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Estimation of greenhouse gas balance for forestry-drained peatlands

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Academic dissertation

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In this study, 1) a model to estimate soil carbon dioxide (CO_2) balance for forestry-drained peatlands was tested on site and countrywide levels in Finland. 2) A dataset of annual soil–atmosphere fluxes of CO_2, methane (CH_4) and nitrous oxide (N_2O) from 68 sites was collected, and models fitted for their upscaling to a countrywide level. 3) The current greenhouse gas impact of the 68 study sites, including soil CO_2, CH_4 and N_2O balances and the CO_2 sink function of tree biomass increment, was estimated.

The soil CO_2 balance estimation, as the difference between litter input to soil and CO_2 efflux from soil, was straightforward to apply, but considerable uncertainty was caused by the inadequate level of knowledge on belowground plant–soil carbon fluxes. Soil–atmosphere gas fluxes could be upscaled to a countrywide level utilizing readily available forest inventory results and weather statistics. Soils in nutrient-rich study sites were sources of greenhouse gases while those in nutrient-poor study sites were sinks, on average. The current greenhouse gas impact, when no forest fellings occurred, was nevertheless climate cooling for both the nutrient-rich and poor sites due to the considerable CO_2 sink formed by increasing tree biomass.

Keywords: carbon dioxide, methane, nitrous oxide, boreal peatland

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Last but not least, my family has successfully kept me from sinking too much into the world of greenhouse gases.

LIST OF ORIGINAL ARTICLES

This dissertation is based on the following articles, which are referred to by their Roman numerals in the text.

I Ojanen P., Minkkinen K., Lohila A., Badorek T., Penttilä T. (2012). Chamber measured soil respiration: A useful tool for estimating the carbon balance of peatland forest soils? Forest Ecology and Management 277: 132–140.
http://dx.doi.org/10.1016/j.foreco.2012.04.027

II Ojanen P., Minkkinen K., Alm J., Penttilä T. (2010). Soil–atmosphere CO_2, CH_4 and N_2O fluxes in boreal forestry-drained peatlands. Forest Ecology and Management 260: 411–421.
http://dx.doi.org/10.1016/j.foreco.2010.04.036

III Ojanen P., Lehtonen A., Heikkinen J., Penttilä T., Minkkinen K. Soil CO_2 balance and its uncertainty in forestry-drained peatlands in Finland. Forest Ecology and Management. In Press.
http://dx.doi.org/10.1016/j.foreco.2014.03.049

IV Ojanen P., Minkkinen K., Penttilä T. (2013). The current greenhouse gas impact of forestry-drained boreal peatlands. Forest Ecology and Management 289: 201–208.
http://dx.doi.org/10.1016/j.foreco.2012.10.008

Paavo Ojanen is fully responsible for the summary of this doctoral thesis. Regarding studies **II** and **IV**, he participated in the planning and collection of field data. Study **I** is based on data collected by others. In study **III**, P. Ojanen created the balance calculation script together with A. Lehtonen. P. Ojanen was responsible for most of the empirical models presented in studies **II** and **III** and for the analysis and interpretation of results in each study. P. Ojanen was the main author and reviser of each manuscript.

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INTRODUCTION

A pristine boreal peatland sequesters atmospheric carbon dioxide (CO_2) into the accumulating peat due to wet, anoxic conditions in the soil (Vasander and Kettunen 2006). On the other hand, it releases methane (CH_4) to the atmosphere. Depending on the balance between its CO_2 sink and CH_4 source, a boreal peatland may have either a climate cooling or climate warming greenhouse gas (GHG) impact across the decadal to centennial time scales (Frolking et al. 2006; Drewer et al. 2010). Over the millennial time scale, the impact is inevitably cooling because of the continuous peat accumulation and the short lifetime of CH_4 in the atmosphere (Frolking et al. 2006; Frolking and Roulet 2007).

The GHG impact of a peatland drained for forestry by ditching (forestry-drained peatland hereafter) is a more complicated issue. If the intended enhancement of forest growth is achieved, tree biomass begins to increase, resulting in a considerable CO_2 sink (Tomppo 1999; Minkkinen et al. 2001; Hargreaves et al. 2003; Meyer et al. 2013). The lowering of the water table (WT) also decreases CH_4 emissions from soil (e.g., Nykänen et al. 1998; von Arnold et al. 2005b, c; Maljanen et al. 2010b). On the other hand, if the peat layer begins decreasing, the soil turns into a CO_2 source. While this generally happens to peatlands after ditching (e.g., Couwenberg et al. 2011), the results on forestry-drained peatlands by eddy-covariance measurements (Hargreaves et al. 2003; Lohila et al. 2011) and long-term soil C storage change assessments (Minkkinen and Laine 1998; Minkkinen et al. 1999; Simola et al. 2012) reveal that both soil CO_2 sinks and sources exist. Nitrous oxide (N_2O) emissions from soil are also possible, at least in the most fertile peatlands (von Arnold et al. 2005b, c; Klemedtsson et al. 2005; Minkkinen et al. 2007a; Maljanen et al. 2010b). The GHG impact of a forestry-drained peatland is the sum of all these sinks and sources (Laine et al. 1996; Lohila et al. 2010).

To understand the impact of forestry-drainage on the global carbon (C) cycle and on climate change, it is necessary to quantify the greenhouse gas balance of forestry-drained peatlands on a large scale. This information can then be applied in earth system models and national GHG reporting. As empirical studies are typically conducted on a site or plot scale, a countrywide estimate of GHG balance is essentially a generalization. Extensive forest inventories (e.g., Gillis et al. 2005; Tomppo et al. 2011) and harvest statistics (e.g., Ylitalo 2012; Christiansen 2013) together with tree biomass models provide a well-studied tool for the countrywide level estimation of tree stand CO_2 balance (Greenhouse gas emissions… 2014; National Inventory Report… 2013).

CH_4 and N_2O fluxes measured by the closed chamber technique (Alm et al. 2007) directly equal the balance, excluding the possible contribution of gas flux through tree stems (Kozlowski 1997; Rusch and Rennenberg 1998; Gauci et al. 2010). For upscaling of annual balances to large areas, e.g. the co-variation of CH_4 balance with WT (Nykänen et al. 1998) and with tree stand stem volume (Minkkinen et al. 2007c) and the co-variation of N_2O balance with soil carbon to nitrogen ratio (CN) (Klemedtsson et al. 2005) can be utilized. Anyhow, the data sets behind these models are collections of case studies. They have not been sampled to be representative of the varying climate and site properties, which would ensure accurate upscaling to a countrywide level.

Soil CO_2 balance cannot be directly measured by chambers under a tree stand. Eddy covariance measurements combined with tree biomass assessments (e.g., Hargreaves et al. 2003; Lohila et al. 2011) are a useful method for case studies, but too expensive and laborious for acquiring extensive data sets. Long-term soil C stock change assessments (e.g., Minkkinen and Laine 1998; Simola et al. 2012) yield mean CO_2 balances for several decades only. These do not necessarily equal with the current soil CO_2 balance, as the ongoing succession in tree stands (Sarkkola et al. 2004) causes a gradual change in WT (Sarkkola et al. 2010) and in the composition of vegetation and litter production (Laiho et al. 2003; Straková et al. 2012).

The national GHG inventories in Finland and Sweden (Greenhouse gas emissions… 2014; National Inventory Report… 2013) have estimated the soil CO_2 balance of forestry-drained peatlands as the difference between chamber measured soil CO_2 efflux from points where living plants have been excluded (von Arnold et al. 2005a; Minkkinen et al. 2007b) and litter input to soil, estimated by applying biomass turnover ratios to forest inventory data. A similar method is also used by the Intergovernmental Panel on Climate Change (IPCC) Wetlands Supplement for the estimation of the latest Tier 1 emission factors for drained inland organic soils (Drösler et al. 2014). While it is rather simple to apply, neither its precision in countrywide estimations nor its accuracy in general is known. The separation of decomposition-originated CO_2 efflux from root respiration by trenching is known to change soil conditions and is thus a source of error (Kuzyakov et al., 2000; Subke et al., 2006; Ngao et al., 2007). The estimation of belowground litter production is also based on root turnover ratios, which are highly uncertain (Strand et al., 2008; Finér et al. 2011; Brunner et al. 2013; Hansson et al. 2013; Leppälammi-Kujansuu et al. 2014). On the countrywide level, the biomass and litter production models and forest inventory sampling needed for the estimation are all sources of random error, together producing an unknown level of precision.

The aim of this thesis was to provide tools for the countrywide estimation of GHG balance for forestry-drained peatlands and to estimate their current GHG impact: **I** A model to estimate soil CO_2 balance was developed and tested at the site level. **II** A geographically representative dataset of soil–atmosphere CO_2, CH_4 and N_2O fluxes was gathered and models were created for upscaling to a countrywide level. **III** Soil CO_2 balance and its uncertainty in Finland's forestry-drained peatlands were estimated. **IV** The current GHG impact of forestry-drained peatlands was assessed. The empirical models developed here are based on data from boreal forestry-drained peatlands in Finland. Results could thus be directly applicable in Fennoscandia and to some extent in other boreal regions. Yet, from the methodological point of view, the results of this thesis are hopefully useful when estimating the greenhouse gas balance of other forested drained peatlands as well.

MATERIAL AND METHODS

Method for soil CO_2 balance estimation I

Throughout the thesis, "soil" includes both soil organic matter and litter C pools, as litter is functionally a component of soil organic matter and any clear boundary where litter C turns into soil C is difficult to define, either theoretically or in practice. This differs from the IPCC guidelines for national greenhouse gas inventories, where soil and litter C pools are treated separately (Aalde et al. 2006). Coarser dead organic matter (dead trees, trunks, big branches, etc.) is excluded from this thesis.

Two methods for estimating soil CO_2 balance were tested with data from Kalevansuo peatland, situated in Southern Finland. The site, originally a dwarf shrub pine bog, was drained in 1971. The main tree species is Scots pine (*Pinus sylvestris* L.). The dense field layer is dominated by various dwarf shrub species. Peat and forest mosses cover nearly 100% of the bottom layer.

In the "**D−L method**" (R_{het} method in **I**), soil CO_2 balance ($NE_{CO2soil}$, ΔC_{soil} in **I**) was calculated as the difference between the input of CO_2-derived carbon to soil in plant litter (L) and decomposition-derived CO_2 efflux from soil (D, R_{het} in **I**):

$$NE_{CO2soil} = -L + D. \tag{1}$$

$NE_{CO2soil}$ defined this way, negative sign indicates a sink and positive sign a source. L was calculated as the sum of aboveground (L_{above}) and belowground (L_{below}) litter production of vascular plants and moss litter production (L_{mosses}). L_{above} was collected using nets placed on the moss surface. L_{below} was estimated by multiplying measured biomasses by their literature-derived turnover ratios (see Table **I**.1). L_{mosses} was estimated by measuring moss biomass growth through nets placed on the moss surface.

D was estimated by measuring soil CO_2 efflux by a portable infrared gas analyzer (EGM-4, PP Systems) equipped with an opaque non-steady state chamber (modified SRC-1, PP Systems). Measurement points were prepared by inserting a 30 cm deep cylinder into the soil and removing aboveground parts of ground vegetation six months prior to the start of measurements to exclude plant respiration and the decomposition of any short-lived organic compounds of mycorrhiza and rhizosphere microbes.

The uncertainty of this method was assessed in two ways: 1) the precision (standard deviation, sd) of the estimated $NE_{CO2soil}$ was estimated by aggregating the standard deviations of L_{above}, L_{below}, L_{mosses} and D. These sds equaled the sampling errors of each component. For D, the uncertainty in the annual flux calculation from measured momentary fluxes (model parameter uncertainty) was also included. 2) The influence of the uncertainty in fine root turnover was tested by applying two different sets of fine root turnover rates: a higher (**HT**) rate: 0.85 $year^{-1}$ for trees and dwarf shrubs (Greenhouse gas emissions… 2013), 1.25 $year^{-1}$ for herbaceous plants (Laiho et al. 2003); and a lower (**LT**) one: 0.12 $year^{-1}$ for dwarf shrubs and 0.34 $year^{-1}$ for trees (Finér and Laine 1998), 1.00 $year^{-1}$ for herbaceous plants (Laiho et al. 2003).

In the "**R_{floor} method**", ecosystem gross primary production (GPP_{eco}) was calculated as the sum of modeled tree stand (GPP_{trees}) and measured forest floor vegetation (GPP_{floor}) gross primary production. Ecosystem respiration (R_{eco}) was calculated as the sum of modeled tree stand aboveground respiration (R_{trees_above}) and measured forest floor respiration (R_{floor}). By allocating net ecosystem CO_2 exchange ($NEE = GPP_{eco} - R_{eco}$) between tree biomass increment ($NE_{CO2biom}$, ΔC_{biom} in **I**) and $NE_{CO2soil}$ ($NEE = NE_{CO2biom} + NE_{CO2soil}$), $NE_{CO2soil}$ could then be solved as:

$$NE_{CO2soil} = -[\, GPP_{trees} + GPP_{floor}] + [R_{trees\_above} + R_{floor}] + NE_{CO2biom}. \tag{2}$$

$NE_{CO2biom}$ was estimated by repeated tree stand measurements, increment coring and single-tree biomass models (Repola 2008, 2009). This method is more laborious than the D−L method, as modeling of tree stand dynamics is needed. On the other hand, the use of uncertain root turnover ratios is avoided. R_{floor} can also be measured from intact points, thus avoiding the difficulties in separating D from R_{floor}. Equations (1) and (2) are interchangeable on the condition that L is an accurate description of C flux from plants to soil.

As a reference $NE_{CO2soil}$ to test the two methods against, an "**EC method**" soil CO_2 balance was estimated as:

$$NE_{CO2soil} = NEE + NE_{CO2biom}. \quad (3)$$

Here, NEE was based on a four-year dataset of eddy covariance measurements with their sd (Lohila et al. 2011). Sd of $NE_{CO2biom}$ included the sampling error of tree stand measurements (Lohila et al. 2011) and the within and between stand random variance components of the biomass models (Repola 2008, 2009).

Soil–atmosphere CO_2, CH_4, and N_2O fluxes and their upscaling II

Annual soil–atmosphere GHG fluxes were estimated for 68 sites, covering the span of the south and middle boreal vegetation zones (Figure 1). Sites belonging to each drained peatland site type (Laine 1989, see Vasander and Laine 2008) were equally included to represent the variation in soil fertility. The poorest Lichen type (Jätkg) sites were excluded from this study and study **IV**, because their share of forestry-drained peatlands is low and they are unproductive for forestry.

Fluxes were measured over the May–October period in 2007 and 2008. D was measured every two to three weeks from five points at each site. Measurements and the preparation of

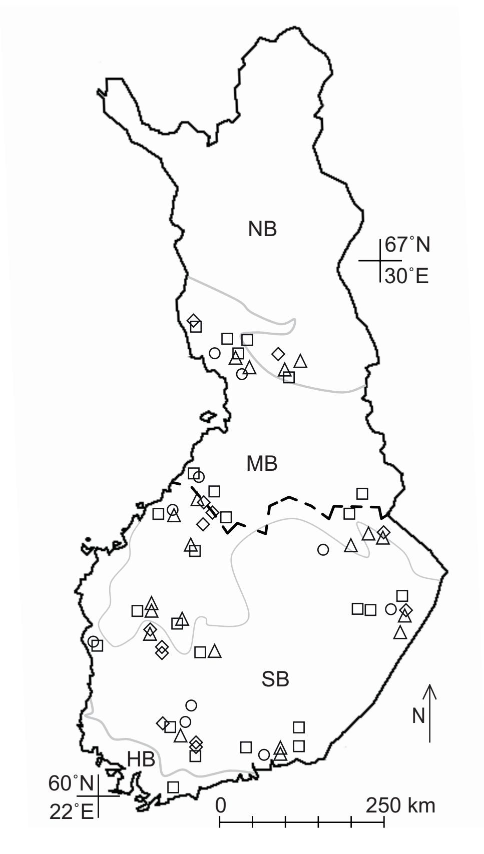

Figure 1. The study sites of studies **II** and **IV** by site type (Laine, 1989) from most to least fertile: ○ Herb-rich type (Rhtkg, n = 10), □ *Vaccinium myrtillus* type I and II (Mtkg I and II, n = 25), Δ *Vaccinium vitis-idaea* type I and II (Ptkg I and II, n = 20), ◇ Dwarf shrub type (Vatkg, n = 13). Grey lines denote the boundaries of vegetation zones (Ahti et al., 1968): HB, hemiboreal, SB, south boreal, MB, middle boreal, NB, north boreal. The dashed line is the border of South and North Finland in study **III**.

measurement points were similar to **I**, but with the addition that the layer of loose litter was removed to facilitate easy cleaning of the points.

CH_4 and N_2O fluxes were measured five to seven times from four points at each site. These points were prepared only by carving a 2-cm deep groove for chamber sealing; the vegetation and litter were left untouched. Gas samples were taken from the headspace of an opaque chamber at 5, 15, 25, and 35 min after installing the chamber at the point. Samples were analyzed in a laboratory using gas chromatography. Fluxes were calculated from the slope of linear regression between gas concentration and chamber closure time.

Annual D was calculated using site-specific soil temperature regressions (Lloyd and Taylor 1994) and simulations in half-hourly time steps. CH_4 and N_2O fluxes for the May–October period were interpolated from the measurements, and the winter proportion of the annual fluxes, 25% for CH_4 and 34% for N_2O, was estimated based on Alm et al. (1999) and Minkkinen et al. (2007b). For the upscaling of annual fluxes to larger areas, regression models with independent site and climate variables available in forest inventory results and weather statistics were then developed.

Countrywide soil CO_2 balance and its uncertainty III

The soil CO_2 balance for each sample plot of the 10th Finnish National Forest Inventory, NFI10 (Korhonen et al. 2013) classified as forestry-drained peatland was estimated. Based on the results from study **I**, the D−L method (Eq. 1) was applied. Mean balances of each sampling region–site type combination were then calculated and finally multiplied by the respective NFI10 area estimates to represent the countrywide $NE_{CO2soil}$ of the 4.76 million ha of forestry-drained peatlands in Finland. New empirical models for the plot-level estimation of D and several components of L were developed based on several published and unpublished data sets (Figure 2). Tree stand foliage and coarse root biomasses were estimated using the single-tree models of Repola (2008, 2009). Turnover ratios of biomass compartments were mainly based on published results from other studies (Figure 2, Table **III**.2).

The precision (variance) of the countrywide $NE_{CO2soil}$ comprised the model error (parameter uncertainty) of the various models (Figure 2) and the NFI10 sampling variance. The variance due to parameter variances and covariances of each model were upscaled to the countrywide level from the respective variance-covariance matrices applying the basic calculus of covariances. NFI10 sampling variance included variance aggregated from NFI10 sample plot cluster-level residuals of $NE_{CO2soil}$ and the variance of NFI10 area estimates. Accuracy of the countrywide $NE_{CO2soil}$ was assessed by varying the turnover ratio of arboreal fine roots (LT: 0.5 year^{-1}, and HT: 0.85 year^{-1}) and by performing a simple sensitivity analysis in which components with unknown model error or with substantial possibility of bias were altered by 20% (Figure 2).

Greenhouse gas impact of forestry-drained peatlands IV

The ecosystem greenhouse gas impact for each study site (Figure 1) was estimated by summing up the balances of CO_2 ($NE_{CO2soil}$, $NE_{CO2trees}$), CH_4 (NE_{CH4}) and N_2O (NE_{N2O}) in CO_2 equivalents (GWP_{100}, Solomon et al. 2007):

$$\text{GHG impact} = NE_{CO2soil} + NE_{CO2trees} + 25 \times NE_{CH4} + 298 \times NE_{N2O}. \qquad (4)$$

$NE_{CO2soil}$ was estimated using the D–L method (Eq. 1). D was the sum of the D estimated in **II** and modelled decomposition of the removed loose litter layer. L was estimated using litter traps, belowground biomass samples, ground vegetation projection coverage and biomass data, and biomass turnover ratios. $NE_{CO2trees}$ was the CO_2 sink in tree stand biomass increment, estimated from repeated tree stand measurements, increment coring, and single-tree biomass models (Repola 2008, 2009). NE_{CH4} and NE_{N2O} were the annual soil–atmosphere fluxes estimated in **II**.

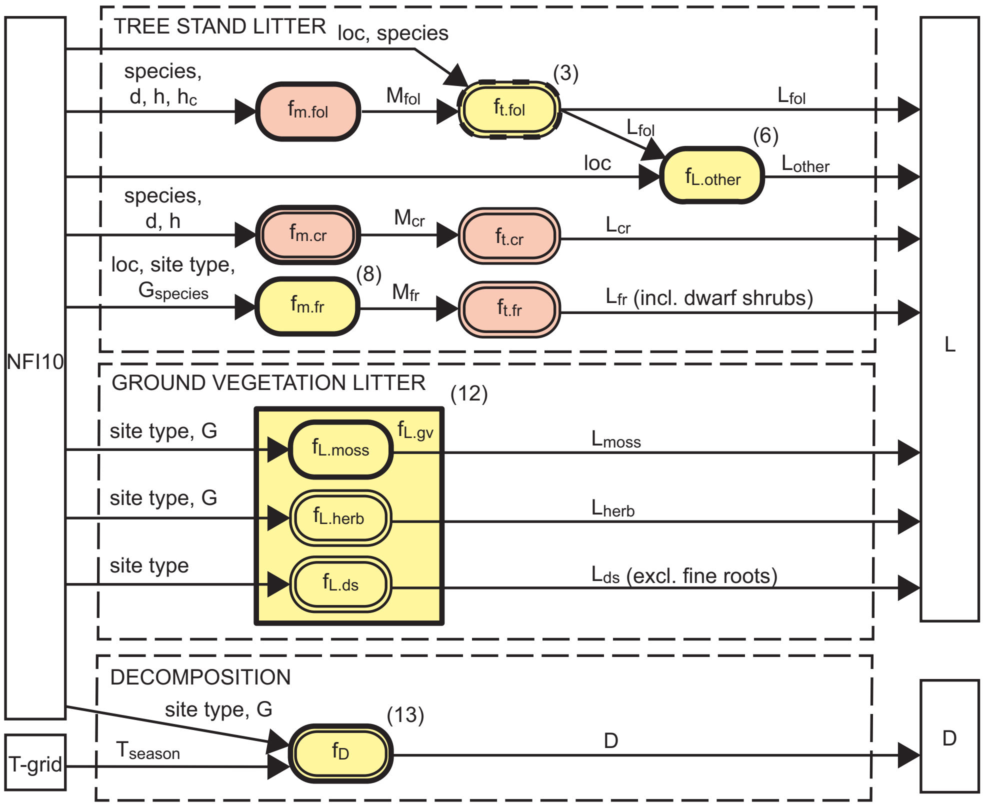

Figure 2. Plot-level estimation functions for the litter production of living tree stand and ground vegetation (L) and decomposition of litter and soil organic matter (D) from National Forest Inventory data (NFI10) and weather statistics (T-grid). The numbers in parentheses refer to equations in article (**III**). Uppercase and lowercase letters refer to stand and tree variables, respectively. fol = foliage, cr = coarse roots, fr = fine roots, M = mass, loc = location (South/North Finland), G = basal area, d = diameter, h = height, h_c = crown base height, species = species group (Scots pine, Norway spruce (*Picea abies* (L.) Karst.), deciduous trees), ds = dwarf shrub, T_{season} = mean May–October air temperature, t = turnover. Bold = included in model error estimation, inner circle = included in sensitivity analysis. The yellow color indicates a function with new models fitted for this study; the red color indicates a function from literature.

RESULTS

Method for soil CO_2 balance estimation I

Applying the D−L method, soil at Kalevansuo was estimated to be a sink of –60±160 g CO_2 m^{-2} $year^{-1}$ (HT) or a source of +390±160 g CO_2 m^{-2} $year^{-1}$ (LT) (Figure 3). Although the balance components were estimated relatively precisely, coefficients of variation ranging from ±4% for L_{above} to ±15% for L_{mosses}, the relative precision of $NE_{CO2soil}$ was only moderate ±40% (HT) or poor ±290% (LT). $NE_{CO2soil}$ with HT did not differ significantly from the EC method $NE_{CO2soil}$, sink of –240±160 g CO_2 m^{-2} $year^{-1}$.

With the R_{floor} method, soil was estimated to be a source of +280 or +420 g CO_2 m^{-2} $year^{-1}$, depending on the stem respiration estimate (Figure 4). The overestimation of $NE_{CO2soil}$ by 520−660 g CO_2 m^{-2} $year^{-1}$ compared to the EC method $NE_{CO2soil}$ was mainly due to an overestimation of R_{eco} by 13−18%.

Soil–atmosphere CO_2, CH_4, and N_2O fluxes and their upscaling II

D correlated with several variables describing climate and soil conditions and the tree stand (Figure 5). Two thirds of the between-site variation could be explained by regression models with four independent variables (Table 1). Although most of the independent variables were inter-correlated, it was useful to include variables that describe the tree stand (stem volume), soil fertility (bulk density or site type), soil moisture (May–October mean water table depth), and temperature (May–October mean air temperature): the inclusion of an extra variable always clearly increased r^2 and reduced the standard error of estimate. As WT is not available in forest inventories, a model without it was fitted for upscaling purposes.

CH_4 emissions showed a clear nonlinear relationship with WT (Figure 6). The division between emission sources and small sinks could also be described by the classification according to mire and forest vegetation dominance in ground vegetation: sites dominated by mire vegetation constituted, on average, a source of +1.16±0.48 g CH_4 m^{-2} $year^{-1}$, while sites dominated by forest vegetation were a sink of −0.28±0.04 g CH_4 m^{-2} $year^{-1}$. This classification is available in NFI10 for upscaling.

N_2O emissions increased with increasing site fertility. This was adequately explained by simply classifying the sites by site type (Table 2). A negative exponential function was also fitted between N_2O emissions and CN (see Figure **II**.7).

Countrywide soil CO_2 balance and its uncertainty III

The choice of fine root turnover ratio had a drastic effect on the estimated net CO_2 exchange of the Finnish forestry-drained peat soils: With LT, a source (± 1 sd) of +3.2 ± 3.3 Tg CO_2 $year^{-1}$ (+20 ± 20 g C m^{-2} $year^{-1}$) was estimated, whereas applying HT yielded a sink of –7.0 ± 3.5 Tg CO_2 $year^{-1}$ (–40 ± 20 g C m^{-2} $year^{-1}$). With LT, most site types were estimated to be CO_2 sources (Figure 7). Only the relatively nutrient-poor Ptkg II and Vatkg -types were sinks. With HT, all types were estimated to be sinks, except for the most fertile ones and the poorest type Jätkg in the north. Site type-specific mean emissions were higher in the north for all site types and for both LT and HT (Figure 7).

The largest model error component was the D model (Figure 8), which solely resulted in an sd of 2.2 Tg CO_2 year^{-1}. All the components of L caused smaller error, yet together generated an sd of the same magnitude: 2.4 (2.7 HT) Tg CO_2 year^{-1}. All the models performed well per se: coefficients of variation ranged from as low as 1% to a moderate 17%. Compared to the $NE_{CO2soil}$ and model error components, both NFI10 area estimates and sampling produced a negligible error, together accounting for an sd of only 0.2 Tg CO_2 year^{-1}.

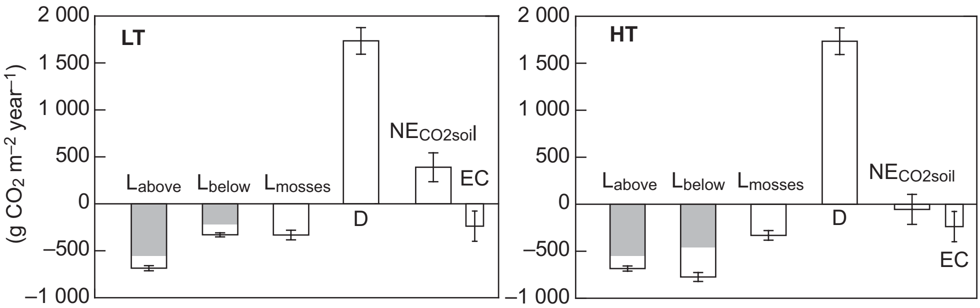

Figure 3. D−L method soil CO_2 balance ($NE_{CO2soil}$) at Kalevansuo for the lower (LT) and higher (HT) fine root turnover ratios. Soil CO_2 balance was estimated as decomposition (D) – above ground (L_{above}) – below ground (L_{below}) litter input from vascular plants – litter input from mosses (L_{mosses}). The grey color marks the share of the tree stand in vascular litter. Error bars are ± standard deviation. The eddy covariance based $NE_{CO2soil}$ (EC) is presented for comparison. Positive values indicate a CO_2 output from soil and a CO_2 source; negative values a CO_2-C input to soil and a CO_2 sink.

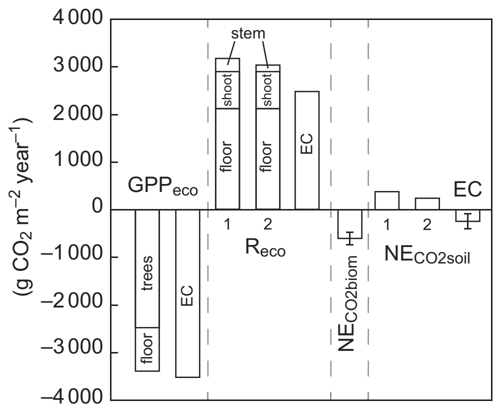

Figure 4. R_{floor} method soil CO_2 balance ($NE_{CO2soil}$) at Kalevansuo. Soil CO_2 balance was estimated as ecosystem respiration (R_{eco}) – ecosystem gross primary production (GPP_{eco}) + CO_2 sink in tree biomass increment ($NE_{CO2biom}$). GPP_{eco} was summed up as the gross primary production of trees (GPP_{trees}) + the gross primary production of forest floor (GPP_{floor}). R_{eco} was summed up as forest floor respiration (R_{floor}) + tree shoot respiration (R_{shoot}) + tree stem respiration (R_{stem}). Eddy covariance (EC) based GPP_{eco}, R_{eco} and $NE_{CO2soil}$ are presented for comparison. Numbers 1 and 2 refer to two alternative stem respiration estimates (1 is based on Zha et al., 2004; 2 is based on Kolari et al., 2009). Negative values indicate gross primary production and a CO_2 sink into biomass and soil; positive values indicate respiration and a CO_2 source. Error bars are ± standard deviation, when available.

Table 1. Results of fitting a general linear model with different site and climate variable combinations to explain estimated decomposition-derived soil CO_2 efflux (D, g m^{-2} $year^{-1}$ of CO_2). error = standard error of estimate for models and standard error of the coefficient/effect for coefficients/effects. n = 67. V = tree stand stem volume (m^3 ha^{-1}), WT = May–October mean water table depth (cm), T_{season} = May–October mean air temperature (°C), BD = bulk density (kg m^{-3}), TKG = site type.

Independent variables	p-value	coeff./eff.	error	r^2, %
V, WT, T_{season}, BD	.	.	260	62.5
Constant	0.059	−884	459	.
V	0.002	1.58	0.484	.
WT	0.010	−6.15	2.33	.
T_{season}	0.007	123	44.0	.
BD	0.007	2.85	1.01	.
V, WT, T_{season}, TKG.	.	.	259	65.3
Constant	0.164	−850	481	.
V	0.166	0.833	0.593	.
WT	< 0.001	−8.96	2.43	.
T_{season}	0.005	135	47	.
TKG	0.038	.	.	.
Rhtkg	.	382	128	.
Mtkg I	.	402	141	.
Mtkg II	.	200	108	.
Ptkg I	.	115	118	.
Ptkg II	.	110	114	.
Vatkg	included in the constant			
V, T_{season}, TKG	.	.	285	57.2
Constant	0.078	−1077	525	.
V	0.034	1.37	0.63	.
T_{season}	0.001	175	50	.
TKG	0.165	.	.	.
Rhtkg	.	286	138	.
Mtkg I	.	341	154	.
Mtkg II	.	250	118	.
Ptkg I	.	121	130	.
Ptkg II	.	74	125	.
Vatkg	included in the constant			

Table 2. Arithmetic means (± standard error) of N_2O balance (g N_2O m^{-2} $year^{-1}$) according to peatland site type (p = 0.07, r^2 = 12.8%, n = 80). In addition to the results of this study, values from Regina et al. (1996, 1998) and Minkkinen et al. (2007a) are included (see Figure **II**.7). Positive value indicates source.

Site type	N_2O balance
Rhtkg	+0.185±0.065
Mtkg I	+0.116±0.035
Mtkg II	+0.167±0.072
Ptkg I	+0.028±0.010
Ptkg II	+0.071±0.016
Vatkg	+0.029±0.007

Greenhouse gas impact of forestry-drained peatlands IV

The soils of the three most fertile site types (Rhtkg and Mtkg) were, on average, CO_2 sources of +190±70 g CO_2 m^{-2} year^{-1}, while the soils of the three poorest site types (Ptkg and Vatkg) were CO_2 sinks of −70±30 g CO_2 m^{-2} year^{-1}. The CO_2 source at the fertile sites increased towards warmer conditions (Figure 9). In contrast, the CO_2 sink at the poor sites showed no correlation with temperature sum. Lowering of WT increased the soil CO_2 source at the fertile sites until −60 cm, after which further lowering decreased it. At the poor sites, lowering of WT decreased the sink until the lowest WT of −60 cm.

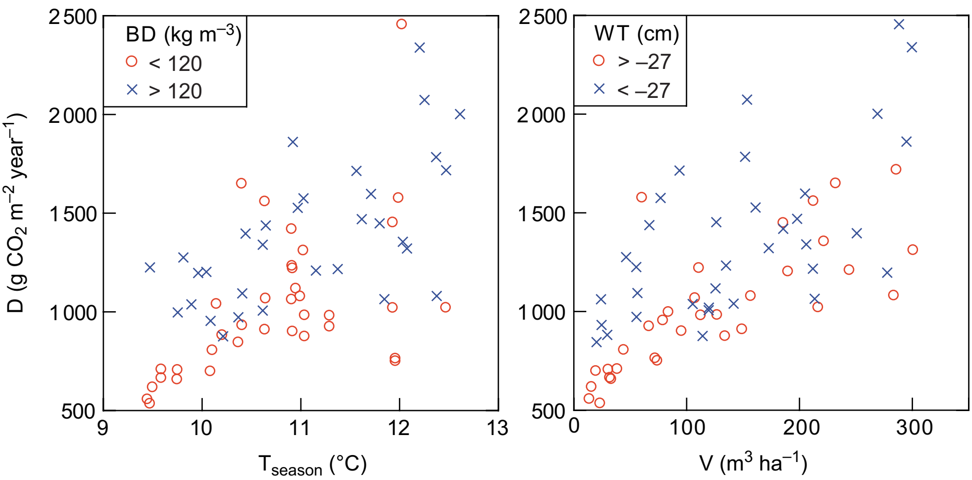

Figure 5. Annual soil CO_2 efflux (D) plotted against summer (May–October) mean air temperature (T_{season}) and tree stand stem volume (V). Sites are divided into two classes according to bulk density (BD) and May–October mean water table (WT, negative values = below soil surface).

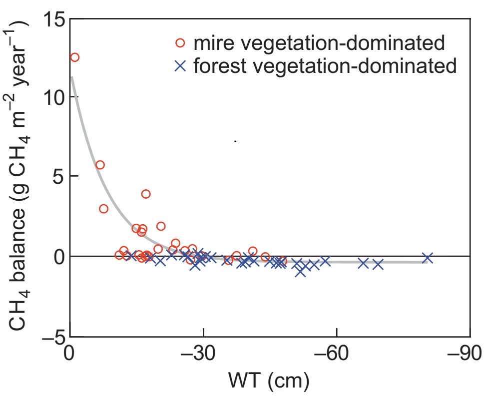

Figure 6. Regression (CH_4 balance = y_0 + ae^{bWT}) between average summer water table depth (WT, negative values = below soil surface) and annual CH_4 balance. Parameters (± asymptotic standard error): y_0 = −0.378 (±0.053), a = 12.3 (±2.7), b = 0.121 (±0.014), r^2 = 0.64, n = 57. Weighting by 1/variance. Positive value indicates source.

Both the fertile and poor sites had, on average, a climate cooling ecosystem GHG impact, mainly due to the large CO_2 sink in the tree biomass increment (Figure 10). On the fertile sites the sink was −690±90 g CO_2 eq. m^{-2} $year^{-1}$ and on the poor sites somewhat lower, −540±70 g CO_2 eq. m^{-2} $year^{-1}$. The soil was a GHG source at fertile sites (+230±70 g CO_2 eq. m^{-2} $year^{-1}$) and a sink at the poor sites (−50±40 g CO_2 eq. m^{-2} $year^{-1}$). Both fertile and poor sites were small CH_4 and N_2O sources. The combined source of those gases was +40±10 g CO_2 eq. m^{-2} $year^{-1}$ on the fertile sites and +20±5 g CO_2 eq. m^{-2} $year^{-1}$ on the poor sites.

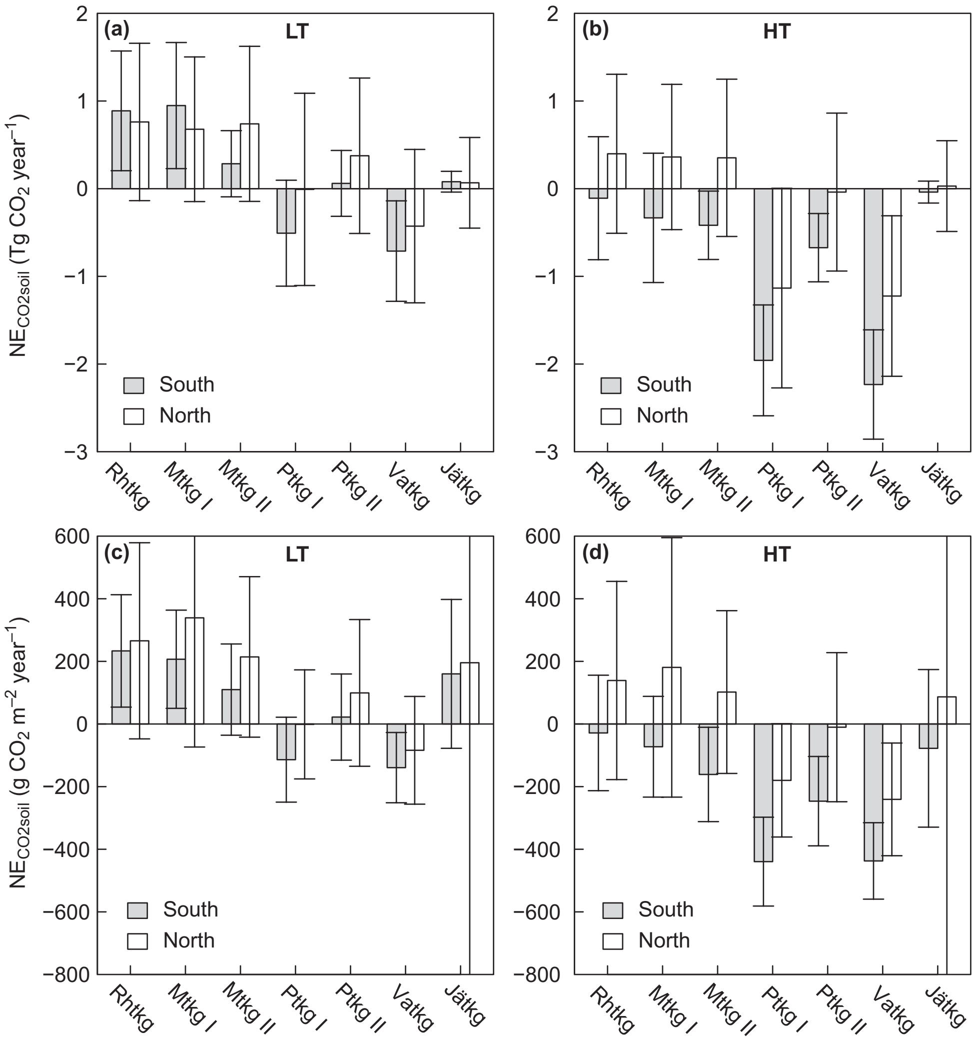

Figure 7. Country-level (a & b) and mean (c & d) soil net CO_2 exchange ($NE_{CO2soil}$) according to site type for South and North Finland (Figure 1) estimated using (a & c) lower (LT, 0.5 $year^{-1}$) and (b & d) higher (HT, 0.85 $year^{-1}$) fine root turnover. Error bars indicate model + sampling error (± 1 sd). Positive values indicate a source and negative values a sink.

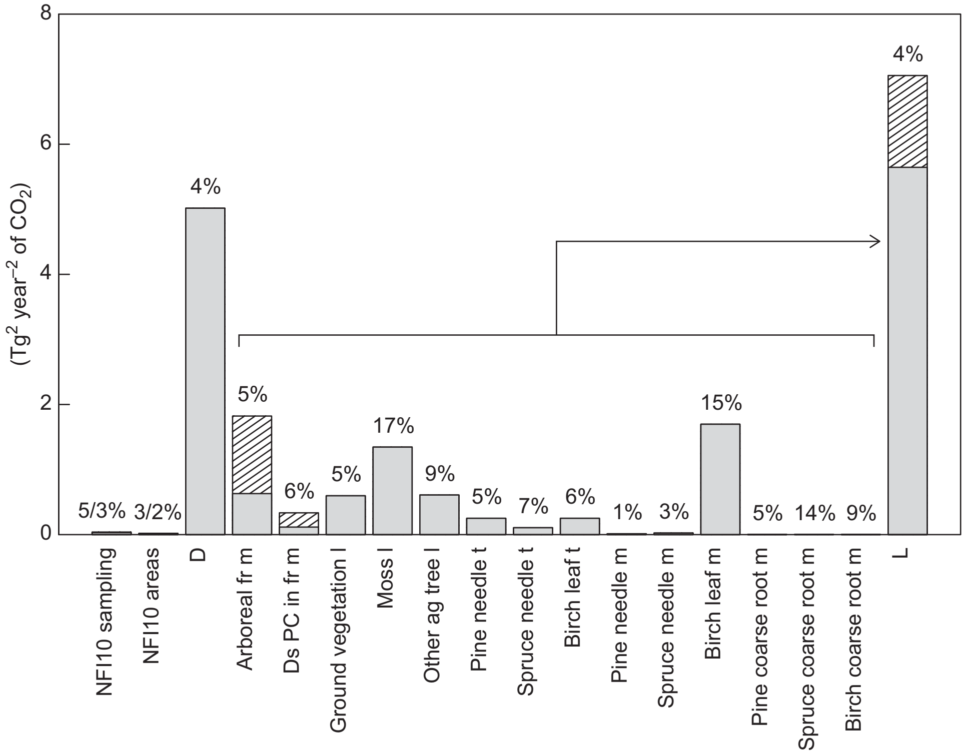

Figure 8. Variances in the countrywide soil net CO_2 exchange due to NFI10 sampling and area estimation, and model parameter uncertainties. Shaded bars denote higher variances with higher fine root turnover rates in affected components. Percentages above the bars are coefficients of variation (= var^{½} / |estimated component| × 100%). The two alternative numbers above the NFI10 sampling & areas bars are due to lower/higher fine root turnover. m = mass, l = litter production, Ds = dwarf shrub, PC = projection coverage, fr = fine root, ag = aboveground.

DISCUSSION

Of the two soil CO_2 balance estimation methods tested at Kalevansuo (**I**), the D−L method proved to be better: First, it produced a balance that did not differ significantly from the eddy covariance based reference balance. Second, D and L are always markedly smaller than GPP_{eco} and R_{eco}. Thus, for the same precision of the balance, the R_{floor} method requires better relative precision of the estimated components than the D−L method. Third, the countrywide estimation of GPP_{eco} and R_{eco} is hindered by the lack of suitable methods. Their accurate estimation was difficult even for a single study site. Thus, the D−L method was chosen for the further studies (**III** and **IV**).

The D−L method was straightforward to apply, both on the site (**I**) and countrywide (**III**) level. Precision was higher for the countrywide mean, ±20 g C m^{-2} year^{-1} (±50–100%), than for the intensively measured Kalevansuo site, ±40 g C m^{-2} year^{-1} (±40–290%): when a

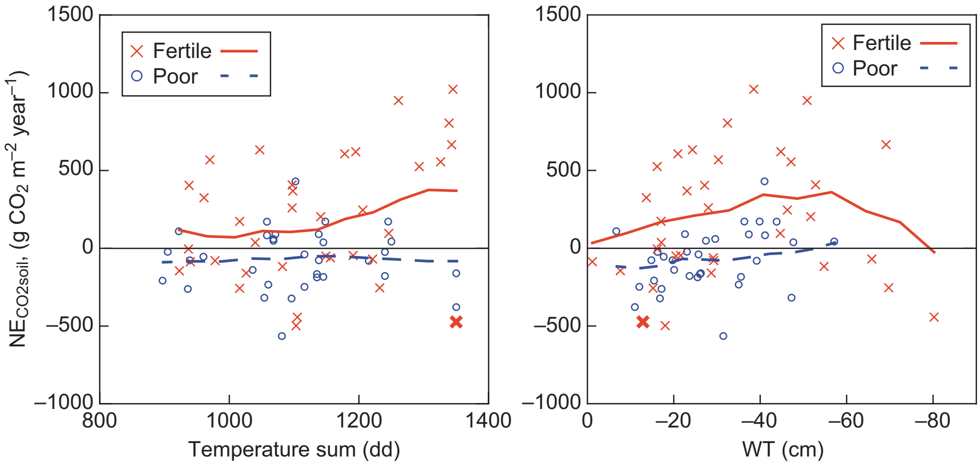

Figure 9. Soil CO_2 balance ($NE_{CO2soil}$) versus temperature sum (threshold +5 °C) and mean May–October water table depth (WT). Sites are divided into two groups: fertile, including Herb-rich and *Vaccinium myrtillus* type sites, and poor, including *Vaccinium vitis-idaea* and Dwarf shrub type sites. Lines depict the running averages (window size = n/2). A positive value indicates a source and a negative value indicates a sink. The fertile site marked in bold is unsuccessfully drained and almost in pristine condition.

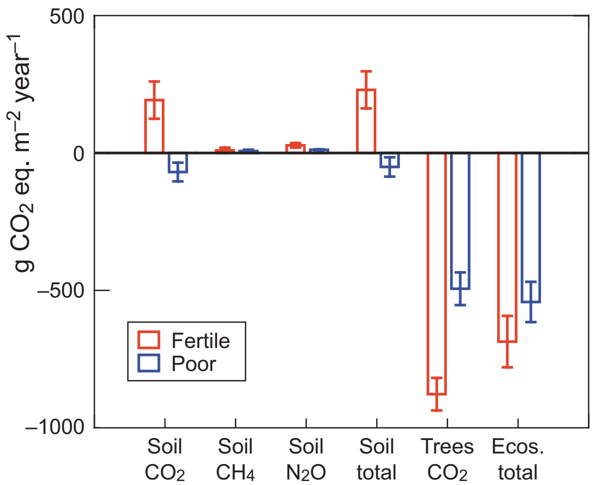

Figure 10. Mean soil CO_2, CH_4 and N_2O and soil total greenhouse gas impact, tree stand CO_2 sink and total ecosystem greenhouse gas impact in CO_2 equivalents for fertile and poor sites. Error bars are ± standard error of mean. Positive values are sources and negative values are sinks.

mean or sum balance is estimated for an extensive data set of independent observations, the random errors even out. These relatively high uncertainties should not be interpreted as due to insufficient data behind the applied models. Sub models in the countrywide estimation (**III**) as well as the component estimates at Kalevansuo (**I**) were reasonably precise (ca. ±10%). A method where large fluxes are subtracted from each other and the remainder is an order of magnitude smaller could yield a result with ±10% precision only if the estimated fluxes had a precision of ±1%, which is difficult to achieve with any reasonable sampling. These uncertainties are of the same order of magnitude than those for C stock changes for mineral forest soils estimated using litter decomposition models and repeated soil sampling (Rantakari et al. 2012; Ortiz et al. 2013).

Boreal forestry-drained peatland soils are, on average, a minor source of CO_2 (**III**; **IV**; Minkkinen and Laine 1998; Lohila et al. 2011; Simola et al. 2012) compared to many other land uses of drained peatlands, such as drainage for agriculture (Maljanen et al. 2001, 2004; Lohila et al. 2004; Elsgaard et al. 2012), afforestation of former agricultural peat soils (Lohila et al. 2007; Meyer et al. 2013), or drainage for tropical plantations (Couwenberg et al. 2010; Hooijer et al. 2012; Jauhiainen et al. 2012). CH_4 emissions are also generally low, and successfully drained soils even turn into small CH_4 sinks (**II**). Fertile sites emit some N_2O (**II**) and drainage ditches are a source of CH_4 (Roulet and Moore 1995; Minkkinen et al. 1997; Minkkinen and Laine 2006), but the CO_2 sink in the growing tree stand overrules these emissions (**IV**). Thus, the current GHG impact of a successfully forestry-drained peatland is climate cooling.

When considering a longer time perspective, forestry-drained sites form two groups. At the most fertile herb-rich and *Vaccinium myrtillus* type sites, the current GHG sink results from the CO_2 sink in tree biomass increment, while the soil is a GHG source (**IV**). Thus, forestry on such sites can be climatically sustainable only if the harvested tree biomass is, e.g., stored in wooden buildings or as biochar in agricultural soils. Oligotrophic *Vaccinium vitis-idaea* and dwarf shrub type sites do not seem to undergo substantial peat degradation (**IV**; Minkkinen and Laine 1998; Lohila et al. 2011). Forestry on these sites could thus be as climatically sustainable as on mineral soils. However, the poorest lichen type sites seem to be CO_2 sources again due to their very low primary production (**III**).

The GHG impact of forestry drainage extends far beyond the ecosystem GHG balance dealt with here, however. The use of tree biomass as raw material or as energy source always displaces some other raw material or energy source. Emissions from the whole life cycle of forest and energy industry products need to be compared with those based on other raw materials and energy sources to estimate the complete GHG impact of forestry-drainage (Pingoud et al. 2010, Helin et al. 2013).

The results of this thesis are quite conclusive for CH_4 and N_2O balance, and the uncertainty in soil CO_2 balance estimation is high only relatively speaking. Yet, because of the vast area of forestry-drained peatlands in Finland (Ylitalo 2012), the uncertainty of the soil CO_2 balance on a countrywide level is high (±10 Tg CO_2 year^{-1}, **III**). To reduce this uncertainty, simply increasing sample size is unfeasible. The key reason for the uncertainty in soil CO_2 balance estimation is that the accurate assessment of plant–soil C fluxes is not yet possible (**I**; **III**). Increased understanding of plant–soil interactions and further testing of the accuracy of soil CO_2 balance estimation methods are needed. For both CH_4 and CO_2 balance, information on water table depth in national land use inventories could improve countrywide level estimation. Especially for N_2O balance, high frequency year-round flux measurements could improve the accuracy of annual flux estimates, as short-living flux peaks can markedly affect annual flux estimates (Pihlatie et al. 2010; Saari et al. 2009; Maljanen et al. 2010a).

Despite the difficulties in the exact quantification of soil CO_2 balance, a clear view has emerged from the studies conducted on drained northern peatlands during the last 15 years: if a peatland is effectively drained and nutrient availability is good due to natural soil fertility (**IV**; Minkkinen and Laine 1998; Minkkinen et al. 1999) or agricultural history (Lohila et al. 2007; Meyer et al. 2013), peat will degrade. Emissions of up to +1 kg CO_2 m^{-2} year^{-1} from soil are possible. On the other hand, peat soil with relatively low soil fertility may act as a small CO_2 sink even after drainage for forestry (**IV**; Minkkinen and Laine 1998; Minkkinen et al. 1999; Lohila et al. 2011).

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