracted from the annual emission from decomposing peat and old litter, 759–1976 g CO_2 m^{-2} a^{-1} (Table 3), the balance appears negative. However, this simple calculation does not include the C input to the soil through above- and below-ground litterfall. When all the actual fluxes are included e.g. using eddy covariance measurements, a lower loss may be expected. Lohila *et al*. (2007) reported a rather small net CO_2 emission of 50 g m^{-2} a^{-1} for the whole stand, afforested 30 years earlier on an organic cropland site. Thus, afforestation can reduce the CO_2 emissions for several decades when the tree stand and belowground biomass increase.

Surprisingly, afforestation did not lower N_2O emissions and the average annual N_2O emission was close to that from organic croplands under active cultivation. There was a high variation between sites, but the N_2O emissions were not clearly correlated with the age of afforestation, stand volume, peat depth, water table level or tree species. In the afforested sites N_2O emissions during winter were 22% of the annual emissions. Afforested croplands were small sinks for atmospheric methane (–0.15 g CH_4 m^{-2} a^{-1}); however, the CH_4 sink in these areas is insignificant compared to the atmospheric impacts of CO_2 and N_2O. Afforestation does not seem to change the soil CH_4 flux of former arable land provided that the drainage system is adequate.

Emissions from peat harvesting areas

Quality of the residual peat (Nykänen *et al*. 1996), moisture of the surface peat, the depth of the water table, and possibly the climatic conditions in the harvesting field affect the fluxes from peat harvesting areas. Unfortunately, there are not enough data to cover all the various conditions of harvested areas. However, flux measurements show similarities in CO_2 fluxes in different harvesting areas, but also illustrate that strikingly higher than average emissions may occur in exceptional conditions, when high temperature is combined with adequate soil moisture. The following assessment is based on data from literature (Ahlholm and Silvola 1990, Nykänen *et al*. 1996) and new data from peat harvesting sites in different regions in Finland (K. Minkkinen unpubl. data, N. Silvan unpubl. data; Figs. 1 and

Table 3. Annual emissions of greenhouse gases CO_2, CH_4, and N_2O from decomposition of peat and > 1 year-old litter in afforested organic croplands and cutaways. Total CO_2 equivalent is calculated using the 100 yr GWP conversion (Watson *et al*. 2001).

GHG species	Afforested croplands	Afforested cutaways	References
CO_2 (g m^{-2} a^{-1}) avg. (min–max)	1354 (759–1976)	1397 (1008–1756)	
CH_4 (g m^{-2} a^{-1}) avg. (min–max)	–0.15 (–0.43–0.81)	–0.05 (–0.03–0.09)	Mäkiranta *et al.* (2007)
N_2O (g m^{-2} a^{-1}) avg. (min–max)	1.02 (0.16–4.71)	0.15 (0.02–0.75)	

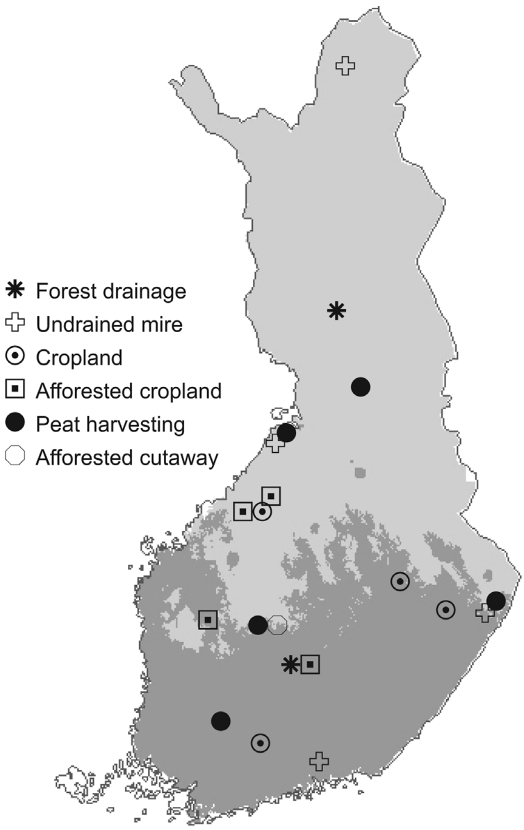

Fig. 1. Location of undrained mires and peatlands drained for different land use, used as study sites in the research programme. The light and dark grey shadows denote the regions where the average temperature sum 1961–1990 was below and over 1100 dd, respectively.

2, Table 4). New flux data were collected from three harvesting fields using closed chamber method and a portable IR analyzer as described for forest floor soil respiration measurements in Minkkinen *et al*. (2007a) and Alm *et al*. (2007). Thirty-year simulations based on 1961–1990 monthly average air temperature and simulation of temperature 5 cm below the peat surface (Alm *et al*. 2007), corresponding to air temperature sums of ca. 950 dd (Oulu) and ca. 1200 dd (Tampere), were used in evaluating the inter-annual variability of CO_2 emissions from the harvesting strips.

The simulated seasonal CO_2 emissions from 1 May to 31 October for the different sites were fairly similar, ranging from 219 to 1260 g CO_2 m^{-2} calculated with the Tampere weather series, and from 224 to 1210 g CO_2 m^{-2} with the Oulu series (averages given in Table 4). For the calculation of a single emission factor estimate, a common response function guided by soil temperature at –5 cm (Fig. 2) was applied. Winter emissions of 278 g CO_2 m^{-2} were estimated on the basis of the average of fluxes measured at or below zero soil temperatures (0.063 g CO_2 m^{-2} h^{-1} ± 0.01 S.E., n = 38, Fig. 2), and weighted with over 181 days to represent the period from 1 November to 30 April. Summing the winter emission to the simulated summer emissions gave annual emissions of 978 g CO_2 m^{-2} a^{-1} for Tampere and 943 g CO_2 m^{-2} a^{-1} for Oulu. The flux

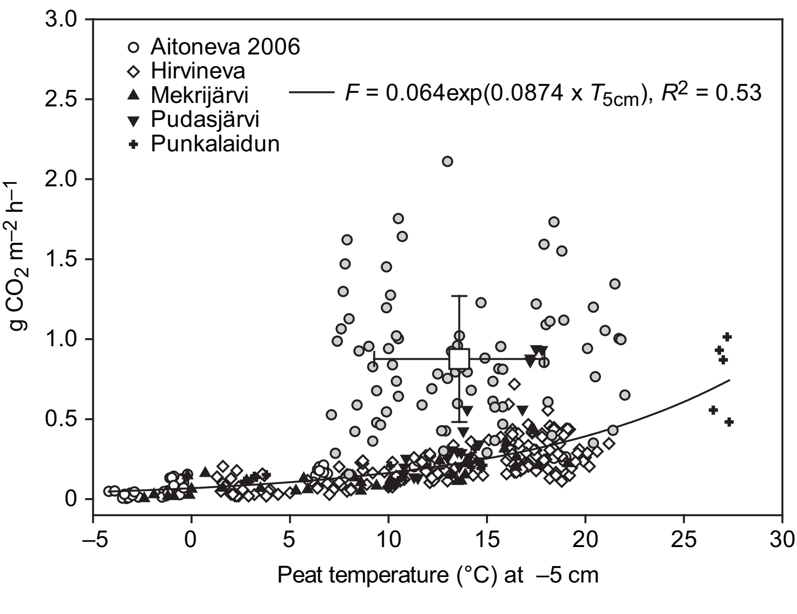

Fig. 2. White markers and the respective regression are used to derive annual CO_2 emission factors for peat harvesting areas; for regression parameters and data locations see the label. The open square with bi-directional error bars show CO_2 flux (Average CO_2 = 0.88 g m^{-2} h^{-1} *vs.* T_{5cm} =13.6 °C ± S.D.) measured in the warm and moist summer season in 2005 at the Aitoneva site (grey markers).

rates behind these figures were similar to those reported for southern (400–1020 g CO_2 m^{-2}) and northern (230–720 g CO_2 m^{-2}) regions in Sweden by Sundh *et al*. (2000); however, the Swedish values represented June−September daytime fluxes only, and ignored the winter emissions.

CO_2 emissions measured at Pudasjärvi, the northernmost peat-harvesting site in our dataset (Figs. 1 and 2), may indicate a higher sensitivity of peat oxidation to soil temperature than what was observed at the more southern sites. High sensitivity to temperature in northern peat soil was also found in the soil respiration results at Kivalo forest drainage site (Minkkinen *et al*. 2007a) and in other studies (Domisch *et al*. 2006). The stronger temperature sensitivity may indicate a higher moisture content in peat. According to data provided by Finnish Meteorological Institute, the thermal summer temperatures are ca. 2 °C lower at the Pudasjärvi region, at the transition of northern and middle boreal climate, than in the southern boreal conditions at Aitoneva. Consequently, potential evapotranspiration (PET) rates should be higher in the south.

A summer withouth drought periods occurred in 2005 in southern Finland (Helminen *et al*. 2005) and the evenly distributed precipitation could be a reason for high CO_2 release rates (daytime average 0.876 g CO_2 m^{-2} h^{-1}) at the well humified Aitoneva harvesting site. The following year 2006 was exceptionally dry at the Aitoneva region (Helminen *et al*. 2006). Precipitation sum from May to September was only 194 mm compared to the 350 mm during the same period in

Table 4. Annual emissions of CO_2, CH_4, and N_2O from milled peat harvesting areas. Emissions in summertime (V–X) and wintertime (XI–IV) are separated. * The annual maximum includes data from the Kihniö Aitoneva exceptionally wet warm summer 2005, which is not taken into account in the simulated values [a]. Total CO_2 equivalent is calculated using the 100 yr GWP conversion (Watson *et al*. 2001).

GHG species	Peat harvesting areas	Stockpiles	References
CO_2 (g m^{-2} a^{-1})			
average (summer)	663	15260 (83 g m^{-2} d^{-1})	Ahlholm & Silvola (1990)
average (winter)	278	25074 (139 g m^{-2} d^{-1})	Nykänen *et al*. (1996)
whole year (min–max)	695–4101*		This study
Tampere (simulated)[a]	980[b]		
Oulu (simulated)[a]	945[b]		
CH_4 (g m^{-2} a^{-1})			Nykänen *et al*. (1996)
average (summer)	6.06[b]	0.56 (0.003 g m^{-2} d^{-1})	This study
min–max	0.32–9.09	0.08–6.38	
average (winter)	1.17	38.61 (0.21 g m^{-2} d^{-1})	
whole year	7.23	19.48	
N_2O (g m^{-2} a^{-1})			Nykänen *et al*. (1996)
average (summer)	0.26[b]	0.34 (0.002 g m^{-2} d^{-1})	This study
min–max	0.06–0.50	0.20–0.48	
average (winter)	0.05	0.08 (0.0004 g m^{-2} d^{-1})	
whole year	0.31	0.42	
Total CO_2-eq. g m^{-2} a^{-1}			
average	1179	15772[c]	
fields + stockpiles 5%–10%, summer	1928–2635[d]		
fields + stockpiles 5%–10%, winter	2459–3697[e]		

[a] Simulated of CO_2 emissions are based on the common temperature response curve estimated for several sites. (Fig. 2).
[b] Ditch emissions added according to Nykänen *et al.* (1996).
[c] Assuming average emissions of summer and winter and that the stockpiles persist over the whole year.
[d] Assuming 5%–10% area of the harvesting field is occupied by stockpiles, and the stockpiles to reside on the field for 6 summer months.
[e] Assuming 5%–10% area of the harvesting field is occupied by stockpiles, and the stockpiles to reside on the field for 6 winter months.

2005 (data from Tampere Airport by Finnish Meteorological Institute). The rates of CO_2 emissions in 2005 exceeded all other data available from harvesting areas in Finland, as shown in Fig. 2. The Aitoneva summer 2005 data did not follow a simple temperature response curve alone, and had to be excluded from the common response function for CO_2 emission from the peat harvesting areas (Fig. 2). On the basis of the average flux, the increase in CO_2 emission in the wet warm summer (Fig. 2), could add almost 3 kg of CO_2 m^{-2} a^{-1} over the estimate calculated using the common temperature response curve. The previous high flux rates may also be associated with aerated but still moist peat milled only recently before the CO_2 measurements were made (Komppula 1979 cited by Ahlholm and Silvola 1990). These observations support the idea of a south–north difference in the temperature response of heterotrophic soil CO_2 release (*see* Minkkinen *et al.* 2007a). The differences in temperature and PET may possibly lead to differences in the aeration of the surface peat, and thus a lower decomposition rate of the fresh soil organic matter in the north. This hypothesis could explain high temperature response in the decomposition rate when exceptionally warm conditions heating the peat surface layer would occur. The decomposition rate of the previously less decomposed soil organic matter could in such conditions be higher in the north than in the south. Current data are not adequate to evaluate the hypothesis and to quantify the regional differences in temperature responses. Thus, the use of present transfer functions and weather data in regional extrapolation of soil CO_2 fluxes becomes questionable, and further research over a range of temperature sum regions and site conditions is needed. This question has special importance because the emission factors should be adaptable to the expected warming in climate (Penman *et al.* 2003) especially in the northern regions.

Methane and N_2O in peat harvesting areas are released mostly from ditches and stockpiles. The CH_4 fluxes measured from ditches in Sweden (Sundh *et al.* 2000) are in line with those measured in Finland (Nykänen *et al.* 1996) as well as with those presented by Minkkinen and Laine (2006) for forest drainage areas, suggesting that the annual emissions from strips, 0.01–1.0 g CH_4 m^{-2} a^{-1}, are accompanied by fluxes from ditches, that add a similar amount to the total emissions from the harvesting area. New data from peat harvesting strips in Finland (Fig. 2 and Table 4) fit in the previously published ranges for both gases. The average CO_2 emissions from stockpiles, 2.12–3.12 g CO_2 m^{-2} h^{-1}, calculated per area of a stockpile from the new measuments, are close to those measured earlier by Ahlholm and Silvola (1990). Similarly the emissions of N_2O from stockpiles are higher, 0.20–0.56 g N_2O m^{-2} over the summer season, than the annual fluxes from harvesting strips. Emissions of CH_4 from stockpiles were very high per unit area, and were highest during the winter (Table 4). Probably the moisture content in the stockpile is adequate to create low oxygen conditions suitable for active methanogenesis. The measurements were made from stockpiles not covered by plastic foils, and should not exaggerate the emissions due to channeling of the gas flows by an impermeable top layer. The total GHG emissions from the harvesting areas depend on the relative area and duration of time the stockpiles may reside on the harvesting strips. Daily average fluxes of CO_2, CH_4, and N_2O from stockpiles (Table 4) can be used to estimate their annual contributions when the accurate areas of stockpiles and their residence time on the field are known.

After-use of cutaway peatlands

At present most of the cutaway peatlands are prepared for forestry as the after-use option (Selin 1999). Emissions of CO_2 increase due to site preparation activities to establish the plantation. The flux estimates for heterotrophic soil respiration are similar to those obtained for afforested croplands, and N_2O emissions between to 0.02–0.75 g N_2O m^{-2} a^{-1} have been reported (Mäkiranta *et al.* 2007). A low rate of CH_4 oxidation, less than 0.15 g CH_4 m^{-2} a^{-1}, is sustained (Table 3). Afforestation decreases the ecosystem CO_2 losses from cutaway peatlands, similarly to afforestation of organic croplands, but may not always lead to net C accumulation to the ecosystem including the tree layer due to the high decomposition rate of the residual peat.

Restored cutaways may start to bind atmospheric CO_2 into a long-term storage, with an accompanying increase of CH_4 emissions. The temporal and regional coverage of data is currently sparce. However, C gas (CO_2 and CH_4) exchange on a single site has been followed by researchers since its restoration in 1994 at Aitoneva, Kihniö in southern Finland (Tuittila 2000, Kivimäki 2006). A 50 year old spontaneously regenerated trench site nearby was studied during the growing seasons 2000–2001 (Yli-Petäys *et al.* 2007). Further, a chronosequence of primary paludification covering a time span from a ca. 100-year-old meadow to a ca. 2500-year-old mire was studied during this research programme. The aim of the chronosequence study was to observe the C gas dynamics during the developing phases of paludification *versus* a more developed mire ecosystem (E.-S. Tuittila unpubl. data).

At early stages of restoration the apparent rate of C gas binding during the growing season seems high, the balance ranging from a net loss of –18 g CO_2 m^{-2} a^{-1} to net binding of –469 g CO_2 m^{-2} a^{-1} (Kivimäki 2006). Lowest in sedge vegetation and highest in mixed vascular and *Sphagnum* vegetation. Similar results were reported in Canada by Waddington and Warner (2001). The figures from Aitoneva include the C losses in CH_4 emission of 1–11 g CH_4 m^{-2} during the growing season. In addition, a C loss outside the growing season of 15% of the annual C release was assumed. The 50 year old trench showed a similar high rate of binding of new organic matter (Yli-Petäys *et al.* 2007), until the new growth in the trench had filled the basin. Both study seasons in the older trench indicated a lower net C balance than in the 10 year old one, ranging from a loss of 946 to a gain of –315 g CO_2 m^{-2} a^{-1} due to the high respiration rate at the site (Yli-Petäys *et al.* 2007). However, the data only covered a short study period, and may not be representative in the long term.

The release of CH_4 from the 50-year-old trench was as high as 4–123 g CH_4 m^{-2} a^{-1}, indicating very efficient decomposition of the new organic matter. Even in such a case the ecosystem's rate of C exchange probably returns into a more moderate level, corresponding to natural mire ecosystems, when the initial resources are depleted and the expansion of vegetation has balanced out. The first results from the chronosequence of the primary mire succession supported the findings from the two regenerated sites of different ages. The youngest natural sites had highest gross photosynthesis rates but more labile CH_4 dynamics than the older mire sites.

Completeness and quality of emission factors

Coverage of emission factors

The procedures applied in derivation of annual emission factors are outlined in Alm *et al.* (2007), and detailed in the original land-use specific papers of this issue. The data obtained during the research program is combined with earlier data measured in Finnish conditions using similar methodologies. The variance in the emission factors is viewed as ranges of observed annual fluxes, and average estimates are given as best estimates of the emission factors for each land use category. We have combined the ecosystem inputs and outputs in gas fluxes into net flux figures when possible. When the whole ecosystem is measurable using chamber techniques, the net flux was directly measured (Maljanen *et al.* 2007, Saarnio *et al.* 2007, Yli-Petäys *et al.* 2007), but when a tree layer is present, a multisource method should be employed. The eddy covariance results measured at one afforested cropland site (Lohila *et al.* 2007) are discussed shortly in this paper, but are not included in the present emission factors.

In the case of peatland forestry, the soil–atmosphere fluxes presented here (Table 1) only comprise the output from peat substrate, root litter, and old aboveground litter. In the Finnish national GHG inventory reporting (NIR) for forests on organic soils, C inputs to the soil, in terms of aboveground and belowground litter from tree stands and ground vegetation, are estimated using tree data from the National Forest Inventory, biomass functions, and litter-fall models (Statistics Finland 2006). Outputs from newly fallen aboveground litter are estimated using the Yasso decomposition model (Liski *et al.* 2005).

Thus, the CO_2 balance, and emission factor for any given forest site, is obtained for a fraction of similar sites in Finland as a unique combination of site characteristics and site type specific soil respiration estimates. An alternative approach for deriving the net soil CO_2 balance of forested sites is facilitated by measuring or estimating all the different input and output fluxes, as demonstrated for two site types at the Vesijako study site (Fig. 1) in Table 5.

Sources of uncertainty in the flux data

Biogeochemical decay processes are diverse, and heterotrophic microorganisms occur both in oxic and anoxic conditions. Fluxes of greenhouse gases between ecosystems and the atmosphere are either positive or negative: The ecosystem may act as a source or sink for a gas species. Typically, both input and output processes are active simultaneously. This is true for CO_2 in photosynthesis *vs*. respiration, for CH_4 in methanogenesis *vs*. methanotrophy (Segers 2001), and for N_2O in production and consumption through denitrification or nitrification (Regina 1998). The decomposition processes involving both carbon and nitrogen cycles are biogeochemically strongly interlinked (Klemedtsson *et al*. 2005, Thauer and Shima 2006). Therefore, the concept of a gas specific emission factor is far from simple.

While litter production depends on seasonal weather and dynamics of irradiation and temperature, the gaseous fluxes of decomposition products follow the dynamics in substrate supply and soil climate. Any measurement of gas exchange, is subject to these sources of variability. The number of flux measurements, made available for each site and microsite under varying environmental conditions, largely determines how reliably the flux rates can be generalized. A much adopted approach is to correlate the variation in flux rates with variation in environmental factors, assumed to control the underlying processes. In the case of soil CO_2 release or net ecosystem CO_2 exchange between ground vegetation and the atmosphere, the daytime measurements in drained peatlands have been expanded using transfer functions over conditions of usually lower nighttime soil temperatures, varying irradiation and seasonal changes in soil moisture and plant phenology (Silvola *et al*. 1996, Alm *et al*. 1997, Tuittila *et al*. 2000, Wilson *et al*. 2006).

A typical feature for boreal peatlands in wintertime is the freeze/thaw cycle. Recent studies have revealed the importance of winter period for the annual emissions of N_2O in the organic croplands (Flessa *et al*. 1998, Groffman *et al*. 2000, Kaiser *et al*. 1998, Papen and Butterbach-Bahl 1999, Koponen *et al*. 2006a, Maljanen *et al*. 2007). Processes involved in CH_4 oxidation and N_2O fluxes show dynamics which do not follow the simple dynamics of temperature alone (Koponen *et al*. 2006b), and for extrapolation of the observed flux values had to be collected into summer or winter period averages, and the annual emission factors were compiled by summing the two estimates. The snow-free season or summer period for calculation of the present emission factors was considered to comprise of

Table 5. Examples of soil CO_2 balances compiled for two peatland forest sites of different fertility (R. Laiho unpubl. data). The more fertile site represents *Vaccinium vitis-idaea–V. myrtillus* type (Ptkg–Mtkg) and the less fertile one *Dwarf shrub–V.vitis-idaea* type (Vatkg–Ptkg), respectively, in Vesijako, central Finland. Litterfall and above ground litter decomposition simulations by T. Penttilä (unpubli. data), below ground decomposition (SR = soil respiration) data from Minkkinen *et al*. (2007a). The residual soil CO_2 balance is calculated as sum of input CO_2 equivalents from above-ground and below-ground litterfall and (negative) output CO_2 flux from litter decomposition.

Site type	Stand volume	Litterfall (CO_2 m^{-2} a^{-1})		Litter decomposition (CO_2 m^{-2} a^{-1})		Soil CO_2 balance
	(m^3)	Above ground	Below ground	Above ground	Below ground (SR)	(g CO_2 m^{-2} a^{-1})
Ptkg II–Mtkg II	185	1199	763	–1027	–1148	–214
Vatkg–Ptkg	164	1030	649	–306	–953	420

the 184 days between 1 May and 31 October, and the rest of the year is considered as the winter period with 181 days (Alm *et al*. 2007). Our choice of the seasonal breakdown in the current computation of emission factors ignores the variability of growing season or winter along the climatic gradient or between years, but is motivated by comparability of the various estimates for different land uses.

The datasets collected in the research programme are mainly from the southern and central parts of the country (Fig. 1), leaving the northern regions and land use categories less covered. The possible south–north difference in temperature sensitivity of heterotrophic soil respiration is the main argument against using regional weather patterns as basis for transfer function extrapolation of the fluxes at this stage. Such transfer functions can be valid only in the populations or regions where the respective data were collected. In a country with a long climatic gradient, a gap in regionally representative measurements in an abundant land use category may form a major source of uncertainty, in the Finnish case this important category is drainage for forestry.

Regional adaptability of emission factors

Biological processes behind the gas fluxes strongly depend on weather related environmental controls such as temperature, soil moisture and oxygen content. Therefore, uncertainties in the emission factors are partly due to the variations in the regional weather patterns. Dynamic emission factors (Shurpali *et al*. 2004) can be produced using hourly weather parameters either in regression based transfer functions or by process models such as DNDC. The regression functions are given in the original articles in this issue. Even if no process models for Tier 3 were available, the application of regression transfer functions gives an idea of how representative the annual flux rates can be as they are based on measurements performed during a few years and at locations with regionally typical weather patterns. The dependence between environmental variables and flux rate estimated by regression, can be utilized by running the transfer function with a realistic, long time series of the explanatory control variables. Due to the statistical nature of regression, the approach is obviously best applied in the region where the underlying fluxes and environmental data have been collected.

Some recent observations indicate that soil respiration rate responds more sharply to increasing temperature in the north compared with the rates measured in southern Finland (Domisch *et al*. 2006) or Estonia (Minkkinen *et al*. 2007a). This feature may correspond to differences in peat quality, as illustrated in the overall south-north decrease in peat C:N ratio (K. Minkkinen unpubl. data), or potential differences in temperature adaptations of microbial communities, as discussed in Domisch *et al*. (2006). If this is the case in general, any locally defined, temperature controlled transfer functions for a southern site would not be valid in the north and vice versa.

Usability of DNDC model of N cycles in boreal peatland conditions

While the emissions of CO_2 can be reproduced to a reasonable degree using regression transfer function approach (Alm *et al*. 2007), modeling of the processes behind N_2O fluxes are more difficult. Successful modeling of N_2O emissions especially in organic croplands would be imperative for the harmonization of European emission inventories since process models are widely used. With this in view, we have compared the performance of a version of DNDC, adapted for agricultural systems, against observed N_2O fluxes from organic grassland in Jokioinen, southern Finland (60°49´´N, 23°30´´E), measured during the years 2000–2002. The field has been cultivated for 100 years. Further details are available in Regina *et al*. (2004). The DNDC model is a process oriented model of soil carbon and nitrogen biogeochemistry, widely used in temperate and tropical conditions (Cai *et al*. 2003, Pathak *et al*. 2006, Frolking *et al*. 2004, Butterbach-Bahl *et al*. 2004, Smith *et al*. 2004, Li *et al*. 2004, Kesik *et al*. 2005, Qiu *et al*. 2005, Hsieh *et al*. 2005, Li *et al*. 2006).

The model was run using the daily time series of air temperature and rainfall from Jokioinen and soil characteristics as inputs. The objective was to explore if process models such as

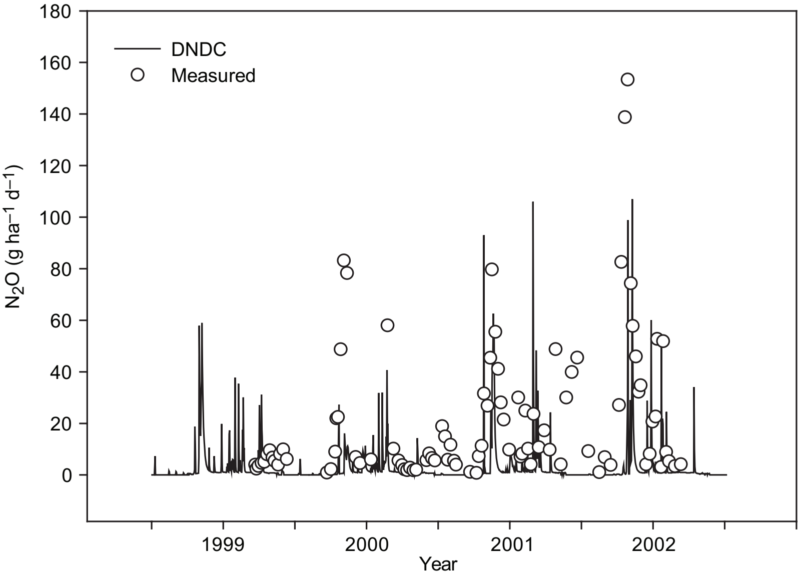

Fig. 3. Comparison of N_2O fluxes, markers, measured at an agricultural soil in Jokioinen, southern Finland during 1999 to 2002, and a DNDC run, adapted to the site conditions, line.

DNDC developed elsewhere could be employed to simulate carbon and nitrogen dynamics under Finnish conditions. The model was calibrated for an organic soil with moist grassland land use type. The initial soil bulk density and soil pH values used in the simulation run were 0.48 g cm^{-3} and 5.8, respectively. The surface layer soil organic carbon was 23%. These values and other information related to cropping history, soil management, fertilizer application rates, harvested biomass yield, flux data on CO_2 and N_2O exchange were obtained from Regina *et al.* (2004). The model has three different input modules: climate, soil and management. The various details in the three input modules were furnished to best represent the grassland cultivation practices on an organic soil under Finish conditions. The simulations were run for two years (2000 and 2001) with climatic input of daily air temperature, precipitation and solar radiation as the main model drivers. The comparison of model output and measured N_2O fluxes (Fig. 3 and Table 6) revealed the following:

- DNDC responded to the summertime variations in the input weather variables.
- DNDC responded to fertilizer applications.
- The timing and magnitudes of the gas emission dynamics were different enough to result in marked differences in the integrated emissions.
- DNDC did not correctly reproduce the wintertime soil conditions and N_2O emissions.

The DNDC available for this study was originally developed for general farmland soils, which differ from peat soils in many aspects. To adopt this model to suit peat soils under boreal conditions , there is a need for modifications in at least three aspects: (1) re-defining the soil thermal, hydraulic, redox and substrate profiles in light of the deep peat accumulations, (2) refining the processes of anaerobic biogeochemistry (e.g., decomposition, nitrification, denitrification, fermentation etc.) in the peat soils, and (3) improving gas diffusion processes in the peat-dominating soil matrix.

Several studies have highlighted that much of the annual N_2O emission from organic soils may be released during the winter (e.g. Koponen *et al.* 2006a, 2006b). Some features in DNDC, related to the misinterpretation of organic soil conditions, critical for N_2O formation during the boreal winter could be identified. The DNDC models evenly distributed soil moisture without implementing a water saturated zone, typical even for drained boreal peatlands, and predicts unrealistically low soil temperatures in snow covered conditions.

Even though the process models such as DNDC give promise for the Tier 3 level inventory, further development and validation is still

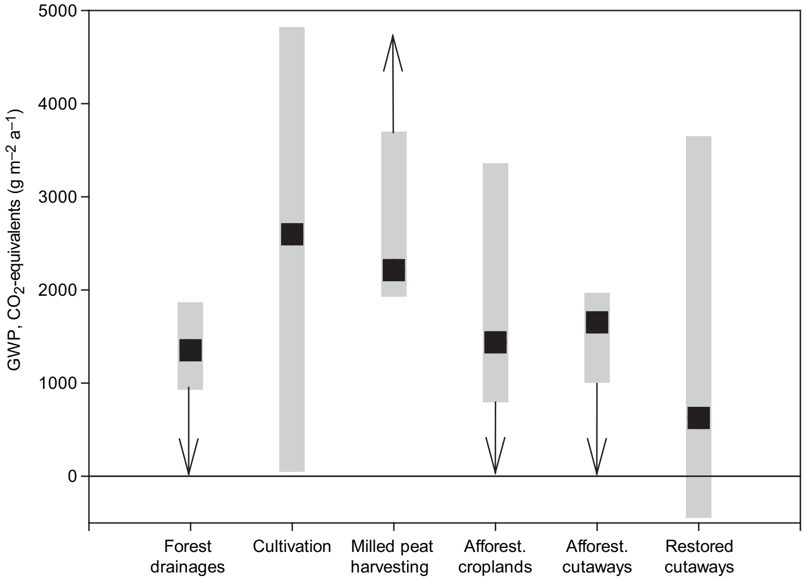

Fig. 4. Ranges of observed soil GHG emissions from the drained organic land use categories as converted to CO_2 equivalent fluxes (bars) derived from Tables 1 and 3–5, and values presented in text for restored peatlands. Black squares indicate expected average (best) estimates of the GWP. In case of restored peatlands, the value of the central estimate was derived from average CO_2 and CH_4 balances of pristine fens (Saarnio *et al.* 2007). The down arrows illustrate the GWP-decreasing impact by the growth of C store in trees, ground vegetation, and litter (above and below ground). The up arrow indicates the possible impact of wet warm conditions increasing the CO_2 and CH_4 emissions in milled peat harvesting areas and stockpiles.

needed, in order to make them operate properly for boreal organic soil conditions, and to be useful in boreal peatland conditions.

Conclusions

The emission factors presented here represent country-specific improvements for the GHG inventory. They are local in nature, but add information to impacts of land use on organic soils in the European boreal zone. The dynamic emission factors for CO_2 fluxes (e.g. temperature dependent regressions) presented in the original articles (this issue) are not readily regionally adaptable due to possible differences in temperature responses of soils in different climatic regions, but further research is needed. Similarly, a process model for C and N cycles (DNDC) must be further developed in order to be used in boreal conditions, especially for simulating the winter emissions of N_2O. Different land use types lead to different emission schemes (Fig. 4). Soil GHG emissions from forested sites are smaller than from agricultural and bare cutaway sites and the emissions are further reduced by C sequestration by the tree stand and ground vegetation.

Table 6. A comparison of modelled and measured summer, winter and annual sums of N_2O emissions (integrated g N_2O m^{-2} per annum or season) from an agricultural soil in Jokioinen, southern Finland during 2000 and 2002. Summer and winter contributions as a percentage of the annual total are shown in parenthesis

Year	Total		Summer		Winter	
	Measured	Model	Measured	Model	Measured	Model
2000	5.5	0.8	4.7 (87)	0.7 (86)	0.7 (13)	0.1 (14)
2001	7.4	1.3	4.1 (55)	1.2 (93)	3.3 (45)	0.1 (7)
2002	7.1	1.1	5.6 (78)	1.0 (93)	1.5 (22)	0.1 (7)

Thus, carbon binding through afforestation can significantly reduce the overall climatic warming impact of croplands and cutaways, even if the net effect still remains on the side of warming. However, if adequate drainage for forest growth is maintained, soil CO_2 and N_2O emissions will in most cases remain at an increased level compared to natural mires, while CH_4 emissions remain significantly lower. Protection measures of soil carbon reserves such as restoration by rewetting at suitable sites should be encouraged, thereby also reducing the N_2O release.

Acknowledgements: The study was funded by the Ministry of Trade and Industry. Dr. Sari Juutinen, Ms. Micaela Morero, and Ms. Pirkko Päiväläinen contributed to the calculations. Thanks are due to Dr. Riitta Pipatti and three other referees who made valuable suggestions to the manuscript.

References

Ahlholm U. & Silvola J. 1990. CO_2 release from peat-harvested peatlands and stockpiles. In: *Proceedings of PEAT 90 versatile peat, International Conference on Peat Production and Use, 11–15 June 1990, Jyväskylä, Finland*, vol. 2: posters, Association of Finnish Peat Industries, University of Jyväskylä, Continuing Education Centre, pp. 1–12.

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

Alm J., Schulman L., Walden J., Nykänen H., Martikainen P.J. & Silvola J. 1999a. Carbon balance of a boreal bog during a year with an exceptionally dry summer. *Ecology* 80: 161–174.

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

Alm J., Shurpali N.J., Tuittila E.-S., Laurila T., Maljanen M., Saarnio S. & Minkkinen K. 2007. Methods for determining emission factors for the use of peat and peatlands — flux measurements and modelling. *Boreal Env. Res.* 12: 85–100.

Augustin J., Merbach W. & Rogasik J. 1998. Factors influencing nitrous oxide and methane emissions from minerotrophic fens in northeast Germany. *Biology and Fertility of Soils* 28: 1–4.

Butterbach-Bahl K., Kesik M., Miehle P., Papen H. & Li C. 2004. Quantifying the regional source strength of N-trace gases across agricultural and forest ecosystems with process based models. *Plant and Soil* 260: 311–329.

Cai Z., Sawamoto T., Li C., Kang G., Boonjawat J., Mosier A., Wassmann R. & Tsuruta H. 2003. Field validation of the DNDC model for greenhouse gas emissions in East Asian cropping systems. *Global Biogeochemical Cycles* 17, 1107, doi:10.1019/2003GB002046.

Clymo R.S., Turunen J. & Tolonen K. 1998. Carbon accumulation in peatland. *Oikos* 81: 368–388.

Domisch T., Finér L., Laine J. & Laiho R. 2006. Decomposition and nitrogen dynamics of litter in peat soils from two climatic regions under different temperature regimes. *European Journal of Soil Biology* 42: 74–81.

Finnish Forest Research Institute 2005. *Finnish statistical yearbook of forestry 2005*.

Flessa H., Wild U., Klemisch M. & Pfadenhauer J. 1998. Nitrous oxide and methane fluxes from organic soils under agriculture *European Journal of Soil Science* 49: 327–335.

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

Frolking S., Li C., Braswell R. & Fuglestvedt J.S. 2004. Short- and long-term greenhouse gas and radiative forcing impacts of changing water management in Asian rice paddies. *Global Change Biology* 10: 1180–1196.

Groffman P.M., Brumme R., Butterbach-Bahl K., Dobbie K.E., Mosier A.R., Ojima D., Papen H., Parton W.J., Smith K.A. & Wagner-Riddle C. 2000. Evaluating annual nitrous oxide fluxes at the ecosystem scale. *Global Biogeochemical Cycles* 14: 1061–1070.

Helminen J., Nordlund A., Karlsson P. & Kersalo J. (eds.) 2005. *Ilmastokatsaus, kesäkuu–syyskuu 2005*. Helsingin yliopisto, Ilmatieteen laitos.

Helminen J., Nordlund A., Karlsson P. & Kersalo J (eds.) 2006. *Ilmastokatsaus, kesäkuu–syyskuu 2006*. Helsingin yliopisto, Ilmatieteen laitos.

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.

Hsieh C.-I., Leahy P., Kiely G. & Li C. 2005. The effect of future climate perturbations on N_2O emissions from a fertilized humid grassland. *Nutrient Cycling in Agroecosystems* 73: 15–23.

Huttunen J., Alm J., Liikanen A., Juutinen S., Larmola T., Hammar T., Silvola J. & Martikainen P.J. 2003. Fluxes of methane, carbon dioxide and nitrous oxide in boreal lakes and potential anthropogenic effects on the aquatic greenhouse gas emissions. *Chemosphere* 52: 609–621.

Joosten H. & Clarke D. 2002. *Wise use of mires and peatlands — Background and principles including a framework for decision-making*. International Mire Conservation Group and International Peat Society. Distributed by NHBS Ltd., Totnes, Devon, UK.

Kaiser E.A., Kohrs K., Kücke M., Schnug E., Heinemeyera O. & Munch J.C. 1998. Nitrous oxide release from arable soil: Importance of N-fertilization, crops and temporal variation *Soil Biology and Biochemistry* 30: 1553–1563.

Keltikangas M., Laine J., Puttonen P. & Seppälä K. 1986. Peatlands drained for forestry in 1930–1978: Results from field surveys of drained areas. *Acta Forestalia Fennica* 193: 1–94. [In Finnish with English summary]

Kesik M., Ambus P., Baritz R., Brüggemann N., Butterbach-Bahl K., Damm M., Duyzer J., Horváth L, Kiese1 R., Kitzler B., Leip A., Li C., Pihlatie M., Pilegaard K., Seufert G., Simpson D., Skiba U., Smiatek G., Vesala T. & Zechmeister-Boltenstern S. 2005. Inventories of N_2O and NO emissions from European forest soils. *Biogeosciences* 2: 353–375.

Kettunen A. 2000. Short-term carbon dioxide exchange and environmental factors in a boreal fen. *Verhandlungen der Internationalen Vereinigung für Limnologie* 27: 1446–1450.

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.

Klemedtsson L., von Arnold K., Weslien P. & Gundersen P. 2005. Soil C:N ratio as a scalar parameter to predict nitrous oxide emissions. *Global Change Biology* 11: 1142–1147.

Kirkinen J., Minkkinen K., Penttilä T., Kojola S., Sievänen R., Alm J., Saarnio S., Silvan N., Laine J. & Savolainen I. 2007. Greenhouse impact due to different peat fuel utilisation chains in Finland — a life-cycle approach. *Boreal Env. Res*. 12: 211–223.

Kivinen E. & Pakarinen P. 1981. Geographical distribution of peat resources and major peatland complex types in the world. *Ann. Acad. Sci. Fenn. A III, Geol.-Geog*. 132: 1–28.

Kivimäki S. 2006. *Sarakasvien (Cyperaceae) ja rahkasammalten (Sphagnum) muodostamien kasvustojen hiilidioksiditaseet ennallistetulla suolla*. M.Sc. thesis, Department of Biological and Environmental Sciences, University of Helsinki.

Komppula J. 1979. *Jyrsinturpeen hengitysaktiivisuus, sen riippuvuus ympäristötekijöistä ja turvelaadusta sekä sen muutokset tuotantoprosessin ja aumavarastoinnin aikana*. M.Sc. thesis, University of Jyväskylä, Department of Biology.

Koponen H.T., Jaakkola T., Keinänen-Toivola M.M., Kaipainen S., Tuomainen J., Servomaa K. & Martikainen P.J. 2006a. Microbial communities, biomass, and activities in soils as affected by freeze thaw cycles. *Soil Biology and Biochemistry* 38: 1861–1871.

Koponen H.T., Duran C.E., Maljanen M., Hytönen J. & Martikainen P.J. 2006b. Temperature responses of NO and N_2O emissions from boreal organic soil. *Soil Biology and Biochemistry* 38: 1779–1787.

Kortelainen P. & Saukkonen S. 1994. Leaching of organic carbon and nitrogen from forested catchments. *Publications of the Academy of Finland* 1/94: 285–290.

Kortelainen P., Rantakari M., Huttunen J.T., Mattsson T., Alm J., Juutinen S., Larmola T., Silvola J. & Martikainen P.J. 2006. Sediment respiration and lake trophic state are important predictors of large CO_2 evasion from small boreal lakes. *Global Change Biology* 12: 1554–1567.

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., Vasander H., Penttilä T. & Laine J. 2003. Dynamics of plant-mediated organic matter and nutrient cycling following water-level drawdown in boreal peatlands. *Global Biogeochemical Cycles* 17(2), 1053, doi:10.1029/2002GB002015, 2003.

Laiho R., Kaunisto S. & Alm J. 2005. Suometsien ravinnetilan kehitys ojituksen jälkeen. *Metsäntutkimuslaitoksen tiedonantoja* 947: 46–60.

Li C., Cui J. & Trettin C. 2004. Modeling impacts of management on carbon sequestration and trace gas emissions in forested wetland ecosystems. *Environmental Management* 33, Suppl. 1: S176–S186.

Li C., Farahbakhshazad N., Jaynes D.B., Dinnes D.L., Salas W. & McLaughlin D. 2006. Modeling nitrate leaching with a biogeochemical model modified based on observations in a row-crop field in Iowa. *Ecological Modelling* 196: 116–130

Liski J. & Westman C.J. 1997. Carbon storage in forest soil in Finland. 2. Size and regional patterns. *Biogeochemistry* 36: 261–274.

Liski J., Palosuo T., Peltoniemi M. & Sievänen R. 2005. Carbon decomposition model Yasso for forest soils. *Ecological Modelling* 189: 168–182.

Lohila A., Aurela M., Regina K. & Laurila T. 2004. Annual CO_2 exchange of 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.

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. 2001. Fluxes of N_2O, CH_4 and CO_2 on afforested boreal agricultural soils. *Plant and Soil* 231: 113–121.

Maljanen M., Liikanen A., Silvola J. & Martikainen P.J. 2003a. Nitrous oxide emissions from boreal organic soil under different land-use. *Soil Biology and Biochemistry* 35: 689–700.

Maljanen M., Liikanen A., Silvola J. & Martikainen P.J. 2003b. Methane fluxes on agricultural and forested boreal organic soils. *Soil Use and Management* 19: 73–79.

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.

Martikainen P.J., Nykänen H., Crill P. & Silvola J. 1993. Effect of a lowered water table on nitrous oxide fluxes from northern peatlands. *Nature* 366(4): 51–53.

Minkkinen K., Laine J., Nykänen H. & Martikainen P.J. 1997. Importance of drainage ditches in emissions of methane from mires drained for forestry. *Canadian Journal of Forest Research* 27: 949–952.

Minkkinen K. & Laine J. 1998. Effect of forest drainage on the peat bulk density of pine mires in Finland. *Canadian Journal of Forest Research* 28: 178–186.

Minkkinen K, Vasander H., Jauhiainen S., Karsisto M. & Laine J. 1999. Post-drainage changes in vegetation composition and carbon balance in Lakkasuo mire, Central Finland. *Plant and Soil* 207: 107–120.

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.

Minkkinen K. & Laine J. 2006. Vegetation heterogeneity and ditches create spatial variability in methane fluxes from peatlands drained for forestry. *Plant and Soil* 285: 289–304.

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.

Myllys M. 1996. Agriculture on peatlands. In: Vasander H. (ed.), *Peatlands in Finland*, Finnish Peatland Society, Helsinki, pp. 64–71.

Myllys M. & Sinkkonen M. 2004. The area and distribution of cultivated organic soils in Finland. *Suo* 55: 53–60. [In Finnish with English abstract].

Nykänen H., Silvola, J., Alm J. & Martikainen P.J. 1996. Fluxes of greenhouse gases CH_4, CO_2 and N_2O on some peat mining areas in Finland. *Publications of the Academy of Finland* 1/96: 141–147.

Nykänen H., Alm J., Silvola J., Tolonen K. & Martikainen P.J. 1998. Methane fluxes on boreal peatlands of different fertility and the effect of long-term experimental lowering of the water table on flux rates. *Global Biogeochemical Cycles* 12: 53–69.

Papen H. & Butterbach-Bahl K. 1999. A 3-year continuous record of nitrogen trace gas fluxes from untreated and limed soil of a N-saturated spruce and beech forest ecosystem in Germany — 1. N_2O emissions. *Journal of Geophysical Research-Atmospheres* 104(D15): 18487–18503.

Pathak H., Li C., Wassmann R. & Ladha J.K. 2006. Simulation of nitrogen balance in rice–wheat systems of the Indo-Gangetic plains. *Soil Science Society of America Journal* 70: 1612–1622.

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.

Pitkänen A., Turunen J. & Tolonen K. 1999. The role of fire in the carbon dynamics of a mire, eastern Finland. *The Holocene* 9: 453–462.

Qiu J., Wang L., Tang H., Li H. & Li C. 2005. Studies on the situation of soil organic carbon storage in croplands in northest of China. *Agricultural Sciences in China* 4(1): 101–105.

Regina K. 1998: Microbial production of nitrous oxide and nitric oxide in boreal peatlands. *University of Joensuu Publications of Sciences* 50: 1–31.

Regina K., Silvola J. & Martikainen P.J. 1998. Mechanisms of N_2O and NO production in the soil profile of a drained and forested peatland, as studied with acetylene, nitrapyrin and dimethyl ether. *Biology and Fertility of Soils* 27: 205–210.

Regina K. Nykänen H., Silvola J. & Martikainen P.J. 1996. Fluxes of nitrous oxide from boreal peatlands as affected by peatland type, water table and nitrification capacity. *Biogeochemistry* 35: 401–418.

Regina K., Syväsalo E., Hannukkala A. & Esala M. 2004. Fluxes of N_2O from farmed peat soils in Finland. *European Journal of Soil Science* 55: 591–599.

Riutta T., Aurela M., Laine J., Tuovinen J.-P., Laurila T., Vesala T., Haapanala S. & Tuittila E.-S. 2006. Impact of spatial variation in plant community scale on ecosystem scale CO_2 dynamics. *Report Series in Aerosol Science* 81B: 510–515

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.

Segers R. 1998. Methane production and methane consumption: a review of processes underlying wetland methane fluxes. *Biogeochemistry* 41: 23–51.

Selin P. 1999. Turvevarojen teollinen käyttö ja suopohjien hyödyntäminen Suomessa. *Jyväskylä Studies in Biological and Environmental Science* 79: 1456–9701.

Sallantaus T. 1992. Leaching in the material balance of peatlands — preliminary results. *Suo* 43: 253–258.

Shurpali N.J., Saarnio S. & Alm J. 2004. Modelling land use impacts on annual emissions of CO_2, CH_4 and N_2O from peatlands in Finland. In: Päivänen J. (ed.), *Wise Use of Peatlands, Proceedings of the 12th International Peat Congress, Tampere, Finland, 6–11 June 2004*, vol. 1: *Oral presentation*, International Peat Society, Jyväskylä, pp. 170–177.

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

Silvola J., Alm J., Ahlholm U., Nykänen H. & Martikainen P.J. 1996b. Contribution of plant roots to CO_2 fluxes from organic soils. *Biology and Fertility of Soils* 23: 126–131.

Smith W.N., Grant B., Desjardins R.L., Lemke R. & Li C. 2004. Estimates of the interannual variations of N_2O emissions from agricultural soils in Canada. *Nutrient Cycling in Agroecosystems*: 68: 37–45.

Statistics Finland 2006. *Greenhouse gas emissions in Finland 1990–2004*. National Inventory Report to the UNFCCC. December 2006. Statistics Finland, Helsinki.

Sundh I., Nilsson M., Mikkelä C., Granberg G. & Svensson B.H. 2000. Fluxes of methane and carbon dioxide on peat-mining areas in Sweden. *Ambio* 29: 499–503.

Thauer R.K. & Shima S. 2006. Methane and microbes. *Nature* 440: 878–879.

Trettin C., Laiho R., Minkkinen K. & Laine J. 2006. Influence of climate change factors on carbon dynamics in northern forested peatlands. *Canadian Journal of Soil Science* 86: 269–280.

Tuittila E.-S. 2000. *Restoring vegetation and carbon dynamics in a cut-away peatland*. Publications in Botany from the University of Helsinki 30.

Turunen J. 1999. *Carbon accumulation of natural mire ecosystems in Finland — application to boreal and subarctic mires*. University of Joensuu, Publications in Sciences 55.

Turunen J., Tomppo E., Tolonen K. & Reinikainen A. 2002. Estimating carbon accumulation rates of undrained mires in Finland — application to boreal and subarctic regions. *The Holocene* 12: 69–80

Vourlitis G.L. & Oechel W.C. 1999. Eddy covariance measurements of net CO_2 flux and energy balance of an Alaskan moist-tussock tundra ecosystem. *Ecology* 80: 686–701.

Watson, R.T. & Core Writing Team (eds.) 2001. *Climate Change 2001: synthesis report*. Stand-alone edition, IPCC, Geneva, Switzerland.

Weiss R., Shurpali N.J., Sallantaus T., Laiho R., Laine J. & Alm J. 2006: Simulation of water table level and peat temperatures in boreal peatlands. *Ecological Modelling* 192: 441–456.

Wilson D., Tuittila E.-S., Alm J., Laine J., Farrell E.P. & Byrne K.A. 2007. Development of a cutaway peatland towards a carbon sink: Does a temperate maritime climate accelerate restoration? *Ecoscience* 14: 71–80.

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.