Associate Editor Decision: Publish subject to minor revisions (review by editor) (20 Oct 2019) by Kees Jan van Groenigen

Comments to the Author:

I would like to thanks the authors for fully addressing the reviewers' concerns. A revised version that includes all proposed changes will be acceptable for publication. With best regards, Kees Jan van Groenigen

Authors’ response: We thank for the smooth review process. As there were no further changes requested, we made only minor technical revisions to the MS.

Reviews and syntheses: Greenhouse gas exchange data from drained organic forest soils – a review of current approaches and recommendations for future research

Jyrki Jauhiainen[1,2], Jukka Alm[3], Brynhildur Bjarnadottir[4], Ingeborg Callesen[5], Jesper R. Christiansen[5], Nicholas Clarke[6], Lise Dalsgaard[7], Hongxing He[8], Sabine Jordan[9], Vaiva Kazanavičiūtė[10], Leif Klemedtsson[11], Ari Lauren[3], Andis Lazdins[12], Aleksi Lehtonen[1], Annalea Lohila[13,14], Ainars Lupikis[12], Ülo Mander[15], Kari Minkkinen[2], Åsa Kasimir[11], Mats Olsson[9], Paavo Ojanen[2], Hlynur Óskarsson[16], Bjarni D. Sigurdsson[16], Gunnhild Søgaard[7], Kaido Soosaar[15], Lars Vesterdal[5], and Raija Laiho[1]

[1] Natural Resources Institute Finland (Luke), Box 2, FI–00791 Helsinki, Finland

[2] Department of Forest Sciences, University of Helsinki, Box 27, FI–00014, Helsinki, Finland

[3] Natural Resources Institute Finland (Luke), FI–80100 Joensuu, Finland

[4] Department of Education, University of Akureyri, IS-600 Akureyri, Iceland

[5] Department of Geosciences and Natural Resource Management, University of Copenhagen, DK–1958 Frederiksberg C, Denmark

[6] Department of Terrestrial Ecology, Norwegian Institute of Bioeconomy Research (NIBIO), Box 115, N–1431 Ås, Norway

[7] Department of Forest and Climate, Norwegian Institute of Bioeconomy Research (NIBIO), Box 115, N–1431 Ås, Norway

[8] Department of Biological and Environmental Sciences, University of Gothenburg, Box 461, SE–40530 Gothenburg, Sweden

[9] Department of Soil and Environment, Swedish University of Agricultural Sciences, Box 7014, SE–75007 Uppsala, Sweden

[10] Vytautas Magnus university, LT-44248 Kaunas, Lithuania~~Lithuanian State Forest Service, LT-51327 Kaunas, Lithuania~~

[11] Department of Earth Sciences, University of Gothenburg, Box 460, SE–40530 Gothenburg, Sweden

[12] Latvian State Forest Research Institute (Silava), Salaspils, LV–2169, Latvia

[13] INAR Institute for Atmospheric and Earth System Research/Physics, Faculty of Science, University of Helsinki, Box 68, FI-00014, Helsinki, Finland

[14] Finnish Meteorological Institute, Climate System Research, Box 503, FI–00101 Helsinki, Finland

[15] Department of Geography, University of Tartu, EE-51014 Tartu, Estonia

[16] Agricultural University of Iceland, IS-311 Hvanneyri, Borgarnes, Iceland

Correspondence to: Jyrki Jauhiainen (jyrki.jauhiainen@helsinki.fi)

Keywords: greenhouse gases, emission factors, peatlands, organic soils

Abstract. Drained organic forest soils in boreal and temperate climate zones are believed to be significant sources of the greenhouse gases (GHG) carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O), but the annual fluxes are still highly uncertain. Drained organic soils exemplify systems where many studies are still carried out with relatively small resources, several methodologies and manually operated systems, which further involve different options for the detailed design of the measurement and data analysis protocols for deriving the annual flux. It would be beneficial to set certain guidelines for how to measure and report the data, so that data from individual studies could also be used in synthesis work based on data collation and modelling. Such synthesis work is necessary for deciphering general patterns and trends related to, e.g., site types, climate, and management, and the development of corresponding emission factors, i.e., estimates of the net annual soil GHG emission/removal, which can be used in GHG inventories. Development of specific emission factors also sets prerequisites for the background or environmental data to be reported in individual studies. We argue that wide applicability greatly increases the value of individual studies. An overall objective of this paper is to support future monitoring campaigns in obtaining high-value data. We analysed peer-reviewed publications presenting $CO_{2,}$ CH_4 and N_2O flux data for drained organic forest soils in boreal and temperate climate zones, focusing on data that have been used, or have the potential to be used, for estimating net annual soil GHG emission/removals. We evaluated the methods used in data collection, and identified major gaps in background/environmental data. Based on these, we formulated recommendations for future research.

1 Introduction

Organic soils contribute to the atmospheric greenhouse gas (GHG) concentrations, as they can both remove and emit GHGs, and have globally extensive carbon (C) and nitrogen (N) stores (Post et al., 1982; FAO, 2012; IPCC, 2014; Oertel et al., 2016; Wilson et al., 2016). Organic soils are, especially in the boreal region, commonly peat, derived from plant remains that have accumulated below the high water-table (WT) of peat-forming wetlands, peatlands. Below the WT, decomposition is anaerobic and generally slow (e.g., Straková et al. 2012). Peatlands have been widely converted into agricultural and forestry land or used for peat extraction (Joosten 2010). These land uses typically involve drainage by ditching. Draining of organic soils enhances aerobic decomposition and thus the mobilization of their C and N stores (e.g., Post et al., 1985; Kasimir-Klemedtsson et al., 1997; Ernfors et al., 2008; Petrescu et al., 2015; Abdalla et al., 2016; Pärn et al., 2018). Forestry is an extensive land-use type on peatlands in northern Europe, especially in the Nordic and Baltic countries (e.g., Barthelmes et al. 2015). The drained organic forest soils of this region may act as significant sources of GHGs (Barthelmes et al. 2015), and their annual carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) emissions and removals have to be reported in the national GHG inventories.

Currently, both the IPCC (2006) agriculture, forestry and other land use (AFOLU) guidelines and the IPCC (2014) Wetlands Supplement may be used for reporting the annual GHG emissions and removals for soils under anthropogenic land uses, such as drained organic forest soils. Area-based emission factors (EFs), describing the net annual soil GHG emissions/removals, have been developed to reflect the impacts of ecosystem type, land management and environmental conditions. Countries may opt for different methodological levels in their GHG reporting, so-called Tiers 1 to 3, where Tier 1 is the simplest approach with default EFs of the IPCC. IPCC (2014)~~,~~ introduced the most recent Tier 1 EFs for drained organic soils (Fig. 1). In practice, most countries currently use the Tier 1 EFs for soil emissions/removals by drained organic forest soils. Tier 1 EFs are mean values of annualised net emission/removal estimates compiled from published data, categorized by climatic zones, and for some zones also by wide soil nutrient status classes “poor” and “rich” (IPCC, 2014). Tier 2 and Tier 3 are methods that use country-specific ~~data~~ EFs (Tier 2) and repeated forest inventories and/or advanced modelling (Tier 3), which should make the national estimates more accurate.

Uncertainty of the estimated emissions is still generally high. For instance, the 95 % confidence interval for the Tier 1 CO_2-C EF for boreal nutrient-poor soils ranges from -0.23 tonnes CO_2-C $ha^{-1}yr^{-1}$ removal to 0.73 tonnes CO_2-C $ha^{-1}yr^{-1}$ emission, and that for the corresponding CH_4 EF from 2.9 to 11 tonnes CH_4 $ha^{-1}yr^{-1}$ emission (IPCC, 2014). Even in Finland where a ~~national~~ Tier 2 method is used, the relative uncertainty of CO_2 emissions from organic soils in the reporting category 'forest remaining forest' is as high as 150 % (Statistics Finland 2019). This means that those soils can be either sinks or sources of CO_2, though the latter is more likely due to the estimated 1.1 Mt C decrease annually in the soil C stock of those lands. The high uncertainty underlines the need for improvement of GHG emission/removal estimation in countries with a high proportion of drained organic forest soils.

Both data collection and method development for reporting the anthropogenic emissions from drained organic soils have duly received increasing attention, with the aim to improve the accuracy of the emission estimates (e.g., IPCC, 2014; Oertel et al., 2016; Tubiello et al., 2016; Kasimir et al., 2018). The accuracy of EFs can be improved as more peer-reviewed data become available and quantify a wider set of specific management options and ecological conditions for a given country or region (e.g., Couwenberg, 2011). However, GHG emission data may be collected with several methodologies, which further involve different options for the detailed design of the measurement and data analysis protocols. Development of more specific EFs also sets prerequisites for the background or environmental data to be reported along with the GHG emission estimates. Since collecting representative GHG emission data is time consuming and thus costly, it would be beneficial to set certain guidelines for how to report the data and related environmental information, so that each individual study would also contribute to more general analyses based on data collation and modelling, or at least simple regression analyses on the factors potentially influencing the emissions. Yet, so far there has been no systematic assessment on how such data are presented in individual studies or how to improve the applicability of the data collected in individual studies in synthesis work aiming to develop more specific EFs. While there is a growing number of long-term GHG measuring stations with standardized protocols (e.g., https://www.icos-ri.eu/), and a vision towards a more integrated approach (Kulmala, 2018), drained organic soils exemplify systems where many studies are still carried out with relatively small resources and manually operated systems. An overall objective of this paper is to assist the measurers-to-be of such campaigns to plan their data collection and presentation protocols, for enhancing the applicability of their data and thus getting the most out of their hard work.

We analysed peer-reviewed publications presenting GHG data for drained organic forest soils in boreal and temperate climate zones. We focused on data that have been used, or have the potential to be used, for estimating the net annual soil GHG emissions/removals for the measured sites. Such data can then be further used for constructing EFs. The emphasis was on emissions/removals of CO_2, CH_4 and N_2O derived from biological processes taking place between vegetation, soil and the atmosphere on-site. We will henceforward call such annual emissions/removal estimates the "soil GHG balance(s)". We set as our aims to i) collate a database that may be used for developing EFs, and ii) to examine:

- the data collection methods and data structure in the peer-reviewed publications potentially qualified for estimation of annual soil GHG balances,
- how the characteristics and applicability of the data produced by different GHG monitoring methods differ,
- which type of background data (e.g., tree stand and site characteristics) is provided in the publications that could be used for generalizations and soil GHG balance modelling, and

- which information would be needed for the publications to provide improved applicability for generalizations and modelling.

Because of higher complexity in processes and monitoring approaches for the CO_2 flux, we will review CO_2 data in more detail than the other gases. Fire-induced emissions will not be dealt with. Water-borne C losses will be assessed to a limited extent only, due to the scarcity of available data for drained organic forest soils, and a recent review published on the subject (Evans et al., 2016).

2 Material of the Review

We searched peer-reviewed original studies on soil GHG exchange or C-stock changes in drained organic forest soils. IPCC (2014) Wetlands Supplement reference list contains most of the GHG flux data published until 2013, and was used as a basis that was complemented using reference data bases, Web of Science, and Google Scholar. Many of the publications are also included in the global soil respiration database, that is open for adding and using published soil respiration data for various ecosystems, including wetlands (Bond-Lamberty and Thompson, 2010; https://github.com/bpbond/srdb).

From the retrieved peer-reviewed publications, we included in the database data that fulfilled the following specifications:

- Data were for forest soils. We followed IPCC (2014), where minimum criteria are 10 per cent canopy coverage and 0.5 ha continuous forest area (as in FAO's FRA, 2015). To qualify as forest, the time passed since afforestation had to be over 20 years for sites previously under some other land use. The sites should have been under conventional management conditions, and thus sites with extreme experimental fertilization or hydrology manipulation were excluded. If the publication mentioned tree presence but did not provide sufficient information to confirm that the above forest criteria were met, the data were excluded.
- Data were for organic soils. As criteria for 'organic soil' we followed Annex 3A.5 in IPCC (2006). This means thickness of the organic horizon greater than or equal to 10 cm, and a minimum of 12 % organic C by mass. In practice this includes both C-rich histosols (peat) and soils typically identified as gleysols, which have characteristically lower C-content than peat. If the publication did not specify the soil type or characteristics in an unambiguous manner, the data were excluded.
- ~~Data were for forest soils. We followed IPCC (2014), where minimum criteria are 10 per cent canopy coverage and 0.5 ha continuous forest area (as in FAO's FRA, 2015). To qualify as forest, the time passed since afforestation had to be over 20 years for sites previously under some other land use. The sites should have been under conventional management conditions, and thus sites with extreme experimental fertilization or hydrology manipulation were excluded. If the publication mentioned tree presence but did not provide sufficient information to confirm that the above forest criteria were met, the data were excluded.~~
- Data were for drained organic soils. Data were excluded, if it was not specified that the studied site was drained or drainage-impacted.
- Data were from the boreal or temperate climate zone as defined in IPCC (2006), and the monitoring/sampling location was detectable by coordinates.

We formed a database (S1, Table S1 and Table S2) that includes publications released prior to year 2018 with data on (i) inventories integrating changes in soil C stocks, and (ii) CO_2, CH_4 and/or N_2O fluxes monitored by (a) chamber technique or (b) eddy covariance (EC) technique. The few existing peer-reviewed soil CO_2 balance estimates based on EC data were assumed to be technically correct. This does not imply that the EC method could be considered "perfect" as such (e.g., Wang et al. 2017). In data derived by chamber methods, we paid attention to i) specification of the flux components monitored (i.e., total vs. autotrophic, ground vegetation presence or removal, inclusion of fluxes from the litter inputs above and belowground), ii) temporal coverage to facilitate forming an annual estimate, iii) spatial coverage at the monitoring site, and iv) description of the methods in flux analysis. For soil inventory methods, we evaluated the ability of the chosen field-work method to provide representative samples with unambiguous references for determining the C-stock change over time. Further, to support constructing EFs and modelling of GHG emissions, the available information on site characteristics, either qualitative or quantitative, was evaluated. Such information includes, e.g., temperature sum, site type (at least rich / poor), soil properties, WT regime, description of the forest stocking, tree species composition, and for afforested sites the time of afforestation and previous land use.

3 Processes and Structural Features to be Covered by Monitoring

Quantifying the soil GHG balance, especially for CO_2, in forests growing on organic soils is technically challenging. Monitoring needs to take into account that i) C-sequestration into plant biomass takes place in a voluminous and usually diverse vegetation community with uneven spatial distribution, ii) the C transfer from biomass into dead organic matter as diverse litter forms takes place both aboveground and belowground with uneven spatial distribution, the belowground transfers being especially challenging to quantify, iii) physical and biochemical characteristics in organic soils change over time, iv) CO_2 release through heterotrophic processes takes place both in recently deposited litter and in a soil composed of previously accumulated dead organic matter, (v) in gaseous flux measurements, CO_2 formed in the heterotrophic processes in soil must be separated from similarly large CO_2 emissions formed in autotrophic root respiration, and vi) rates of biological processes change over the year and differ between years depending on weather conditions, stand development and management (points i-v shown in Fig. 1). In this paper "soil CO_2 balance" includes C transfer fluxes to the soil as above-ground and belowground litter, and losses by decomposition of litter and soil organic matter.

The methods used to quantify soil CO_2 balance can be classified into gaseous flux monitoring methods and soil inventory methods. The two method groups differ profoundly in the way they quantify the components of the soil C balance. Multiple monitoring setups are available in both methods, which may influence the estimate formed. This should be considered carefully when planning the measurements, because monitoring setups in most studies are chosen to provide data for answering specific research questions, and they do not always aim to quantify the annual soil CO_2 balance. A more detailed description of the methods, with their advantages, weaknesses and caveats, is given in supplement (S2). The flux methods include i) EC flux monitoring by sensors located above the canopy, and ii) chamber techniques involving chambers enclosing a known gas space over soil with or without ground vegetation, litter and roots. Data processing in flux-based methods usually requires additional data on mass-based C stock changes, such as C inputs as litter, or change in vegetation C stock. The soil inventory methods integrate the outcome from all processes affecting the soil C stock over time. C in mass based C-stock change is converted to CO_2 by multiplying with 3.67 (the mass ratio between CO_2 and C, 44/12).

For forming the EFs for CH_4 and N_2O there is no guidance on how living vegetation presence or litter dynamics should be taken into account in flux measurements, except that vegetation presence can be reported for CH_4 monitoring locations (IPCC, 2014). However, wetland plants that have roots with aerenchymatous tissue are known to pipe out CH_4

from waterlogged peat layers (Askaer et al., 2011). One of such plants is cottongrass (*Eriophorum vaginatum*), a widespread sedge that is found also on drained sites (e.g., Kokkonen et al., 2019). Excluding these plant types may lead to severe underestimation of the CH_4 flux (Askaer et al., 2011). However, in drained sites sedges may also attenuate the emissions (Strack et al., 2006). Further, methanotrophic symbionts dwelling in hyaline cells of *Sphagnum* mosses are able to oxidise CH_4 in solutes to CO_2 that is consumed in photosynthesis (Raghoebarsing et al., 2005; Larmola et al., 2010). So far, such observations are available for undrained peatlands only. There are also reports indicating that stem bark and leaves are able to transport N_2O and CH_4 from soil to the atmosphere in trees such as black alder (*Alnus glutinosa* L.) (e.g. Rusch and Rennenberg, 1998; Gauci et al., 2010; Machacova et al., 2013; Covey and Megonigal, 2019; Welch et al., 2019), but the magnitude of such tree-mediated pathways is still largely unknown. Furthermore, belowground biomass disturbance, e.g. rhizosphere and mycorrhizal mycelia removal by trenching, has been shown to result in increased N_2O flux in drained organic forest soils (Ernfors et al., 2011). We therefore paid attention to vegetation disturbance / removal when reviewing the CH_4 and N_2O studies. It seems clear, however, that in future studies of CH_4 and N_2O, vegetation should be kept intact.

When estimating CH_4 fluxes, it is important to consider the drainage ditches (Fig. 1). They represent wet areas in a drained landscape, and may be local hotspots for emissions from ditch floor and the water column. CH_4 emissions can be released by diffusion through the water body, by ebullition and by gas transport through the vegetation, especially sedges (Frenzel and Rudolph, 1998; Saarnio and Silvola, 1999; Natchimuthu et al., 2017), which need to be considered in monitoring. Tier 1 EFs have been constructed for ditch CH_4 emissions in IPCC (2014). Information on the proportion of the drainage ditch network area in the landscape is further needed for estimating the emissions. For further modeling of ditch emissions, information on ditch water levels and flow rates~~ and levels~~, ditch characteristics, vegetation composition, and ditch network maintenance likely have importance.

Formatted: Not Superscript/ Subscript

4 Availability of published data for soil GHG balance estimation

We reviewed about 130 papers, and finally retrieved 52 studies that reported GHG fluxes or C-stock changes in drained organic forest soils in boreal and temperate zones with potential data for estimating soil GHG balance (S1). Several studies included more than one GHG species monitored (thus, the total n of publications in Table 1 appears to be higher). Most of the CO_2~~/C~~ studies used flux monitoring methods; however, studies using inventory methods covered, on average, more sites (Table 1). Studies on CO_2 had the highest total number of sites (133), while N_2O monitoring studies had the lowest (61).

The number of publications in our database (Table 1), complemented with more recent data, became notably higher than that in the IPCC (2014). Our database is not fully matching with the data included in the IPCC (2014) even concerning older data. This is firstly because some studies (8) in the former were replaced by newer publications using the same field data. Secondly, some publications did not match with our criteria, as described in the section 'Material of the Review' (S1, Table S4). We identified each monitored site based on coordinates, site type, and other information provided in the publications, which prevented double-counting of sites that were, e.g., included in review papers. The number of N_2O monitoring sites was further reduced by recent error detection for 40 sites (Ojanen et al., 2018).

Common reasons for exclusion of a study were insufficient descriptions of the monitored site and methods, unclear data presentation, or the same data found in multiple publications (S1 Table S4). Information about the soil type, forest characteristics, or drainage status are important, and insufficient characterization may prevent a conclusion that the

studied site represents drained organic forest soils. Unusual forest management conditions, such as experimentally applied unconventionally high amounts of lime or fertilizers, restrict data inclusion from such monitoring sites.
Somewhat more difficult question is how to deal with data quality. Data quality remains undefined if the design of spatial and temporal extent of soil sampling or flux monitoring, or the analytical procedures in the laboratory are not clearly described. Whereas the EC method is expected to integrate the C balance over a large area around the sampling spot, absence of spatial replicates on the heterogeneous forest floor in the chamber and soil inventory methods raises concern regarding the representativeness of the monitoring setup. Another concern in flux monitoring by chambers can be a low sampling frequency and/or extent over time. Conditions in the environment, e.g. vegetation, soil temperature and WT, change over time, and need to be included in monitoring not only during the warm season but also during shifts from/to colder seasons. ~~Modest number of EC studies (3) in drained organic forest soils limits comparisons in data features in the method. Recent syntheses on EC flux data collected from various ecosystems worldwide are available in Wang et al. (2018).~~ It becomes also overly challenging to estimate cumulative seasonal or annual fluxes if data are presented as series of daily flux values, daily mean flux values or a range of flux values. Some of the methods are no longer considered to produce reliable results, e.g., soda lime absorption for CO_2 flux estimation in field conditions (see S1 Table S4, S2). The modest number of EC studies (3) in drained organic forest soils limits comparisons in data features in the method. Recent syntheses on EC flux data collected from various ecosystems worldwide are available in Wang et al. (2018).

5 Applicability of the published data for soil GHG balance estimation

5.1 Carbon dioxide

5.1.1 Chamber methods

Flux data monitored by dark chambers forms the largest data set for forests on drained organic soils (Fig. 2, S1). However, complete soil CO_2 balance estimates based primarily on data collected on-site are rare (Ojanen et al., 2010, 2013; Meyer et al., 2013; Uri et al., 2017). Ideally, a setup for forming the soil CO_2 balance by dark chamber techniques would include quantification of the heterotrophic emission sources (litter and soil) without autotrophic emissions from live plants (S2). Pavelka et al. (2018) provides broad recommendations for chamber measurements in different terrestrial ecosystems.
Generally, cooler night-time temperatures result in lower emissions (Brændholt et al., 2017). Not accounting for this pattern results in overestimated emissions. Automated gas flux monitoring with short intervals ensures capturing the impact of diurnal soil temperature differences on CO_2 emissions. Diurnal CO_2 flux monitoring by automated chambers has been deployed in two studies (Ball et al., 2007; Meyer et al., 2013). In manual chamber data, the diurnal temperature differences have been taken into account mostly by applying temperature modelling into fluxes monitored during day-time in the boreal zone studies. However, only 36 % of the temperate zone studies accounted for diurnal temperature differences by collecting flux data also during night-periods or by modelling (S1). Consideration given to soil temperature impacts on GHG fluxes should be a requirement in data collection, processing and reporting in studies using manual GHG flux data collection.
Soil C balance is the balance between C added in litter inputs and C lost as CO_2 in emissions from litter and soil organic matter decomposition. The most typical data lacking for completion of the soil CO_2 balance estimate in the reviewed publications was the annual rate of litterfall (Fig. 1 & 2, S1 Table S1). Emissions from decomposing litter are included

in CO_2 flux monitoring by having the deposited litter on the soil surface intact, but even then the rate of litter inputs need to be measured, or estimated, to complement the balance. In studies where the monitored surfaces are kept clean from litter, the above-ground litter CO_2 emission must be estimated separately, which may be laborious and result in bias or error. Extensive studies on annual aboveground litter production and decomposition with impact assessment to soil CO_2 balance have been made for the boreal zone in Finland (Ojanen et al., 2013, 2014). Comparable integrated assessments for the temperate region, and for afforested sites, formerly used for peat mining or as cropland, are still lacking. Species-specific aboveground litter production estimates are available for birch, pine and spruce, if measures quantifying the tree biomass are known (e.g., Repola 2008, 2009). Considerably less specific data are available on understory litter production (Straková et al., 2010), litter decomposition (Domisch et al., 2000; Tuomi et al., 2010; Straková et al., 2012; Ťupek et al., 2015), and, especially, on belowground (fine root) litter production and decomposition rates (Laiho et al., 2003, 2014; Finér et al., 2011; Jagodzinski et al., 2016; Bhuiyan et al., 2017). Use of generic values for litterfall and litter decomposition cannot be recommended because these rates are site-type specific, typically differing between nutrient-poor and rich sites, and also depend on growing season length (Straková et al., 2010, 2011, 2012; Ojanen et al., 2013; Lehtonen et al., 2016). For more accurate soil CO_2 balance estimates, work towards reduced uncertainty in the inputs and decomposition rates of different litter types under different conditions is needed.

Above- and belowground autotrophic respiration of vegetation remaining inside the chamber is a CO_2 flux source that was often acknowledged but not always quantified in the dark chamber studies (Fig. 2, S1 Table 1). These fluxes are practically impossible to quantify afterwards, and thus should be given consideration when performing the measurements and reporting the results. In some studies the soil surface has been free of ground vegetation either naturally due to shading by tree canopy, or kept free by frequent clipping. Living roots of both ground vegetation and trees extending to the monitoring plot may still add autotrophic CO_2 emission unless specifically excluded by trenching (Subke et al., 2006). Although an approximately 0.5~~0 %~~ proportion between total and autotrophic respiration is a fairly common outcome in studies conducted on both organic and mineral soils (e.g., Bond-Lamberty et al., 2004; Comsted et al., 2011), use of a literature-based fixed coefficient induces a source of uncertainty with a potentially high impact on the soil CO_2 balance estimate. For example, in Uri et al. (2017) the proportion between heterotrophic and total soil respiration was between 0.6 and 0.7 in five downy birch (*Betula pubescens*) stands on nutrient-rich drained temperate peatlands. The soil CO_2-C balances in Uri et al. (2017) would differ on average by 54 % from the reported estimate if the simple 0.5 proportion between the heterotrophic and total soil respiration fluxes were used in the calculation. Data quantifying both total and autotrophic respiration for sites potentially influenced by preceding management impacts, such as afforested former peat mining areas or croplands on organic soils, are currently not available at all.

Modelling, based on on-site flux monitoring, has been done to separate the autotrophic and heterotrophic soil respiration (Ojanen et al., 2010, 2013; Uri et al., 2017). These studies indicated that annual total and heterotrophic respiration both correlate with soil temperatures, but there is substantial between-site variation in the annual fluxes. The share between heterotrophic and autotrophic respiration further varies over the growing season depending on the phenology of trees and understorey vegetation, and this introduces another source of uncertainty in data where heterotrophic emission is proportioned from the monitored total soil CO_2 flux. Use of original site-specific heterotrophic emission data integrates local environmental conditions best and should be quantified in flux monitoring. However, it would be useful if general models estimating the proportion between total and autotrophic soil respiration in different types of forests in open, maturing and mature stages, in conditions created by recent management, and with seasonal impacts were further developed.

Several studies monitored CO_2 exchange using transparent chambers, but their flux estimates were only rarely suitable for estimating soil CO_2 balance in the forest ecosystem. The advantage is the possibility for estimating ground vegetation C balance. However, a complication of the method in forests is that tree root respiration is also included, difficult to discern from the fluxes. Trenching can be a way to avoid this complexity, but this may also disturb the ground vegetation inside the plot, especially clonal plants for which the rhizomes may extend far beyond the plot limits. That is why this method may produce quite ambiguous results if applied in forests.

5.1.2 Eddy covariance method

Eddy covariance (EC) method was applied in three studies (Lohila et al., 2007, 2011; Meyer et al., 2013). The EC method yields the net CO_2 exchange (NEE) between the ecosystem and the atmosphere, and a set of calculations as well as additional measurements are needed for producing the soil CO_2 balance (S2, Lohila et al., 2007, 2011; Meyer et al., 2013). EC data typically combine high temporal flux sampling intensity with a large areal coverage, i.e. the data has good representativeness for the studied area, and has a relatively small standard error in the NEE estimate (Lohila et al., 2011). For estimating soil CO_2 balance as 'NEE minus change in vegetation biomass' (S2), the greatest biomass change in forested sites is naturally in the tree stand. If ground vegetation biomass is low under closed canopy conditions, it can be neglected. The tree biomass change data are usually based on systematic stem radial growth and height growth measurements providing cumulative annual data that is combined with biomass allocation models. The errors can be propagated as in Lohila et al. (2011), in which study they were 11.4 % of the mean for NEE and 20 % for annual tree biomass increment. Meyer et al. (2013) compared CO_2 balances derived from EC and automated chamber methods and concluded that the larger accumulated uncertainty for the latter method makes the EC method more reliable. However, the two methods differ by data types and contributing sources of error to an extent that makes it difficult to compare the uncertainties.

5.1.3 Inventory methods

Inventory methods were applied in five studies (Minkkinen and Laine, 1998; Minkkinen et al., 1999; Simola et al., 2012; Pitkänen et al., 2013; Lupikis and Lazdins, 2017). On average, these studies included a higher number of monitored sites compared to studies using flux methods (Table 1). In the largest study, the soil C-stock change estimates of 273 peatland sites were pooled into groups representing three site types for five regions in Finland (Minkkinen and Laine, 1998), while site specific estimates were given in the other studies. In this method, soil C stocks are estimated at least twice. Volumetric soil samples are taken from the peat surface down to the bottom of the peat deposit. Alternatively, sampling may be extended down to a clearly definable reference layer. The C-stock is calculated from the soil bulk densities and C concentrations. The stock change is then simply the difference in the C-stock estimates between the time points. Soil CO_2-C balance estimates based on inventory data integrate the outcome from all C-stock contributing processes over long (decadal) periods. Thus, the method is good for monitoring soil C-stock differences over time in stabilized conditions. The drawback is the difficulty in determining a small temporal change in a very large soil C stock (e.g. Minkkinen and Laine, 1998). Year-to-year differences in soil C stock or specific forms of C or GHGs cannot be studied, which limit the use of the method only for Tier 1 EFs. Reliable estimates may be obtained only if the bottom of the peat deposit is defined accurately and in a similar manner in the repeated sampling, or if an unambiguous reference layer is used that is located deeper in the soil profile than the depth to which anthropogenic changes may be expected to extend (S2). These conditions cannot usually be met, and thus the inventory methods usually involve very high variation around the estimates. This uncertainty is further contributed to by the spatial variation in peat characteristics and the topography of the bottom of the basin, since exactly the same spots cannot be resampled.

5.2 Methane and nitrous oxide

N_2O and CH_4 fluxes have been studied specifically or together with CO_2 flux monitoring (S1 Table S1 and Table S2). Most studies (90 %) on CH_4 and/or N_2O fluxes used chambers with retained ground vegetation, if any was present. In three studies vegetation was regularly removed (Danevcic et al., 2010; Ernfors et al., 2011; Holz et al., 2016). In combined CO_2, CH_4 and N_2O monitoring plots, where surface vegetation and litter is removed and/or soil is trenched for studying the heterotrophic CO_2 flux, the caused disturbances in vegetation and soil conditions may influence the CH_4 and N_2O fluxes. In Tier 1 EFs by IPCC (2014) only climate, land use and soil nutrient status information is used. Presence or absence of plant species that are able to transport CH_4 can be accounted in a Tier 2 method, but there is no specific guidance for how to stratify. For Tier 2 EFs, guidance and clarification on how to include ground vegetation, rhizosphere and litter would be useful. For constructing Tier 2 factors it should be recommended in any case that ground vegetation should be kept intact in CH_4 and N_2O monitoring.

Drained organic forest soils are often small annual sinks of CH_4 (Minkkinen et al., 2007a; Ojanen et al., 2010). Yet, ditches in such sites may yield significant emissions. A relatively small number of studies have quantified the contribution of drainage ditches to CH_4 fluxes in forests (Roulet and Moore, 1995; von Arnold et al., 2005b; Minkkinen and Laine, 2006; Glagolev et al., 2008; Sirin et al., 2012). To our knowledge only Peacock et al. (2017) has measured N_2O emissions from ditches at semi-natural and cropland sites, and found them to be significant. Additional flux data are therefore needed for quantification of this flux in drained forests. To increase applicability, publications on ditch GHG emissions should also provide information on the ditch characteristics, such as size, spacing, current maintenance regime, water level and flow rates during monitoring, and vegetation.

5.3 Water-borne C

Both pristine and drained organic soils show C losses in drainage waters (e.g., Strack et al., 2008; Urbanová et al., 2011; Nieminen et al., 2015). Water draining from organic soils contains dissolved organic C (DOC, typically defined as C passing through a 0.45 µm membrane filter) and particulate organic C (POC), the sum of DOC and POC being total organic carbon (TOC). To estimate water-borne C fluxes, quantification of water flux as well as C concentrations is necessary. Also, incoming C in precipitation and influx from surrounding forest soils should be accounted for, when estimating net water-borne C fluxes. There are several publications reporting the C concentrations in waters, but complete water flux estimates for a specific forest area/catchment are rare (S1 Table S3). In practice, the water fluxes are often estimated using models. Current data are too limited for forming explicit views about data applicability. For advancing the knowledge base, it would in any case be useful to include site characteristics and climatic conditions in data collection and reporting. Waterborne C loss on drained peatlands is included in the review by Evans et al. (2016).

5.4 Reporting of key drivers for soil GHG balance

We currently have the understanding that the GHG fluxes from drained organic forest soils generally depend on site nutrient status, size and characteristics of the tree stand, soil temperature, and the WT regime (von Arnold et al., 2005a, 2005b; Ojanen et al., 2010, 2013, 2014). These parameters are not, however, routinely reported in studies quantifying GHG fluxes (Table 2).

In the reviewed data, a surprisingly large proportion of the papers failed to provide information on the basic characteristics of the tree stand (Table 2). Stand volume was the most commonly reported parameter, but still only in 50 % of the studies. The tree stand may influence the soil GHG balance in several ways. A large stand volume lowers the WT through canopy interception of precipitation and evapotranspiration (Sarkkola et al., 2010), which may lead to high CO_2 emissions and a soil sink of CH_4 (Minkkinen et al., 2007a; Ojanen et al., 2010). Different tree species produce litters of different quality (e.g., Straková et al., 2010), which decompose at different rates (e.g., Straková et al. 2012) and have been found to result in differing soil GHG fluxes on mineral soils (e.g., Papen and Butterbach-Bahl, 1999; Butterbach-Bahl et al., 2002). Further, tree stand information may be needed for estimating tree litter inputs if those have not been measured.

The volume of increasingly oxic soil above the WT is important for aerobic decomposition processes producing CO_2. Also for the balance in processes producing and consuming CH_4 in soil, i.e. methanogenesis and methanotrophy, the WT depth influence on oxic and anoxic soil environment is critical. Data provided on WT depth and dynamics were often either lacking, were presented as line graphics only, or were provided for the day of flux monitoring or as average over an arbitrary period. Average annual or seasonal WT were provided in less than half (44 %) of the publications (Table 2). This lack of applicable WT data seriously hampers using this data for meta-analyses and development of more dynamic EFs. Having both mean annual WT and more detailed WT characteristics (e.g., monthly mean and median, quartiles for growing season, frost free period and year) in the publication would allow inspection of soil GHG fluxes in specific conditions, such as comparisons between shallow-drained and deep-drained (WT≤30 cm vs. WT>30 cm from the soil surface; IPCC 2014) conditions.

Less than a third of the publications reported physical (e.g., bulk density) or chemical characteristics (e.g., C, N, and P concentrations, pH) of the soil (Table 2). Moreover, differences in the extent of surface soil layers sampled in the studies reduce data comparability. Chemical quality of the organic matter is known to constrain its decomposition rate (e.g. Straková et al., 2012) and the resulting GHG fluxes. Site type, CN-ratio and bulk density have been found to correlate with heterotrophic CO_2 emission (Ojanen et al., 2010), whereas N_2O flux increases with lower peat CN-ratio (Klemedtsson et al., 2005; Ojanen et al., 2010, 2018; Pärn et al., 2018). To some extent, this soil quality aspect is taken into account in IPCC (2014) Tier 1 level EFs by using 'nutrient-poor' and 'nutrient-rich' site categories. For generalization of GHG fluxes in different site conditions and organic soil types, e.g. by model development, concentrations of the key elements (C, N, P) that are part of the decomposition process should preferably be included in reporting. Sampling depth for determining soil characteristics in drained forest soils should be within the vegetation rooting zone and above the WT. A 0–20 cm soil layer was the most commonly used, and would be an easy standard as it does not require very specific sampling tools like deeper coring. Both the rooting zone and the WT are often deeper than this, however, and a specific study might lead to a better-motivated standard. Also, it should be noted that on long-drained sites, there may be a thick surface layer accumulated from post-drainage tree litter (e.g., Saarinen and Hotanen, 2000; Straková et al. 2010), corresponding to mineral soil forest O and H horizons. Such layer may be difficult to separate from the actual peat soil (Laiho and Pearson, 2016), but should also better not be separated, since it is also affecting the soil GHG fluxes and balance.

All studies commendably reported the coordinates of the sites. This is important since coordinates unambiguously specify site location, and, e.g., allow retrieval of climate data.

5.5 Spatial scale covered with different methods

Spatial scale varies for methods used for GHG and soil C-stock change monitoring from point measurements (peat cores) in inventory methods, to ca. 0.5–1 m^2 in plots monitored by chambers, and further to a flux source area (footprint area) of over thousand square meters in the case of EC monitoring. An increase in the number of spatial replicates, i.e. the number of monitoring points, increases the spatial representativeness in both inventory and gaseous flux monitoring by chambers. In the reviewed soil inventory studies, multiple-site surveys included 1–5 sampling points at each site and 1–3 replicate cores at each sampling point. In studies utilizing chamber techniques, on an average there were 8 replicate flux monitoring points per site for CO_2 (range 2 to 48), 5 for CH_4 (2 to 16) and 5 for N_2O (2 to 16). The size of flux monitoring points varied from 10 cm diameter areas monitored by cylindrical chambers to 60 cm × 60 cm areas enclosed by permanently installed frames. It can be reasoned that one EC tower gives an integrated flux for the whole footprint area, while the representativeness in flux estimates based on chambers can be limited if common site vegetation, soil, or topography characteristics are not covered by the monitoring points, and/or if the areal proportions of these properties are unknown. On the other hand, the closed chamber technique is the best option for studying GHG fluxes from (small-scale) specific soil surfaces, and is often used to complement EC monitoring. In soil inventory methods as well, attention to representative sampling at the study site is important. This can, however, not always be realized, as the repeated sampling needs to follow the initial sampling design of the former study in the past, which has typically been designed for other purposes (Minkkinen and Laine, 1998; Simola et al., 2012).

Sampling procedures are strongly constrained by resources and are often trade-offs between spatial and temporal representativeness. It has not been thoroughly investigated so far, how the spatial and temporal measurement frequencies affect the precision of the estimated soil GHG balance. Such an analysis would be beneficial for structuring measurements towards better landscape-level soil GHG budgets, and such analysis could be based on, e.g., data from sites where both EC and chamber methods have been applied.

5.6 Temporal scale covered with different methods

The temporal scale of GHG flux sampling ranges from continuous sampling with EC, to automated chamber monitoring at varying frequencies, and non-continuous manually performed (day-time) sampling from chambers in intervals of several days to weeks. If GHG flux data collection is continued over several years, the multiple annual soil GHG balance estimates obtained yield a valuable description of the dynamics of the GHG fluxes in varying environmental conditions.

In about half (53 %) of the flux studies GHG monitoring lasted for at least 2 years, and thus nearly half of the publications included data from one-year or shorter monitoring. Most studies (77 %) included also at least some flux monitoring events during cold (winter/frosted soil/snow cover) periods, while a small (7 %) proportion of the studies were restricted to the ‘warm season’. Such ‘seasonal’ flux data collection periods were described, for example, as ‘snow-free period’~~,~~ or ‘warm season’, ~~or a period between two specific dates,~~ which does not provide an unambiguous or easy way to extrapolate the results of the monitoring period to the rest of the year. The IPCC (2014) applied an annualization coefficient of 1.15 for the few ‘seasonal’ GHG flux estimates that excluded the cold period. This coefficient was formed for boreal and subarctic climate regions on the basis of studies in which both warm and cold season GHG fluxes were quantified (Dise, 1992; Aurela et al., 2002; Kim et al., 2007; Alm et al., 1999b; Leppälä et al., 2011). Use of such a fixed coefficient is a source of uncertainty, since i) the length of the (un)monitored period may vary from study to study, and ii) 'seasonal' flux data and data used for forming the coefficient may not come from comparable climatic or site conditions. Although winter-time fluxes form a relatively small proportion of the annual flux (15 % as applied in IPCC, 2014), more year-round field data from a larger number of sites in drained conditions would be beneficial for further modelling of cold season GHG fluxes. This may be especially critical for regions where the frost-free part of the cold season is lengthening, which may well affect the soil GHG balance.

Of the three GHGs dealt with, at least CO_2 flux correlates even with small changes in the topsoil temperatures (e.g., Brændholt et al., 2017). Thus, flux monitoring should cover the diurnal and annual temperature conditions reliably (Sander and Wassmann, 2014), and ideally should be as continuous as possible over seasons. If automated chamber monitoring is not possible, irregular and diurnally imbalanced GHG flux monitoring data should be corrected by soil temperature – GHG flux relation.

Soil inventory methods, in contrast to flux monitoring methods, integrate all soil C-stock changes (C losses as CO_2 and CH_4, water-borne C losses, and new C accumulation from litter inputs) over time, into one soil CO_2~~-C~~ balance estimate. Thus, inventory studies done with sufficient spatial coverage and accuracy in determining the boundaries of the studied layer would give the most robust estimates on soil CO_2~~-C~~ balance, especially when carried out over a period with no major land-use or environmental changes. When several land-use or management changes have taken place during the time period covered by the repeated sampling, the average soil CO_2~~-C~~ balance obtained may not describe any specified condition. Thus, it may be concluded that generally, estimates obtained by flux methods are better suited for GHG inventories aiming to report current fluxes and their dynamic responses to management. Having said that, GHG flux studies on the impacts of typical management events (e.g. thinning, clear cutting, draining improvements) or covering a complete forest rotation cycle (open, maturing and matured stages) are yet to come.

6 Summarizing conclusions on data and further data needs

Basic definitions and guidelines for forming EFs for GHG inventories on organic soils are provided by IPCC (2006, 2014). Datasets used for forming EFs have passed peer reviewing during the publication process, and later evaluation by expert teams, but there are no guidelines for the data content and reporting. Consistent data would increase the applicability of the data for forming more specific Tier 2 EFs, and in other synthesizing assessments. We have identified issues in data content and reporting that have potential to further increase applicability of the data for these purposes. Each data collection method and data type has its strengths and weaknesses that contribute to the final outcome when converted to soil GHG balance estimates. It would be highly beneficial to consider post-publication data use already during reporting by providing details on site characteristics and conditions, relatively easily acquirable measurements that have potential to correlate with GHG fluxes (Table 2). We identified major gaps in data, and provide some development suggestions for future data collection, as follows:

- Lack of applicable data, mostly due to a lack of environmental data, hampers developing more dynamic EFs than mere averages that currently provide the most basic Tier 1 level for GHG inventories.
- More details on the characteristics and conditions at the monitoring sites (Table 2) are necessary to better analyse and synthesize the general dependencies between the GHG fluxes and environmental parameters.
- Consideration given to diurnal and longer term soil temperature impacts on monitored GHG fluxes should be a requirement for manual GHG flux data collection by chambers.

- More empirical cold season GHG flux data is needed for modelling.
- Flux monitoring period restricted to ‘seasonal’ (warm period) monitoring should preferably be ~~dated by~~ started and ended by ~~including~~ defined weather conditions, e.g. soil frost free period or growing season, which would help in ~~extrapolating~~ annualization of the results~~ of the monitoring period to the rest of the year more consistently in modelling~~.
- There is a lack of studies relating GHG fluxes and long-term WT regimes (e.g., shallow drained vs. deep drained conditions) and of unambiguous water table summaries in GHG flux reporting in general.
- A m~~M~~odel needs to be developed for estimating the contribution of autotrophic respiration to the total soil CO_2 emissions in different types of forests at different stages of stand development.
- Work toward reduced uncertainty in production and decomposition rates ~~in~~ of belowground litter types, e.g., fine roots, in different conditions is needed because these data are still only sparsely available and typically not quantified in flux studies.
- There is a need for integrated studies on annual aboveground litter production and decomposition with impact assessment to soil CO_2 balance for the temperate region and for afforested sites, formerly used for peat mining or as cropland.
- GHG and environmental data collection should cover whole forest rotations, by selecting comparable sites representing different stages of stand development for monitoring~~, as most of the current data are primarily snapshots covering a few years at best~~.
- The indirect short- or longer-term impact on GHG fluxes of forest management events, such as clear cutting, thinning and ditch network maintenance, should be quantified.
- CH_4 and N_2O fluxes from trees should be quantified, for different tree species under different WT regimes.
- In future studies of CH_4 and N_2O fluxes, vegetation and litter should be kept intact in the flux measurement points.
- CH_4 and N_2O flux data quantifying emissions from drainage ditches are needed for different site types and ditch conditions. Ditch characteristics should be reported for the monitored sites.
- Current water-borne C-flux data are very limited, and thus there is need for data quantifying these C-fluxes from drained organic forest soils.

Author contributions. All authors planned the research jointly and contributed to data collection. JJ retrieved and reviewed the data, compiled the database, wrote the first draft of the manuscript, compiled supplementary information, coordinated the commenting and revisions that were provided by all authors, and compiled the following versions together with RL. KM drafted the description of inventory method (S2.1), ALo the description of EC method (S2.2.), and PO the description of chamber method (S2.3), which are presented in the Supplement.

Acknowledgements. The study is part of SNS-120 project ‘Anthropogenic greenhouse gas emissions from organic forest soils: improved inventories and implications for sustainable management’ funded by Nordic Forest Research (SNS). SNS-120 is a spin-off of the CAR-ES network also funded by SNS. This study was further supported by the Academy of Finland (grant 289116), Ministry of Education and Research of Estonia (grant PRG-352), Danish Innovation Fund for the Facce-Eragas project INVENT (grant 7108-00003b), University of Helsinki grant to ‘Peatland Ecology Group’, and the European Union through the Centre of Excellence EcolChange in Estonia.

References

Abdalla, M., Hastings, A., Truu, J., Espenberg, M., Mander, Ü., and Smith, P.: Emissions of methane from northern peatlands: a review of management impacts and implications for future management options. Ecol. Evol., 6, 7080–7102, https://doi.org/10.1002/ece3.2469, 2016.

Alm, J., Schulman, L., Walden, J., Nykänen, H., Martikainen, P. J., and Silvola, J.: Carbon balance of a boreal bog during a year with an exceptionally dry summer. Ecology, 80(1), 161–174, https://doi.org/10.2307/176987, 1999.

Askaer, L., Elberling, B., Friborg, T., Jørgensen, C. J., and Hansen, B. U.: Plant-mediated CH_4 transport and C gas dynamics quantified in-situ in a *Phalaris arundinacea*-dominant wetland. Plant Soil, 343, 287–301, https://doi.org/10.1007/s11104-011-0718-x, 2011.

Aurela, M., Laurila, T., and Tuovinen, J.-P.: Annual CO_2 balance of a subarctic fen in northern Europe: Importance of the wintertime efflux, J. Geophys. Res., 107(D21), 4607, https://doi.org/10.1029/2002JD002055, 2002.

Baldocchi, D. D.: Assessing the eddy covariance technique for evaluating carbon dioxide exchange rates of ecosystems: Past, present and future. Global Change Biol., 9(4), 479–492, https://doi.org/10.1046/j.1365-2486.2003.00629.x, 2003.

Ball, T., Smith, K. A., and Moncriff, J. B.: Effect of stand age on greenhouse gas fluxes from a Sitka spruce [*Picea sitchensis* (Bong.) Carr.] chronosequence on a peaty gley soil. Global Change Biol., 13, 2128–2142, https://doi.org/10.1111/j.1365-2486.2007.01427.x, 2007.

Barthelmes, A., Couwenberg, J., Risager, M., Tegetmeyer, C., and Joosten, H.: Peatlands and Climate in a Ramsar context: A Nordic-Baltic Perspective, https://doi.org/10.6027/TN2015-544, 2015.

Bhuiyan, M. R., Minkkinen, K., Helmisaari, H.-S., Ojanen, P., Penttilä, T., and Laiho, R.: Estimating fine-root production by tree species and understorey functional groups in two contrasting peatland forests. Plant Soil, 412(1-2), 299–316, https://doi.org/10.1007/s11104-016-3070-3, 2017.

Bond-Lamberty, B. and Thomson, A.: A global database of soil respiration data. Biogeosciences, 7, 1915–1926, https://doi.org/10.5194/bg-7-1915-2010, 2010.

Bond-Lamberty, B., Wang, C., and Gower, S. T.: A global relationship between the heterotrophic and autotrophic components of soil respiration? Global Change Biol., 10, 1756–1766, https://doi.org/10.1111/j.1365-2486.2004.00816.x, 2004.

Brændholt, A., Steenberg Larsen, K., Ibrom, A., and Pilegaard, K.: Overestimation of closed-chamber soil CO_2 effluxes at low atmospheric turbulence. Biogeosciences, 14, 1603–1616, https://doi.org/10.5194/bg-14-1603-2017, 2017.

Butterbach-Bahl, K., Rothe, A. and H. Papen, H.: Effect of tree distance on N_2O and CH_4-fluxes from soils in temperate forest ecosystems. Plant Soil, 240, 91–103, https://doi.org/10.1023/A:1015828701885, 2002.

Covey, K. R. and Megonigal, J. P.: Methane production and emissions in trees and forests. New Phytol., 222, 35–51, https://doi.org/10.1111/nph.15624, 2019.

Dise, N. B.: Winter fluxes of methane from Minnesota peatlands. Biogeochemistry, 17, 71–83, https://doi.org/10.1007/BF00002641, 1992.

Domisch, T., Finér, L., Laiho, R., Karsisto, M., and Laine, J.: Decomposition of Scots pine litter and the fate of released carbon in pristine and drained pine mires. Soil Biol. Biochem., 32, 1571–1580, https://doi.org/10.1016/S0038-0717(00)00070-5, 2000.

Ernfors, M., Rütting T, and Klemedtsson, L.: Increased nitrous oxide emissions from a drained organic forest soil after exclusion of ectomycorrhizal mycelia. Plant Soil, 343, 161–170, https://doi.org/10.1007/s11104-010-0667-9, 2011.

Ernfors, M., von Arnold, K., Stendahl, J., Olsson, M., and Klemedtsson, L.: Nitrous oxide emissions from drained organic forest soils - an up-scaling based on C:N ratios. Biogeochemistry, 89, 29–41, https://doi.org/10.1007/s10533-008-9190-y, 2008.

Evans, C. D., Renou-Wilson, F., and Strack, M.: The role of waterborne carbon in the greenhouse gas balance of drained and re-wetted peatlands. Aquat. Sci., 78, 573–590, https://doi.org/10.1007/s00027-015-0447-y, 2016.

FAO: Peatlands - Guidance for climate change mitigation by conservation, rehabilitation and sustainable use, Rome, Food and Agriculture Organization of the United Nations, (eds) Joosten H., Tapio-Biström M. -L., Tol S., available at: http://www.fao.org/docrep/015/an762e/an762e.pdf, 2012.

Finér, L., Ohashi, M., Noguchi, K., and Hirano, Y.: Fine root production and turnover in forest ecosystems in relation to stand and environmental characteristics. Forest Ecol. Manag., 262, 2008–2023, https://doi.org/10.1016/j.foreco.2011.08.042, 2011.

Frenzel, P. and Rudolph, J.: Methane emission from a wetland plant: the role of CH_4 oxidation in Eriophorum. Plant Soil, 202, 27–32, https://doi.org/10.1023/A:1004348929219, 1998.

Gauci, V., Gowing, D. J. G., Hornibrook, E. R. C., Davis, J. M., and Dise, N. B.: Woody stem methane emission in mature wetland alder trees. Atmos. Environ., 44, 2157–2160, https://doi.org/10.1016/j.atmosenv.2010.02.034, 2010.

Glagolev, M. V., Chistotin, M. V., Shnyrev, N. A., and Sirin, A. A.: The emission of carbon dioxide and methane from drained peatlands changed by economic use and from natural mires during the summer-fall period (on example of a region of Tomsk oblast). Agrochemistry, 5, 46–58, 2008.

Holz, M., Aurangojeb, M., Kasimir, Å., Boeckx, P., Kuzyakov, Y., Klemedtsson, L., and Rütting, T.: Gross Nitrogen Dynamics in the Mycorrhizosphere of an Organic Forest Soil. Ecosystems 19(2), 284–295, https://doi.org/10.1007/s10021-015-9931-4, 2016.

IPCC: 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Prepared by the National Greenhouse Gas Inventories Programme, Eggleston H. S., Buendia L., Miwa K., Ngara T., and Tanabe K. (eds). Published: IGES, Japan, https://www.ipcc-nggip.iges.or.jp/public/2006gl/, 2006.

IPCC: 2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands, Hiraishi, T., Krug, T., Tanabe, K., Srivastava, N., Baasansuren, J., Fukuda, M., and Troxler, T. G. (eds). Published: IPCC, Switzerland. 353 p., https://www.ipcc-nggip.iges.or.jp/public/wetlands/, 2014.

Jagodzinski, A. M., Ziółkowski, J., Warnkowska, A., and Prais, H.: Tree age effects on fine root biomass and morphology over chronosequences of *Fagus sylvatica*, *Quercus robur* and *Alnus glutinosa* stands. PLoS ONE, 11(2): e0148668, https://doi.org/10.1371/journal.pone.0148668, https://doi.org/10.1371/journal.pone.0148668, 2016.

Joosten, H.: The Global Peatland CO_2 Picture: Peatland Status and Drainage Related Emissions in All Countries of the World (Wetland International, Ede, The Netherlands), https://www.wetlands.org/publications/the-global-peatland-co2-picture/, 2010.

Kasimir, Å., He, H., Coria, J., and Nordén, A.: Land use of drained peatlands: Greenhouse gas fluxes, plant production, and economics. Global Change Biol., 24, 3302–3316, https://doi.org/10.1111/gcb.13931, 2018.

Kasimir-Klemedtsson, Å, Klemedtsson, L., Berglund, K., Martikainen, P., Silvola, J., and Oenema, O.: Greenhouse gas emissions from farmed organic soils: a review. Soil Use Manage., 13, 245–250, https://doi.org/10.1111/j.1475-2743.1997.tb00595.x, 1997.

Kim, Y., Ueyama, M., Nakagawa, F., Tsunogai, U., Harazono, Y., and Tanaka, N.: Assessment of winter fluxes of CO_2 and CH_4 in boreal forest soils of central Alaska estimated by the profile method and the chamber method: a diagnosis of methane emission and implications for the regional carbon budget. Tellus, 59B, 223–233, https://doi.org/10.1111/j.1600-0889.2006.00233.x, 2007.

Klemedtsson, L., von Arnold, K., Weslien, P., and Gundersen, P.: Soil CN ratio as a scalar parameter to predict nitrous oxide emissions. Global Change Biol., 11, 1142–1147, https://doi.org/10.1111/j.1365-2486.2005.00973.x, 2005.

Kokkonen, N., Laine, A., Laine, J., Vasander, H., Kurki, K., Gong, J., and Tuittila, E.-S.: Responses of peatland vegetation to 15-year water level drawdown as mediated by fertility level. J. Veg. Sci., https://doi.org/10.1111/jvs.12794, 2019.

Komulainen, V.-M., Nykänen, H., and Martikainen, P. J., Laine, J.: Short-term effect of restoration on vegetation change and methane emissions from peatlands drained for forestry in southern Finland. Can. J. Forest Res., 28(3), 402–411, https://doi.org/10.1139/x98-011, 1998.

Komulainen, V.-M., Tuittila, E.-S., Vasander, H., and Laine, J.: Restoration of drained peatlands in southern Finland: initial effects on vegetation change and CO_2 balance. J. Appl. Ecol., 36, 634–648, https://doi.org/10.1046/j.1365-2664.1999.00430.x, 1999.

Krüger, J. P., Alewell, C., Minkkinen, K., Szidat, S., and Leifeld, J.: Calculating carbon changes in peat soils drained for forestry with four different profile-based methods. Forest Ecol. Manag., 381, 29–36, https://doi.org/10.1016/j.foreco.2016.09.006, 2016.

Kulmala, M.: Build a global Earth observatory. Nature, 553, 21–23, https://doi.org/10.1038/d41586-017-08967-y, 2018.

Laiho, R. and Pearson, M.: Surface peat and its dynamics following drainage - do they facilitate estimation of carbon losses with the C/ash method? Mires Peat, 17, Article 08, 1–19, https://doi.org/10.19189/MaP.2016.OMB.247, 2016.

Laiho, R., Vasander, H., Penttilä, T., and Laine, J.: Dynamics of plant-mediated organic matter and nutrient cycling following water-level drawdown in boreal peatlands. Global Biogeochem. Cy., 17(2), 1053, https://doi.org/10.1029/2002GB002015, 2003.

Laiho, R., Bhuiyan, R., Straková, P., Mäkiranta, P., Badorek, T., and Penttilä, T.: Modified ingrowth core method plus infrared calibration models for estimating fine root production in peatlands. Plant Soil, 385, 311–327, https://doi.org/10.1007/s11104-014-2225-3, 2014.

~~Laiho, R., Vasander, H., Penttilä, T., and Laine, J.: Dynamics of plant-mediated organic matter and nutrient cycling following water-level drawdown in boreal peatlands. Global Biogeochem. Cy., 17(2), 1053, https://doi.org/10.1029/2002GB002015, 2003.~~

Larmola, T., Tuittila, E.-S., Tiirola, M., Nykänen, H., Martikainen, P. J., Yrjälä, K., Tuomivirta, T., and Fritze, H.: The role of Sphagnum mosses in the methane cycling of a boreal mire. Ecology, 91(8), 2356–2365, https://doi.org/10.1890/09-1343.1, 2010.

Lehtonen, A., Palviainen, M., Ojanen, P., Kalliokoski, T., Nöjd, P., Kukkola, M., Penttilä, T., Mäkipää, R., Leppälammi-Kujansuu, J., and Helmisaari. H.-S.: Modelling fine root biomass of boreal tree stands using site and stand variables. Forest Ecol. Manag., 359, 361–369, https://doi.org/10.1016/j.foreco.2015.06.023, 2016.

Leppälä, M., Laine, A.M., and Tuittila, E.-S.: Winter carbon losses from a boreal mire succession sequence follow summertime patterns in carbon dynamics. Suo, 62(1), 1–11, www.suo.fi/pdf/article9874.pdf, 2011.

Lohila, A., Laurila, T., Aro, L., Aurela, M., Tuovinen, J.-P., Laine, J., Kolari, P., and Minkkinen, K.: Carbon dioxide exchange above a 30-year-old Scots pine plantation established on organic-soil cropland. Boreal Environ. Res.., 12, 141–157, www.borenv.net/BER/pdfs/ber12/ber12-141.pdf, 2007.

Lohila, A., Minkkinen, K., Aurela, M., Tuovinen, J.-P., Penttilä, T., and Laurila, T.: Greenhouse gas flux measurements in a forestry-drained peatland indicate a large carbon sink. Biogeosciences, 8, 3203–3218, https://doi.org/10.5194/bg-8-3203-2011, 2011.

Lupikis, A. and Lazdins, A.: Soil carbon stock changes in transitional mire drained for Forestry in Latvia: a case study. Res. Rural Dev., 1, 55–61, https://doi.org/10.22616/rrd.23.2017.008, 2017.

Machacova, K., Papen, H., Kreuzwieser, J., and Rennenberg, H.: Inundation strongly stimulates nitrous oxide emissions from stems of the upland tree *Fagus sylvatica* and the riparian tree *Alnus glutinosa*. Plant Soil, 364, 287–301, https://doi.org/10.1007/s11104-012-1359-4, 2013.

Meyer, A., Tarvainen, L., Nousratpour, A., Björk, R. G., Ernfors, M., Grelle, A., Kasimir Klemedtsson, Å., Lindroth, A., Räntfors, M., Rütting, T., Wallin, G., Weslien, P., and Klemedtsson, L.: A fertile peatland forest does not constitute a major greenhouse gas sink. Biogeosciences, 10, 7739–7758, https://doi.org/10.5194/bg-10-7739-2013, 2013.

Minkkinen, K. and Laine, J.: Long-term effect of forest drainage on the peat carbon stores of pine mires in Finland. Can. J. For. Res., 28, 1267–1275, https://doi.org/10.1139/x98-104, 1998.

Minkkinen, K. and Laine, J.: Vegetation heterogeneity and ditches create spatial variability in methane fluxes from peatlands drained for forestry. Plant Soil, 285, 289–304, https://doi.org/10.1007/s11104-006-9016-4, 2006.

Minkkinen, K., Vasander, H., Jauhiainen, S., Karsisto, M., and Laine, J.: Post-drainage changes in vegetation composition and carbon balance in Lakkasuo mire, Central Finland. Plant Soil, 207, 107–120, https://doi.org/10.1023/A:1004466330076, 1999.

Minkkinen, K., Laine, J., Shurpali, N. J., Mäkiranta, P., Alm, J., and Penttilä, T.: Heterotrophic soil respiration in forestry-drained peatlands. Boreal Environ. Res., 12, 115–126, www.borenv.net/BER/pdfs/ber12/ber12-115.pdf, 2007b.

Minkkinen, K., Penttilä, T., and Laine, J.: Tree stand volume as a scalar for methane fluxes in forestry-drained peatlands in Finland. Boreal Environ. Res., 12, 127–132, www.borenv.net/BER/pdfs/ber12/ber12-127.pdf, 2007a.

Minkkinen, K., Byrne, K.A., and Trettin, C.: Climate impacts of peatland forestry. In: Strack, M. (ed.), *Peatlands and climate change*, International Peat Society, Jyväskylä, Finland, 98–122, http://www.peatsociety.org/peatlands-and-peat/peatlands-and-climate-change, 2008.

~~Minkkinen, K., Laine, J., Shurpali, N. J., Mäkiranta, P., Alm, J., and Penttilä, T.: Heterotrophic soil respiration in forestry-drained peatlands. Boreal Environ. Res., 12, 115–126, www.borenv.net/BER/pdfs/ber12/ber12-115.pdf, 2007b.~~

~~Minkkinen, K., Penttilä, T., and Laine, J.: Tree stand volume as a scalar for methane fluxes in forestry-drained peatlands in Finland. Boreal Environ. Res., 12, 127–132, www.borenv.net/BER/pdfs/ber12/ber12-127.pdf, 2007a.~~

~~Minkkinen, K., Vasander, H., Jauhiainen, S., Karsisto, M., and Laine, J.: Post-drainage changes in vegetation composition and carbon balance in Lakkasuo mire, Central Finland. Plant Soil, 207, 107–120, https://doi.org/10.1023/A:1004466330076, 1999.~~

Natchimuthu, S., Wallin, M. B., Klemedtsson, L., and Bastviken, D.: Spatio-temporal patterns of stream methane and carbon dioxide emissions in a hemiboreal catchment in Southwest Sweden. Sci. Rep., 7, Article Number: 39729, https://doi.org/10.1038/srep39729, 2017.

Nieminen, M., Koskinen, M., Sarkkola, S., Laurén, A., Kaila, A., Kiikkilä, O., Nieminen, T.M., and Ukonmaanaho, L.: Dissolved organic carbon export from harvested peatland forests with differing site characteristics. Water Air Soil Poll., 225, 181, https://doi.org/10.1007/s11270-015-2444-0, 2015.

Oertel, C., Matschullat, J., Zurba, K., Zimmermann, F., and Erasmi, S.: Greenhouse gas emissions from soils—A review. Geochemistry, 76, 327–352, https://doi.org/10.1016/j.chemer.2016.04.002, 2016.

~~Ojanen, P., Lehtonen, A., Heikkinen, J., Penttilä, T., and Minkkinen, K.: Soil CO_2 balance and its uncertainty in forestry-drained peatlands in Finland. Forest Ecol. Manag., 325, 60–73, https://doi.org/10.1016/j.foreco.2014.03.049, 2014.~~

Ojanen, P., Minkkinen, K., Alm, J., and Penttilä, T.: Soil – atmosphere CO_2, CH_4 and N_2O fluxes in boreal forestry-drained peatlands. Forest Ecol. Manag., 260, 411–421, https://doi.org/10.1016/j.foreco.2010.04.036, 2010.

Ojanen, P., Minkkinen, K., and Penttilä, T.: The current greenhouse gas impact of forestry-drained boreal peatlands. Forest Ecol. Manag., 289, 201–208, https://doi.org/10.1016/j.foreco.2012.10.008, 2013.

Ojanen, P., Lehtonen, A., Heikkinen, J., Penttilä, T., and Minkkinen, K.: Soil CO_2 balance and its uncertainty in forestry-drained peatlands in Finland. Forest Ecol. Manag., 325, 60–73, https://doi.org/10.1016/j.foreco.2014.03.049, 2014.

Ojanen, P., Minkkinen, K., Alm, J., and Penttilä, T.: Corrigendum to "Soil–atmosphere CO_2, CH_4 and N_2O fluxes in boreal forestry-drained peatlands" [For. Ecol. Manage., 260, 411–421, 2010], https://doi.org/10.1016/j.foreco.2018.01.020, 2018.

~~Ojanen, P., Minkkinen, K., Alm, J., and Penttilä, T.: Soil – atmosphere CO_2, CH_4 and N_2O fluxes in boreal forestry-drained peatlands. Forest Ecol. Manag., 260, 411–421, https://doi.org/10.1016/j.foreco.2010.04.036, 2010.~~

~~Ojanen, P., Minkkinen, K., and Penttilä, T.: The current greenhouse gas impact of forestry-drained boreal peatlands. Forest Ecol. Manag., 289, 201–208, https://doi.org/10.1016/j.foreco.2012.10.008, 2013.~~

Päivänen, J.: The bulk density of peat and its determination. Silva Fenn., 3(1), 1–19, https://doi.org/10.14214/sf.a14569, 1969.

Papen, H. and Butterbach-Bahl, K.: 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. J. Geophys. Res.., 1041, 18487–18504, https://doi.org/10.1029/1999JD900293, 1999.

Pärn, J., Verhoeven, J., Butterbach-Bahl K.,, Dise, N., Ullah, S., Aasa, A., Egorov, S., Espenberg, M., Järveoja, J., Jauhiainen, J., Kasak, K., Klemedtsson, L., Kull, A., Laggoun-Défarge, F., Lapshina, E., Lohila, A., Lõhmus, K., Maddison, M., Mitsch, W., Müller, C., Niinemets, Ü., Osborne, B., Pae, T., Salm, J.-O., Sgouridis, F., Sohar, K., Soosaar, K., Storey, K., Teemusk, A., Tenywa, M., Tournebize, J., Truu, J., Veber, G., Villa, J., Zaw, S., and Mander, Ü.: Nitrogen-rich organic soils under warm well-drained conditions are global nitrous oxide emission hotspots. Nature Commun., 9, 1135, https://doi.org/10.1038/s41467-018-03540-1, 2018.

Formatted: English (Canada)

Formatted: English (Canada)

Formatted: English (Canada)

Pavelka, M., Acosta, M., Kiese, R., Altimir, N., Brümmer, C., Crill, P., Darenova, E., Fuß, R., Gielen, B., Graf, A., Klemedtsson, L., Lohila, A., Longdoz, B., Lindroth, A., Nilsson, M., Jiménez, S. M., Merbold, L., Montagnani, L., Peichl, M., Pihlatie, M., Pumpanen, J., Ortiz, P. S., Silvennoinen, H., Skiba, U., Vestin, P., Weslien, P., Janous, D., and Kutsch, W.: Standardisation of chamber technique for CO_2, N_2O and CH_4 fluxes measurements from terrestrial ecosystems. Int. Agrophys., 32, 569–587, https://doi.org/10.1515/intag-2017-0045, 2018.

Peacock, M., Ridley, L. M., Evans, C. D., and Gauci, V.: Management effects on greenhouse gas dynamics in fen ditches. Sci. Total Environ., 578, 601–612, https://doi.org/10.1016/j.scitotenv.2016.11.005, 2017.

Petrescu, A. M. R., Lohila, A., Tuovinen, J.-P., Baldocchi, D. D., Desai, A. R., Roulet, N., Vesala T., Dolman, A. J., Oechel, W. C., Marcolla, B., Friborg, T., Rinne, J., Matthes J. C., Merbold, L., Meijide, A., Kiely, G., Sottocornola, M., Sachs, T., Zona, D., Varlagin, A., Lair, D. Y. F, Veenendaal, E., Parmentier, F .-J. W., Skiba, U., Lund, M., Hensen, A., van Huissteden, J., Flanagan, L. B., Shurpali, N. J., Grünwald, T., Humphreys, E. R., Jackowicz-Korczynski, M., Aurela, M. A, Laurila, T., Grüning, C., Corradi, C. A. R., Schrier-Uijls, A. P., Christensen, T. R., Tamstorf, M. P., Mastepanov, M., Martikainen, P. J., Verma, S. B., Bernhofer, C., and Cescatti, A.: The uncertain climate footprint of wetlands under human pressure. P. Natl. Acad. Sci. USA, 112(15), 4594–4599, https://doi.org/10.1073/pnas.1416267112, 2015.

Pitkänen, A., Turunen, J., Tahvanainen, T., and Simola, H.: Carbon storage change in a partially forestry-drained boreal mire determined through peat column inventories. Boreal Environ. Res., 18, 223–234, www.borenv.net/BER/pdfs/ber18/ber18-223.pdf, 2013.

Post, W. M., Emanuel, W. R., Zinke, P. J., and Stangenberger, A. G.: Soil carbon pools and world life zones. Nature, 298, 156–159, https://doi.org/10.1038/298156a0, 1982.

Post, W. M., Pastor, J., Zinke, P. J., and Stangenberger, A. G.: Global patterns of soil nitrogen storage. Nature, 317, 613–616, https://doi.org/10.1038/317613a0, 1985.

Raghoebarsing, A. A., Smolders, A. J. P., Schmid, M. C., Rijpstra, W. I. C., Wolters-Arts, M., Derksen, J., Jetten, M. S. M., Schouten, S., Damste~~é~~, J. S. S., Lamers, L. P. M., Roelofs, J. G. M., Op den Camp, H. J. M., and Strous, M.: Methanotrophic symbionts provide carbon for photosynthesis in peat bogs. Nature, 436, 1153–1156, https://doi.org/10.1038/nature03802, 2005.

Repola, J.: Biomass equations for birch in Finland. Silva Fenn., 42(4), 605–624, https://doi.org/10.14214/sf.236, 2008.

Repola, J.: Biomass equations for Scots pine and Norway spruce in Finland. Silva Fenn., 43(4), 625–647, https://doi.org/10.14214/sf.184, 2009.

Rusch, H., and Rennenberg, H.: Black alder (*Alnus Glutinosa* (L.) Gaertn.) trees mediate methane and nitrous oxide emission from the soil to the atmosphere. Plant Soil, 201, 1–7, https://doi.org/10.1023/A:1004331521059, 1998.

Saarinen, M. and Hotanen. J-P.: Covariation between raw humus layer and vegetation on peatlands drained for forestry in western Finland (in Finnish, summary and graphics in English). Suo, 51, 227–242, www.suo.fi/pdf/article9807.pdf, 2000.

Saarnio, S., and Silvola, J.: Effects of increased CO_2 and N on CH_4 efflux from a boreal mire: a growth chamber experiment. Oecologia, 119, 349–356, https://doi.org/10.1007/s004420050795, 1999.

Sander, B. O. and Wassmann, R.: Common practices for manual greenhouse gas sampling in rice production: a literature study on sampling modalities of the closed chamber method. Greenhouse Gas Measurement and Management~~GHGMM~~, 4, 1–13, https://doi.org/10.1080/20430779.2014.892807, 2014.

Sarkkola, S., Hökkä, H., Koivusalo, H., Nieminen, M., Ahti, E., Päivänen, J., and Laine, J.: Role of tree stand evapotranspiration in maintaining satisfactory drainage conditions in drained peatlands. Can. J. Forest Res., 40, 1485–1496, https://doi.org/10.1139/X10-084, 2010.

Silc, T. and Stanek, W.: Bulk density estimation of several peats in northern Ontario using the von Post humification scale. Can. J. Soil Sci., 51, 138–141, https://doi.org/10.4141/cjss77-010, 1977.

Simola, H., Pitkänen, A., and Turunen, J.: Carbon loss in drained forestry peatlands in Finland, estimated by re-sampling peatlands surveyed in the 1980s. Eur. J. Soil Sci., 63, 798–807, https://doi.org/10.1111/j.1365-2389.2012.01499.x, 2012.

Sirin, A. A., Suvorov, G. G., Chistotin, M. V., and Glagolev, M. V.: Values of methane emission from drainage ditches. Environmental Dynamics and Climate Change, 3, 1–10, https://doi.org/10.17816/edgcc321-10, 2012.

Statistics Finland: Greenhouse gas emissions in Finland 1990 to 2017. National Inventory Report under the UNFCCC and the Kyoto protocol. Submission to the European Union. Statistics Finland, https://unfccc.int/documents/194637, 2019.

Strack, M., Waddington, J. M., Bourbonniere, R. A., Buckton, L., Shaw, K., Whittington, P., and Price, J. S.: Effect of water table drawdown on peatland dissolved organic carbon export and dynamics. Hydrol. Process., 22, 3373–3385, https://doi.org/10.1002/hyp.6931, 2008.

Strack, M., Waller, M. F., and Waddington, J. M.: Sedge succession and peatland methane dynamics: A potential feedback to climate change. Ecosystems, 9, 278–287, https://doi.org/10.1007/s10021-005-0070-1, 2006

~~Straková P., Penttilä T., Laine J., and Laiho R.: Disentangling direct and indirect effects of water table drawdown on above- and belowground plant litter decomposition: Consequences for accumulation of organic matter in boreal peatlands. Global Change Biol., 18, 322–335, https://doi.org/10.1111/j.1365-2486.2011.02503.x, 2012.~~

Straková, P., Anttila, J., Spetz, P., Kitunen, V., Tapanila, T., and Laiho, R.: Litter quality and its response to water level drawdown in boreal peatlands at plant species and community level. Plant Soil, 335, 501–520, https://doi.org/10.1007/s11104-010-0447-6, 2010.

Straková, P., Niemi, R. M., Freeman, C., Peltoniemi, K., Toberman, H., Heiskanen, I., Fritze, H., and Laiho, R.: Litter type affects the activity of aerobic decomposers in a boreal peatland more than site nutrient and water table regimes. Biogeosciences, 8, 2741–2755, https://doi.org/10.5194/bg-8-2741-2011, 2011.

Straková P., Penttilä T., Laine J., and Laiho R.: Disentangling direct and indirect effects of water table drawdown on above- and belowground plant litter decomposition: Consequences for accumulation of organic matter in boreal peatlands. Global Change Biol., 18, 322–335, https://doi.org/10.1111/j.1365-2486.2011.02503.x, 2012.

Subke, J.-A., Inglima, I., and Cotrufo, M. F.: Trends and methodological impacts in soil CO_2 efflux partitioning: A meta-analytical review. Global Change Biol., 12, 921–943, https://doi.org/10.1111/j.1365-2486.2006.01117.x, 2006.

Tubiello, F. N., Biancalani, R., Salvatore, M., Rossi, S., and Conchedda, G. : A Worldwide assessment of greenhouse gas emissions from drained organic soils. Sustainability, 8, 371, https://doi.org/10.3390/su8040371, 2016.

Tuomi, M., Laiho, R., Repo, A., and Liski, J.: Wood decomposition model for boreal forests. Ecol. Model., 222(3), 709–718, https://doi.org/10.1016/j.ecolmodel.2010.10.025, 2010.

Ťupek, B., Mäkipää R., Heikkinen J., Peltoniemi M., Ukonmaanaho L., Hokkanen T., Nöjd P., Nevalainen, S., Lindgren M., and Lehtonen A.: Foliar turnover rates in Finland – comparing estimates from needle-cohort and litterfall-biomass methods. Boreal Environ. Res., 20, 283–304, www.borenv.net/BER/pdfs/ber20/ber20-283.pdf, 2015.

Urbanová, Z., Picek, T., and Bárta, J.: Effect of peat re-wetting on carbon and nutrient fluxes, greenhouse gas production and diversity of methanogenic archaeal community. Ecol. Eng., 37, 1017–1026, https://doi.org/10.1016/j.ecoleng.2010.07.012, 2011.

Uri, V., Kukumägi, M., Aosaar, J., Varik, M., Becker, H., Morozov, G., and Karoles, K.: Ecosystems carbon budgets of differently aged downy birch stands growing on well-drained peatlands. Forest Ecol. Manage., 399, 82–93, https://doi.org/10.1016/j.foreco.2017.05.023, 2017.

von Arnold, K., Nilsson, M., Hånell, B., Weslien, P., and Klemedtsson, L.: Fluxes of CO_2, CH_4 and N_2O from drained organic soils in deciduous forests. Soil Biol. Biochem., 37, 1059–1071, https://doi.org/10.1016/j.soilbio.2004.11.004, 2005a.

von Arnold, K., Weslien, P., Nilsson, M., Svensson, B. H., and Klemedtsson, L.: Fluxes of CO_2, CH_4 and N_2O from drained coniferous forests on organic soils. Forest Ecol. Manage., 210, 239–254, https://doi.org/10.1016/j.foreco.2005.02.031, 2005b.

Wang, X., Wang, C., and Bond-Lamberty, B.: Quantifying and reducing the differences in forest CO_2-fluxes estimated by eddy covariance, biometric and chamber methods: A global synthesis. Agric. For. Meteorol., 247, 93–103, https://dx.doi.org/10.1016/j.agrformet.2017.07.023, 2018.

Weiss, R., Alm, J., Laiho, R., and Laine, J.: Modelling moisture retention in peat soils. Soil Sci. Soc. Am. J., 62, 305–313, https://doi.org/10.2136/sssaj1998.03615995006200020002x, 1998.

Welch, B., Gauci, V., and Sayer, E. J.: Tree stem bases are sources of CH_4 and N_2O in a tropical forest on upland soil during the dry to wet season transition. Global Change Biol., 25, 361–372, https://doi.org/10.1111/gcb.14498, 2019.

Wilson, D., Blain, D., Couwenberg, J., Evans, C. D., Murdiyarso, D., Page, S. E., Renou-Wilson, F., Rieley, J. O., Sirin, A., Strack, M., and Tuittila, E.-S.: Greenhouse gas emission factors associated with rewetting of organic soils. Mires Peat, 17, Article 4, 1–28, https://doi.org/10.19189/MaP.2016.OMB.222, 2016.

Table 1. Number of sites and publications estimating annual soil balances of CO_2, CH_4 and N_2O for drained organic forest soils in boreal and temperate zones in this study and in the IPCC (2014) Wetlands Supplement.

GHG	Method	This study		IPCC 2014[1]	
		n–sites	n–publications[2]	n–sites	n–publications[2]
CO_2	Inventory	45	5	-	-
	Flux (chambers)	85	19	-	-
	Flux (eddy covariance)	3	3	-	-
	Total	133	27	133	13
CH_4	Flux (chambers)	101	32	143	22
N_2O	Flux (chambers)	61	31	131	20

[1] Data from the IPCC (2014) Wetlands Supplement Tables 2.1, 2.3 and 2.5.
[2] Some publications include estimates for multiple GHGs.

Table 2. Potential GHG flux drivers, and respective information availability for the monitored sites in the reviewed ~~published~~ 52 soil GHG flux ~~studies~~ publications on drained organic forest soils.

	Measure	Papers (1)	Possible relation in soil GHG fluxes ~~in~~ to larger data analysis
Management	Time of site draining	38 (73 %)	Describes land management duration as (forestry) drained site. May affect GHG fluxes since length of time during which efficient aerobic decomposition of surface peat has taken place may affect peat characteristics.
	Management history described	52 (100 %)	Draining improvements, fertilization, thinning, selective logging and other operations conducted in known time periods in the past may have influence on soil GHG balances.
	Ditch spacing and characteristics described	1 (2 %)	Indicates draining conditions and is useful for assessing ditch GHG emissions.
	Ditch maintenance condition described	0 ~~(0 %)~~	_ " _
Tree stand	Volume Basal area Stem number Stand age	26 (50 %) 5 (10 %) 7 (13 %) 16 (31 %) (2)	Describes forest above-ground C stocking and litter input capacity, correlated with WT through rain interception and evapotranspiration.
	Species composition	52 (100 %)	Deciduous / conifer dominance, or mixed forest structure may produce aboveground litter types with differing characteristics and thereby influence decomposition. Different species may also have differing transpiration rates, affecting WT.
	Productivity	1 (2 %)	Classification based on expected tree growth potential to 'typical' and 'low productivity ' sites, where the latter includes sites with characteristically low forest stand stocking and growth due to nutrient deficiency, nutrient imbalance or hydrological conditions (despite draining), and this has impact on soil GHG balances (as in IPCC 2014).
Site and soil	Site type (4)	50 (96 %)	Similar sites likely have similarities in GHG dynamics, and thus useful to group sites into similar categories (i.e. by vegetation type or soil nutrient status etc.).
	Ground vegetation composition and cover	32 (62 %)	Indicator of soil fertility, moisture and shading conditions, and important for decomposition activity in soil.
	Presence and proportions of different plant functional types in the ground vegetation	0 (5)	Simple classification based on ground vegetation dominance by shrubs / herbs / grasses likely indicate soil nutrient status, thereby possibly influencing decomposition, and this classification can be practical for grouping sites into similar categories.
	Pre-drainage ombrotrophy or minerotrophy	52 (100 %)	In general, peats of ombrotrophic and minerotrophic sites differ in soil quality and decomposition activity.
	Soil type	52 (100 %)	Peat and other organic soil types (gleysols, muck etc.) differ by formation and characteristics, which may influence soil GHG balances.
	Organic soil thickness (3)	29 (56 %)	Shallow organic soil may be impacted by minerogenic waters and mineral soil underneath, and thus have higher decomposition activity than deeper organic soils.
	Soil bulk density	26 (60 %)	High bulk density values may indicate presence of mineral substrates, non-peat soils and/or possible disturbance in organic soil layer, which may influence soil GHG balances. Bulk density is also correlated with the degree of decomposition (e.g., Päivänen, 1969; Silc and Stanek, 1977) and water retention characteristics of the peat (e.g., Weiss et al., 1998), which may affect the GHG fluxes.
	pH C	30 (58 %) 18 (35 %)	Topsoil nutrient status and pH may influence vegetation composition, rate of C sequestration by tree stand, litter quality,

	N C/N-ratio P	24 (46 %) 24 (46 %) 14 (27 %)	and decomposition rate. Peat layers for which data have been given also vary. A common standard could be 0–20 cm layer.
Drainage	Average WT levels in soil: • Annual • Warm season [6] • Cold season [6]	 23 (44 %) 4 (8 %) 0	WT level has major impact on decomposition processes and CH_4 production and oxidation rates, and thus basic WT characteristics would be useful to summarize in numeric form, e.g., monthly mean and median, and also quartiles for growing season, frost free period and year.
Climate and weather	Average air temperatures: • Annual • July • February • Monitoring period [6]	 34 (65 %) 9 (17 %) 9 (17 %) 0	Air temperature has impact on litter production and topsoil decomposition processes. Inter-annual differences in air temperatures are potentially useful for modeling and detecting weather extremes during measurements.
	Annual air temperature sum	7 (13 %)	Describes the temperature climate and annual conditions in a cumulative manner.
	Average soil temperatures: • Annual • Monitoring period [6]	 5 (10 %) 0	Topsoil temperatures influence especially aerobic decomposition processes and are influenced by diurnal air temperature, and temperatures below the WT influence anaerobic decomposition processes. Measurements at 5 cm and 30 cm were most commonly used and could serve as standards.
	Precipitation: • Annual • Warm season [6] • Cold season [6]	 32 (62 %) 0 0	Cumulated precipitation may influence decomposition processes in soil (form a proxy for soil wetness or dryness).

(1) Number (and proportion) of papers included in the database that provide the specified information
(2) For planted sites time of planting given with precision from year to a decade
(3) Specific or average values for the monitoring site soil characteristics, not minimum/maximum or a range
(4) Site type based on defined generally applied classification system
(5) Not countable from the papers in unambiguous way for comparisons
(6) Not countable from the papers in unambiguous way as the data collection periods were described, for example, as 'snow-free period', 'warm season', or as a period between two dates

845 **Figure 1: CO_2, CH_4 and N_2O fluxes and mass transfer components contributing to soil C-stock changes in a forest ecosystem on drained organic soil, as in IPCC (2014). Arrows indicate flux/transfer direction.**

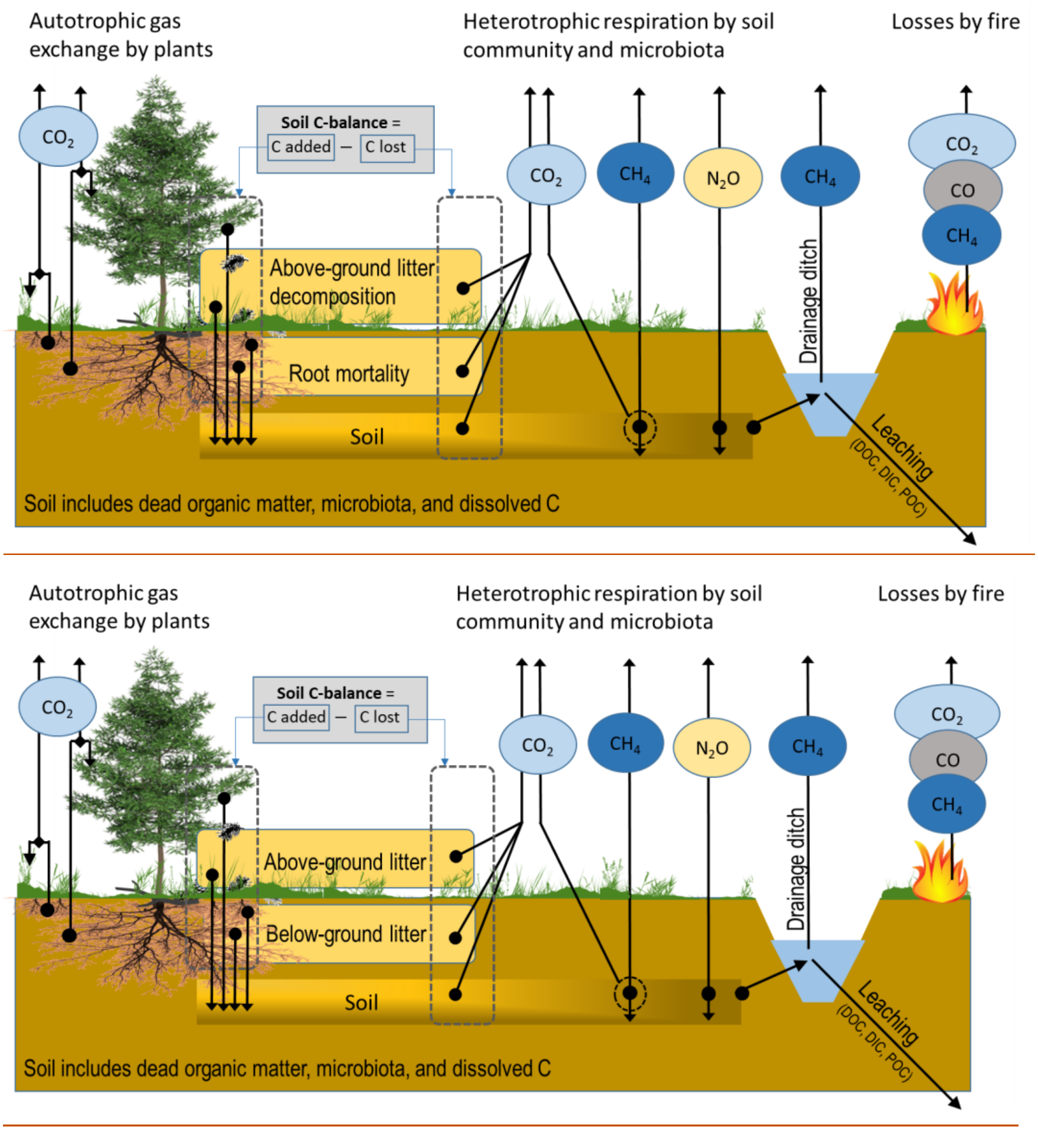
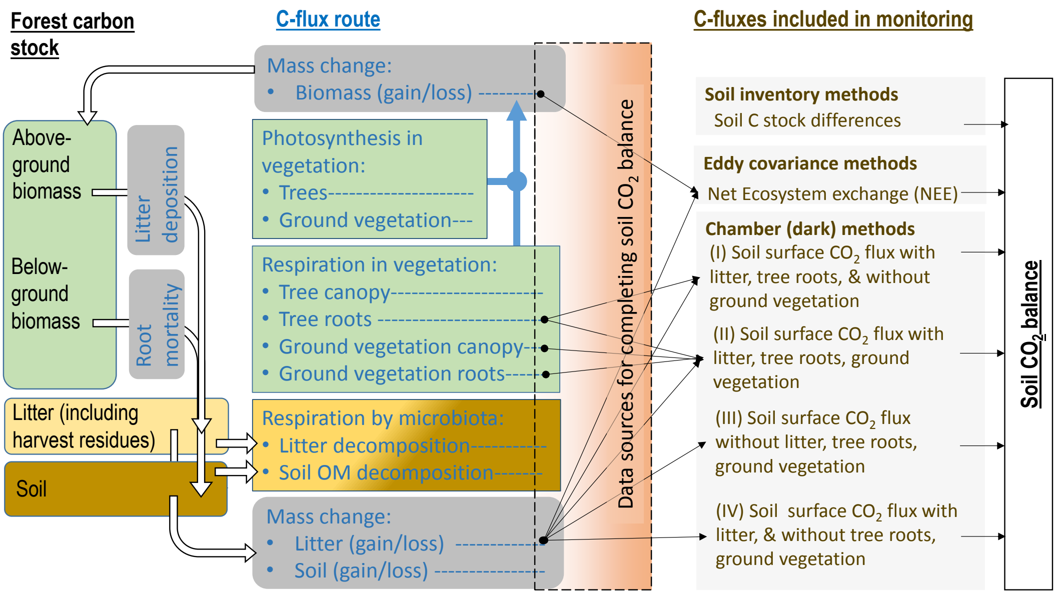


Figure 2: Forest C stock, processes resulting in changes in the dead organic matter C stock in soil, C fluxes typically monitored (see also S1 Table 1), and complementary data sources needed for forming soil CO_2 balance estimates (black arrows) in incomplete flux monitoring setups, according to IPCC (2014). Numbers I-IV next to monitoring setups by dark chambers refer to respective studies listed in S1 Table 1. Water-borne C losses and losses by fires are excluded from the figure.



S1. Data materials

Reference numbers used in Table S1 and S2~~Publications in this study~~; (1) Ball et al., 2007; (2) Brumme et al., 1999; (3) Christiansen et al., 2012; (4) Danevčič et al., 2010; (5) Eickenscheidt et al., 2014; (6) Ernfors et al., 2011; (7) Glenn et al., 1993; (8) Holz et al., 2016; (9) Huttunen et al., 2003a; (10) Klemedtsson et al., 2010; (11) Komulainen et al., 1998; (12) Korkiakoski et al., 2017; (13) Lohila et al., 2007; (14) Lohila et al., 2011; (15) Lupikis and Lazdins 2017; (16) Maljanen et al., 2003a; (17) Maljanen et al., 2003b; (18) Maljanen et al., 2006; (19) Maljanen et al., 2010b; (20) Maljanen et al., 2012; (21) Maljanen et al., 2014; (22) Mander et al., 2008; (23) Martikainen et al., 1992; (24) Martikainen et al., 1993; (25) Martikainen et al., 1995b; (26) McNamara et al., 2008; (27) Meyer et al., 2013; (28) Minkkinen and Laine 1998b; (29) Minkkinen and Laine 2006; (30) Minkkinen et al., 1999; (31) Minkkinen et al., 2007b; (32) Moilanen et al., 2012; (33) Mustamo et al., 2016; (34) Mäkiranta et al., 2007; (35) Nykänen et al., 1998; (36) Ojanen et al., 2010; (37) Ojanen et al., 2013; (38) Pihlatie et al., 2004; (39) Pitkänen et al., 2013; (40) Regina et al., 1998; (41) Saari et al., 2009; (42) Salm et al., 2012; (43) Sikström et al., 2009; (44) Silvola et al., 1996; (45) Simola et al., 2012; (46) Uri et al., 2017; (47) Weslien et al., 2009; (48) von Arnold et al., 2005a; (49) Väisänen et al., 2013; (50) Yamulki et al., 2013; (51) Komulainen et al., 1999; (52) von Arnold et al. 2005b

Table S1. Publications having data with high potential for quantification of annual soil CO_2 balance ~~(CO_2 and CO_{2eq})~~ for drained organic forest soils in boreal and temperate climate regions. 'Method' identifies whether flux monitoring was implemented by soil inventory methods, eddy covariance method, or chamber methods. The numbers I–IV next to 'CH' in this column denote for chamber methods the C-flux sources included in typical data collection setups shown in Fig. 2. 'C-measures in monitoring' lists the variables included in data collection by eddy covariance method and dark and light chamber methods that can be used for forming an annual soil CO_2 balance estimate. 'Additional requirements for forming annual soil CO_2 balance estimate' lists the extra measurements and data needs for forming the estimate.

Climate region	Method	C-measures in monitoring	Additional requirements for forming annual soil CO_2 balance estimate	Notes	Reference / (reference number~~r in this study~~)
Temperate	CH (II)	TOT_{Grs}	Subtracting tree root respiration. Subtracting ground vegetation dark respiration. Subtracting above- and belowground litter production rates.	Annual flux estimate is based on median values. Ground vegetation contributions in the flux and to the soil C-stock change are not considered in the estimate. Whole year flux monitoring.	Salm et al., 2012 / (42)
Temperate	CH (II)	TOT_{Grs}	Subtracting tree root respiration. Subtracting ground vegetation dark respiration. Subtracting above- and belowground litter production rates.	Ground vegetation contributions in the flux and to the soil C-stock change are not considered in the estimate. Whole year flux monitoring.	Sikström et al., 2009 / (43)
Temperate	CH (IV)	S_{rs}; $L_{in/t.o}$; $FR_{in/t.o}$; Di	-	Trenched plots. Estimates annualized in the	Uri et al., 2017 / (46)

				publication.	
Temperate	CH (II)	TOT_{Grs}; NPP_{tr}	Subtracting above- and belowground litter production rates.	Forest floor vegetation contributions assumed to be negligible. Value from literature is used the for the tree root respiration contributions. Some of the values in reporting are available with a higher precision in von Arnold et al. 2005c. Whole year flux monitoring.	von Arnold et al., 2005b / (52)
Temperate	CH (II)	TOT_{Grs}; NPP_{tr}	Subtracting ground vegetation dark respiration. Subtracting above- and belowground litter production rates.	Ground vegetation contributions in the flux and to the soil C-stock change are not considered in the estimate. Value from literature is used for the tree root respiration contributions. Whole year flux monitoring.	von Arnold et al., 2005a / (48)
Temperate	CH (II)	TOT_{Grs}; Di	Subtracting tree root respiration. Subtracting ground vegetation dark respiration. Subtracting above- and belowground litter production rates.	Ground vegetation contributions in the flux and to the soil C-stock change are not considered in the estimate. Whole year flux monitoring.	Yamulki et al., 2013 / (50)
Temperate	CH (II)	TOT_{Grs}	Subtracting ground vegetation dark respiration. Subtracting above- and belowground litter production rates.	Value from literature is used for the tree root respiration contributions. Ground vegetation contributions in the flux and to the soil C-stock change are not considered in the estimate. Whole year flux monitoring.	Klemedtsson et al., 2010 / (10)
Temperate	CH (II)	TOT_{Grs}	Subtracting above- and belowground litter production rates.	Annual flux estimate is based on median values (data in all other publications are average values). Autotrophic respiration contributions are based on literature values. Ground vegetation contributions in the flux and to the soil C-stock change are not considered in the estimate. Gas sampling procedures unclear.	Mander et al., 2008 / (22)
Temperate	CH (I)	TOT_{Grs}; Di	Subtracting tree root respiration.	Ground vegetation is assumed to be absent in closed canopy sites. Study includes also automated chamber data collection. Estimate annualized in the publication.	Ball et al., 2007 / (1)
Temperate	EC, CH	NEE; NPP_{tr};	-	Trenched plots included.	Meyer et al.,

	(IV)	G_{rs}; S_{rs}; L_{Ars}; Di		Two calculus approaches in the publication. Assumed equal annual production and decomposition of litter from both leaves and roots. Whole year flux monitoring.	2013 / (27)
Temperate	INV	-	-	-	Lupikis and Lazdins 2017 / (15)
Boreal	CH (IV)	P_{rs}; $L_{in/to}$; Di	-	Multiple values from literature are used in the estimate. Whole year flux monitoring.	Väisänen et al., 2013 / (49)
Boreal	CH (II, III, IV)	A_{GV}; GV_{rs}; Di	Annualization needed.	Trenched plots. Transparent and dark chambers.	Komulainen et al., 1999 / (51)
Boreal	CH (III)	S_{rs}; Di	Incorporating above- and belowground litter production and decomposition rates.	Trenched plots. Whole year flux monitoring.	Minkkinen et al., 2007b / (31)
Boreal	CH (III)	S_{rs}; Di	Incorporating above- and belowground litter production and decomposition rates.	Trenched plots. Whole year flux monitoring.	Moilanen et al., 2012 / (32)
Boreal	CH (III)	G_{rs}; Di	Subtracting tree root respiration. Annualization needed.	-	Mustamo et al., 2016 / (33)
Boreal	CH (II, IIII, IV)	TOT_{Grs}; S_{rs}; RS_{prop}; Di	-	Trenched and non-trenched plots. Estimate annualized in the publication.	Ojanen et al., 2010 / (36)
Boreal	CH	$L_{in/t.o}$; $FR_{in/t.o}$; Di	Data from Ojanen et al., 2010	-	Ojanen et al., 2013 / (37)
Boreal	CH (I)	G_{rs}; L_{Ars}; Di	Subtracting tree root respiration.	Whole year flux monitoring.	Silvola et al., 1996 / (44)
Boreal	CH (III)	S_{rs}; Di	Incorporating above- and belowground litter production and decomposition rates.	Trenched plots. Whole year flux monitoring.	Mäkiranta et al., 2007 / (34)
Boreal	EC	NEE; TOT_{Ers}; NPP_{tr}; Di	-	Whole year flux monitoring.	Lohila et al., 2011 / (14)
Boreal	EC, (CH)	NEE; NPP_{tr}; S_{rs};Di	-	Peat heterotrophic emission value for the site from Mäkiranta et al. 2007. Whole year flux monitoring.	Lohila et al., 2007 / (13)
Boreal	INV	-	-	-	Minkkinen and Laine 1998b / (28)
Boreal	INV	-	-	-	Minkkinen et al., 1999 / (30)

Boreal	INV	-	-	-	Pitkänen et al., 2013 / (39)
Boreal	INV	-	-	-	Simola et al., 2012 / (45)

CH = flux monitoring by dark and/or light chambers, EC = eddy covariance method, INV = ~~organic~~ soil inventory method.
TOT_{Grs} = heterotrophic respiration in soil and litter, and autotrophic respiration contributions from ground vegetation above and belowground parts and from tree roots (i.e. ground level total respiration).
TOT_{Ers} = heterotrophic respiration in soil and litter, and autotrophic respiration contributions from above and belowground parts of ground vegetation and trees (i.e. ecosystem level total respiration).
G_{rs} = Heterotrophic respiration in soil (excluding recently deposited litter contribution) and autotrophic contributions from tree roots.
S_{rs} = Heterotrophic respiration in soil (excluding recently deposited litter contribution).
L_{Ars} = Heterotrophic respiration in litter on the soil surface.
RS_{prop} = Proportion between autotrophic respiration from vegetation (trees) and heterotrophic respiration from soil decomposition.
GV_{rs} = Ground vegetation autotrophic respiration contributions from above and belowground parts.
TR_{rs} = Tree root autotrophic respiration contributions.
$L_{in/t.o}$ = Litter input and ~~turnover~~ decomposition on the soil surface.
$FR_{in/t.o}$ = Fine root production and ~~turnover~~ decomposition~~by trees and ground vegetation~~.
NEE = Net ecosystem CO_2 exchange.
NPP = Net primary production in ecosystem.
NPP_{tr} = Net primary production in trees.
A_{GV} = Gross primary CO_2 assimilation in ground vegetation.
Di = Flux estimate takes into account diurnal temperature variation by data modelling or by diurnal flux monitoring.

Table S2. Publications allowing quantification of annual soil CH_4 or N_2O balance for drained organic forest soils in boreal and temperate climate regions. All studies were conducted using the chamber method.

GHG measured	Climate region	Additional requirements for forming annual soil GHG balance estimate, and notes	Reference / (reference number~~ in this study~~)
CH_4, N_2O	Temperate	Diurnal. Estimates annualized in the publication. Ground vegetation is assumed to be absent in closed canopy sites.	Ball et al., 2007 / (1)
N_2O	Temperate	Whole year flux monitoring. Vegetation retained on the soil surface.	Brumme et al., 1999 / (2)
CH_4, N_2O	Temperate	Whole year flux monitoring. Vegetation likely retained on the soil surface.	Christiansen et al., 2012 / (3)
CH_4, N_2O	Temperate	Whole year flux monitoring. Vegetation removed from the soil surface.	Danevčič et al., 2010 / (4)
N_2O	Temperate	Whole year flux monitoring. Vegetation retained on the soil surface.	Eickenscheidt et al., 2014 / (5)
N_2O	Temperate	Whole year flux monitoring. Vegetation removed or partly removed, roots trenched or roots and mycelia trenched in monitoring setups.	Ernfors et al., 2011 / (6)
CH_4	Temperate	Annualization needed. Vegetation likely retained on the soil surface.	Glenn et al., 1993 / (7)
N_2O	Temperate	Whole year flux monitoring. Roots trenched or roots and mycelia trenched, and ground vegetation likely removed or partly removed in monitoring setups.	Holz et al., 2016 / (8)
CH_4, N_2O	Temperate	Whole year flux monitoring. Vegetation likely retained on the soil surface.	Klemedtsson et al., 2010 / (10)
CH_4, N_2O	Temperate	Whole year flux monitoring. Vegetation likely retained on the soil surface.	Mander et al., 2008 / (22)
CH_4	Temperate	Whole year flux monitoring. Vegetation	McNamara et al., 2008 / (26)

		likely retained on the soil surface.	
CH_4, N_2O	Temperate	Whole year flux monitoring. Vegetation likely retained on the soil surface.	Salm et al., 2012 / (42)
CH_4, N_2O	Temperate	Whole year flux monitoring. Vegetation retained on the soil surface.	Sikström et al., 2009 / (43)
CH_4, N_2O	Temperate	Whole year flux monitoring. Vegetation retained on the soil surface.	von Arnold et al., 2005a / (49)
CH_4, N_2O	Temperate	Whole year flux monitoring. Vegetation retained on the soil surface.	von Arnold et al., 2005b / (52)
CH_4, N_2O	Temperate	Whole year flux monitoring. Vegetation likely retained on the soil surface.	Weslien et al., 2009 / (47)
CH_4, N_2O	Temperate	Whole year flux monitoring. Vegetation retained on the soil surface.	Yamulki et al., 2013 / (50)
CH_4, N_2O	Boreal	Annualization needed. Vegetation likely retained on the soil surface.	Huttunen et al., 2003 / (9)
CH_4	Boreal	Annualization needed. Ground vegetation retained or removed in monitoring setups.	Komulainen et al., 1998 / (11)
CH_4	Boreal	Whole year flux monitoring by automated chambers. Vegetation retained on the soil surface.	Korkiakoski et al., 2017 / (12)
CH_4, N_2O	Boreal	Whole year flux monitoring. Vegetation likely retained on the soil surface.	Lohila et al., 2011 / (14)
CH_4, N_2O	Boreal	Whole year flux monitoring. Vegetation retained on the soil surface	Mäkiranta et al., 2007 / (34)
CH_4	Boreal	Whole year flux monitoring. Vegetation retained on the soil surface.	Maljanen et al., 2003a / (16)
N_2O	Boreal	Whole year flux monitoring. Vegetation retained on the soil surface.	Maljanen et al., 2003b / (17)
CH_4, N_2O	Boreal	Vegetation likely retained on the soil surface. Estimates annualized in the publication Maljanen et al., (2010c).	Maljanen et al., 2006 / (18)
CH_4, N_2O	Boreal	Whole year flux monitoring. Vegetation retained on the soil surface.	Maljanen et al., 2010b / (19)
N_2O	Boreal	Whole year flux monitoring. Vegetation likely retained on the soil surface.	Maljanen et al., 2012 / (20)
CH_4, N_2O	Boreal	Whole year flux monitoring. Vegetation retained on the soil surface.	Maljanen et al., 2014 / (21)
CH_4	Boreal	Annualization needed. Vegetation retained on the soil surface.	Martikainen et al., 1992 / (23)
N_2O	Boreal	Whole year flux monitoring. Vegetation likely retained on the soil surface.	Martikainen et al., 1993 / (24)
CH_4	Boreal	Whole year flux monitoring. Vegetation likely retained on the soil surface.	Martikainen et al., 1995b / (25)
CH_4, N_2O	Boreal	Diurnal. Whole year flux monitoring. Vegetation removed from the soil surface.	Meyer et al., 2013 / (27)
CH_4	Boreal	Diurnal. Whole year flux monitoring. Vegetation retained on the soil surface.	Minkkinen and Laine, 2006 / (29)
CH_4, N_2O	Boreal	Whole year flux monitoring. Vegetation retained on the soil surface.	Mustamo et al., 2016 / (33)
CH_4	Boreal	Annualization needed. Vegetation retained on the soil surface.	Nykänen et al., 1998 / (35)
CH_4, N_2O	Boreal	Diurnal. Annualized in the publication. Vegetation retained on the soil surface	Ojanen et al., 2010 / (36); corrigendum Ojanen et al., 2018
N_2O	Boreal	Annualized in the publication. Vegetation likely retained on the soil surface.	Pihlatie et al., 2004 / (38)
N_2O	Boreal	Annualized in the publication. Vegetation retained on the soil surface.	Regina et al., 1998 / (40)
CH_4, N_2O	Boreal	Whole year flux monitoring. Vegetation retained on the soil surface.	Saari et al., 2009 / (41)
CH_4, N_2O	Boreal	Whole year flux monitoring. Vegetation	Väisänen et al., 2013 / (49)

		retained on the soil surface.	
Diurnal = Flux estimate takes into account diurnal temperature variation, incorporated in the estimate by modelling or by diurnal flux data collection Annualization needed = Annualization coefficient should be applied to the seasonal flux estimate presented in the publication.			

Table S3. Publications quantifying C losses in drainage waters from drained organic forest soils in boreal and temperate regions.

Climate region	Reported	Reference
Boreal	DOC, POC, TOC	Kolka et al., 1999
Boreal	TOC	Kortelainen et al., 1997
Boreal	TOC	Kortelainen et al., 2006
Boreal	TOC	Mattsson et al., 2003
Boreal	DOC	Nieminen et al., 2015
Boreal	TOC	Rantakari et al., 2010
Boreal	DOC	Sallantaus, 1993
Boreal	TOC	Sarkkola et al., 2009

Table S4. Examples of common reasons resulting in exclusion of a reviewed publication from the study.

Reason for exclusion	Reference
Ground vegetation autotrophic respiration from above- and/or below ground parts remains as unknown proportion of the monitored CO_2 flux.	Glenn et al., 1993; Coles and Yavitt, 2004; Badorek et al., 2011; Hommeltenberg et al., 2014
Soil inventory method is poorly described and the applied reference type in peat profile is currently considered unreliable for the purpose (e.g., Laiho and Pearson 2016).	Braekke, 1987; Braekke and Finér, 1991
A closed chamber technique using soda lime as CO_2 absorbing agent is currently considered unreliable for field studies. Undrained forest.	Byrne and Farrell, 2005
Low number of monitoring events and several assumed parameter values are used (Hargreaves et al., 2003), or low number of flux monitoring events and information concerning the number of replicates on the site is missing (Maljanen et al., 2001).	Maljanen et al., 2001[1]; Hargreaves et al., 2003
Flux monitoring setups focusing on immediate impacts of experimental ash addition on soil GHG fluxes (part of the data are excluded).	Klemedtsson et al., 2010; Moilanen et al., 2012
Another study based on inventory method (Minkkinen et al., 1999) includes the same sites and additional sites.	Krüger et al., 2016
Values are published in another publication, or data is from a model based on data published in other publications.	Martikainen et al., 1995b[1]; Laine et al., 1996[1]; von Arnold et al., 2005c; Ernfors et al., 2008; Laurila et al., 2007[1]; Minkkinen et al., 2007a[1]
Undrained sites or site not specified to be on organic soil.	Moore and Knowles, 1990[1]; Maljanen et al., 2010a[1]
Only means for daily fluxes on sites are presented.	Regina et al., 1996[1]
[1] Publications included in the IPCC (2014) emission factor database	

S2. Soil GHG monitoring methods in a nutshell.

S2.1. Inventory methods

The most simple and direct method to estimate ecosystem / soil C loss or gain is to measure the C stocks twice and calculate the difference (e.g., Simola et al., 2012). To measure the peat C stock, one simply needs to take volumetric soil samples from the peat surface down to the bottom of the peat basin, or to a clear and stable reference layer that can be found at consecutive sampling times, and that preferably lies below the layer in which changes may have occurred. Next, one determines the peat bulk density (dry mass per sample volume) and C concentration, and multiplying these yields the C stock in a defined soil column. Then why is this method not used more, if it is so simple and easy? The reason is that in drained organic forest soils under cool climate the annual changes are very small compared to the total C stock (e.g., on average c. 0.1 kg C m^{-2} yr^{-1} soil stock change vs. 75 kg C m^{-2} total soil stock in 273 plots studied in the boreal zone (Minkkinen and Laine, 1998b)), and thus relatively small errors in determining the stocks result in relatively large errors in the C stock change estimates. Errors can be caused firstly by uneven or poorly defined bottom; the method requires an even bottom and a sharp border between peat and the underlying soil. The relative significance of this error increases with decreasing depth of the peat deposit. Further errors may be caused by heterogeneity in the composition of peat, and disturbance caused by earlier sampling. Thus, decadal time series and many replicate samples are needed to reliably monitor the change. Different modifications of the inventory method have been used (A, B, C, and D below), often aiming at capturing the total impact of drainage and land-use change, but in some studies aiming to simply cover a change between time points. Reasoning behind different modifications may include, e.g., some missing data in the initial sampling, e.g., C concentration of the samples.

(A) Subsidence measurements combined with oxidation estimates. Subsidence is the term for a decline in peat surface elevation relative to an earlier state (e.g., Laiho and Pearson, 2016). Subsidence of the peat surface after drainage results first mainly from physical compaction (or collapse) of the soil matrix, and later mainly from soil organic matter decomposition and oxidation to CO_2. Thus, the measurement of subsidence can be used to estimate the soil C balance, if it is monitored based on elevation-fixed bench marks, e.g. fixed poles reaching the mineral soil below the peat deposit, where the peat surface position at the onset of measurements has been marked (Hutchinson, 1980). Further, the share of mass loss due to oxidation in the change in bulk density causing the subsidence should be known. In temperate agricultural soils oxidation has been estimated to cause 70–80% of long-term subsidence, which is typically 1–2 cm yr^{-1} (Oleszczuk et al., 2008), allowing rough estimation of soil C loss. Similar estimates have not been published for drained organic forest soils, and since the ecosystem dynamics and management are very different from agricultural lands, the same oxidation percentages cannot be assumed.

(B) Combined estimation of subsidence and changes in peat bulk density and C concentration (e.g. Minkkinen and Laine, 1998a,b; Lupikis and Lazdins, 2017). The accuracy of this method is dependent on the accuracy of the subsidence measurement and the estimation of the pre-drainage/initial-sampling bulk density. The range of peat bulk densities in undrained and forestry-drained conditions, c. 40–200 kg m^{-3} (e.g., Minkkinen and Laine, 1998a) equal to 0.4–2 kg C m^{-2} in 1-cm peat layer. The subsidence estimate of Minkkinen and Laine (1998b) was based on measuring the peat depth in the same spots before and after drainage. The pre-drainage bulk density is often not available, and Minkkinen and Laine (1998b) used material from reference sites on undrained peatlands to estimate that. The reference sites represented the same vegetation types as the drained sites reportedly were before drainage. However, some random variation is inevitably involved in the use of reference sites (e.g., Laiho and Pearson, 2016).

(C) Comparisons of peat C-stocks on drained and undrained sides of the same peatland over synchronous reference layers in the peat profile (Minkkinen et al., 1999; Krüger et al., 2016; Pitkänen et al., 2013 used the same approach but sampled the full peat deposit). The determination of the synchronous layer can be based on, e.g., pollen profiles or synchronous layers of charcoal or tephra. If the reference layer is well-defined and located below the peat layer where drainage-induced changes may be expected to have taken place, and it can be verified that the areas on both sides of the ditch were similar before drainage, this method may result in the most reliable estimates of post-drainage C-stock changes among the different versions of the inventory method. If the time since drainage is known, the C-stock change may be transformed to an average change per year. It should be noted, however, that the difference between the undrained and drained parts depends, in addition to the drainage-induced changes in the drained side, also on the extent that C accumulation has taken place in the undrained side during the post-drainage period.

(D) Comparisons based on the proportions of ash or other elements versus C in peat layers of corresponding drained and undrained peatlands (e.g. Kareksela et al., 2015; Krüger et al., 2016). This method is based on the fact that when peat decomposes, it loses C but the main constituent of ash, Si, as well as some other elements are retained. Thus, an increase in ash/C quotient in peat can be used to estimate the C loss. This method involves in practise several uncertainties that were recently reviewed by Laiho and Pearson (2016), who concluded that the results from this method for drained organic forest soils are highly suspect.

The advantage of inventory methods is that they produce long-term averages, based on different years with different weather conditions, and should thus give robust estimates of soil C balance. Also, they involve all processes and C forms affecting the balance. At the same time they are, however, estimates of the past, and may not be applicable in the changing climate, or when forest structure changes due to aging or forest operations. Also, they add little knowledge on ecosystem processes and cannot be used for modelling C dynamics. Although the inventory methods are basically simple, they become complex and laborious when some data are missing, and have to be estimated from other data or models. For example, space for time comparisons between different sites (method types 'C' and 'D') assume that the sites were identical prior to draining, which can introduce some unknown and potentially large errors to those estimates (Laiho and Pearson, 2016). Consequently, the uncertainty of the estimates remains high. Thus a large number of sites / samples per site are needed to get reliable estimates. Various kinds of assumptions in these methods also introduce bias into the estimates, the quantity of which is difficult or impossible to determine.

S2.2. Flux methods – Eddy covariance method

The EC method offers direct, area-integrating and continuous monitoring of the biosphere-atmosphere exchange of GHGs (Baldocchi, 2003; Foken et al., 2012). The method is based on a high-frequency monitoring of the studied gas concentration in the air, and simultaneous measurement of the vertical wind speed using a 3-D anemometer. The flux is obtained as the covariance of these two variables typically averaged over a 30-min period. The method involves a requirement of horizontally homogeneous ground surface on the measurement area (of several hectares) (Munger et al., 2012). The measurements are conducted in the atmosphere above the ecosystem and the method provides an estimate of the net gas exchange between the atmosphere and the whole ecosystem. This net ecosystem exchange (NEE) includes thus the uptake and release from both soil and vegetation, i.e. trees in the case of forests. However, by installing the instruments below the canopy, the EC system can also be used to study below-canopy exchange (Launiainen et al., 2005).

From the measured net ecosystem exchange, it is possible to estimate also the total ecosystem respiration (R_{tot}) and gross primary production (GPP) by employing simple response functions. Typically at least temperature (air or soil) and photosynthetically active radiation are utilized as explaining variables, but sometimes also water-table level, relative humidity, and variables describing plant phenology are used (e.g., Aurela et al., 2002; Reichstein et al., 2005; Lohila et al., 2011). The partitioning is based on the fact that during the night-time when the photosynthetic apparatus is not active, NEE equals R_{tot}, which can then be parameterized using air or soil temperature. Then using this R_{tot} parameterisation during the day it is possible to derive GPP from the daytime NEE values (NEE = GPP – R_{tot}).

Although the EC method produces continuous NEE data, gaps in the data are unavoidable in long data series and gap-filling based on, e.g., the response functions discussed above is needed. One important advantage in continuous gaseous flux monitoring by EC methods is the potential to detect short-term responses in the system to the environmental conditions, which at best form a detailed temporal description at both diurnal (day and night fluxes) and annual (all year round) timescales.

To estimate annual soil CO_2 balance using EC data, in addition to the total annual NEE, annual increase in biomass (forest vegetation growth in above and below ground parts) is needed. These data are usually available at a much rougher scale than the gas exchange data. The annual increase in aboveground tree biomass C may be based on consecutive tallies of the tree diameters in sample plots representing the footprint area, application of general allometric functions for biomass fractions, and application of measured or average estimates for the C concentrations in the different biomass fractions. A similar procedure may be used for the coarse root system C, if allometric functions are available.

Syntheses on flux data in various ecosystems worldwide (Barba et al., 2018; Wang et al., 2018) find EC monitoring sensitivity to differ by ecosystems, where forest systems in northern areas appear to form challenging environments for integrating diurnal and seasonal fluxes generally due to footprint related issues, below-canopy horizontal advection, and issues arising from correlation between temperature and respiration.

S2.3 Flux methods – Chamber techniques

Closed chamber measurement techniques can be roughly divided into dark and transparent chamber methods. Dark chamber measurements capture the gas exchange between the soil and the atmosphere, and also ground vegetation and tree root respiration, if the vegetation or tree roots have not been removed. Transparent chambers also include ground vegetation CO_2 assimilation through photosynthesis, but trees, the main component of forest vegetation, usually do not fit into a chamber. Chamber methods are used because the equipment is relatively inexpensive and portable chambers enable extensive studies covering even dozens of study sites (e.g., Ojanen et al., 2010). On the negative side, the accuracy of chamber measured gas fluxes is not obvious: chamber and collar design, deployment time and flux calculation method may greatly and systematically affect the results (e.g., Pumpanen et al., 2004; Christiansen et al., 2011; Lai et al., 2012; Koskinen et al., 2014; Jovani-Sancho et al., 2017; Korkiakoski et al., 2017). Potential CO_2 flux sources included in the monitoring are multiple: heterotrophic respiration from decomposition in soil and in litter, including CO_2 from possible CH_4 production and oxidation processes in the soil, and autotrophic respiration of vegetation above and below ground. Thus, it is highly recommended to carefully consider methodological issues before starting chamber measurements, so that at least the most obvious sources of bias can be avoided.

When estimation of annual soil CO_2 balance is aimed at, dark chambers are typically used to estimate the CO_2 efflux from the forest floor. If measurement plots are treated to include only heterotrophic respiration resulting from litter and SOM decomposition (as in Ojanen et al., 2013; Uri et al., 2017), annual soil CO_2 balance can be estimated by subtracting annualized heterotrophic CO_2 flux (R_{het}) from litter production (L), Eq. (1):

Soil CO_2 balance = L – $\mathbf{R_{het}}$. (1)

While this is a simple equation, it involves two problems: 1) to include only heterotrophic respiration, ground vegetation must be removed from the plot and the incoming tree roots cut by trenching. This is technically easy. However, trenching will cause firstly an additional CO_2 flux from the cut-off roots that start decomposing, and may also cause priming of decomposition due to the extra input of organic matter that also involves labile C compounds as a readily exploitable energy source (Kuzyakov et al., 2000). Still further, the production of new belowground litter and root exudates stops and this can influence the decomposition activity over time (Subke et al., 2006), even though research into this impact has not found clear effects in peat soils (Basiliko et al., 2012; Linkosalmi et al., 2015). Also soil moisture can be affected as root water uptake is prevented by trenching. The exact magnitude of these artefacts is hard to estimate. 2) Aboveground litter production can be directly measured, but the estimation of belowground litter input depends on estimates of root and rhizome production or turnover that are currently highly uncertain (Ojanen et al., 2014; Bhuiyan et al., 2017).

Both these problems related to Eq. (1) above could in principle be avoided by basing the estimation of soil CO_2 balance on forest floor respiration (R_{floor}) measured from untreated plots, i.e. total soil respiration (see Ojanen et al., 2012), Eq. (2):

Soil CO_2 balance = $GPP_{trees} + GPP_{floor} - R_{trees\_above} - \mathbf{R_{floor}} - \Delta C_{biom}$, (2)

where GPP_{trees} is gross primary production of tree stand, GPP_{floor} is gross primary production of forest floor vegetation, R_{trees_above} is tree stand above ground respiration, and ΔC_{biom} is annual change in carbon stocks of biomass.

It is possible to directly measure all these components of gross primary production (GPP) and respiration (R). But in practice this leads to complicated modelling resulting in a vast amount of work and uncertain estimates even at a single study site (see Ojanen et al., 2012).

As there are a lot of published data on R_{floor} (or R_{floor} without ground vegetation) (see Supplement 1), it would be possible to extract R_{het} from these data by subtracting the autotrophic respiration of tree roots and ground vegetation (R_{aut}) from R_{floor}, Eq. (3):

$R_{het} = R_{floor} - R_{aut}$. (3)

However, to estimate R_{aut}, we are back at the complicated modelling of a poorly known flux. A shortcut would be to assume that R_{het} is a constant share A of R_{floor} (e.g., von Arnold et al., 2005a, b), Eq. (4):

$R_{het} = A\ R_{floor}$. (4)

This is again technically easy, and there are several publications where this proportion is estimated in drained organic forest soils (e.g., Silvola et al., 1996: Komulainen et al., 1999; Minkkinen et al., 2007b; Ojanen et al., 2010; Moilanen et al., 2012; Meyer et al., 2013), as well as a literature review for forests in different climate zones (Bond-Lamberty et al., 2004). But as R_{floor} from drained peat includes a varying amount of decomposition from pre-drainage peat and as this amount is not directly constrained by the productivity of current vegetation, any constant proportion from literature applied to other study sites forms a source of uncertainty. So we are again back at Eq. (1).

Soil CO_2 flux measurements can also be performed using transparent chambers on vegetated surfaces. The system is operated in such way that a measurement session with transparent chamber is followed by a session with dark chamber, the latter by covering the transparent chamber by material impenetrable to light. These measurements produce net exchange and total respiration ~~is method produces total daytime respiration and~~

~~nighttime respiration~~ of the soil and of the vegetation inside the chamber. The gross assimilation of the vegetation enclosed in the chamber can be quantified from the measurements if the proportion of heterotrophic emission from soil (R_{het}) is known and there are no other flux sources present (e.g., roots extending into chamber area from outside). In forests on drained organic soils, use of this method for estimating soil CO_2 balance is complicated because; i) emissions from soil decomposition processes must be quantified by a different monitoring setup, ii) autotrophic respiration of tree roots must be excluded from monitored surfaces (e.g., by trenching), and iii) C-balance in belowground tree litter deposition and decomposition rates must be quantified by other ways – all these issues (i–iii) are examined in the previous sections (see also Ojanen et al., 2012). The value of transparent chamber method in forests on organic soils is mainly in the potential to estimate ground vegetation C-balance.

Chamber methods typically involve CO2 efflux from several forest floor sources, and to form annual soil CO_2 balance estimates one needs to carefully consider which sources are involved. If the efflux includes decomposition of annual litter inputs, the amount of these inputs needs to be estimated. If litter is removed from the measurement plots, the rates of both the input and decomposition of litter need to be estimated. As big fluxes are subtracted from each other to achieve typically (in boreal-temperate conditions) an order of magnitude smaller balance, great care should be taken to accurately estimate these fluxes to avoid bias in the annual soil CO_2 balance (Ojanen et al., 2012, 2014).

References

Aurela, M., Laurila, T., and Tuovinen, J.-P.: Annual CO_2 balance of a subarctic fen in northern Europe: Importance of the wintertime efflux, J. Geophys. Res., 107(D21), 4607, https://doi.org/10.1029/2002JD002055, 2002.

Badorek, T., Tuittila, E.-S., Ojanen, P., and Minkkinen, K.: Forest floor photosynthesis and respiration in a drained peatland forest in southern Finland. Plant Ecol. Divers., 4, 227–241, https://doi.org/10.1080/17550874.2011.644344, 2011.

Baldocchi, D. D.: Assessing the eddy covariance technique for evaluating carbon dioxide exchange rates of ecosystems: Past, present and future. Global Change Biol., 9(4), 479–492, https://doi.org/10.1046/j.1365-2486.2003.00629.x, 2003.

Ball, T., Smith, K. A., and Moncriff, J. B.: Effect of stand age on greenhouse gas fluxes from a Sitka spruce [*Picea sitchensis* (Bong.) Carr.] chronosequence on a peaty gley soil. Global Change Biol., 13, 2128–2142, https://doi.org/10.1111/j.1365-2486.2007.01427.x, 2007.

Barba, J., Cueva, A., Bahn, M., Barron-Gafford, G. A., Bond-Lamberty, B., Hanson, P. J., Jaimes, A., Kulmala, L., Pumpanen, J., Scott, R. L., Wohlfahrt, G., and Vargas, R.: Comparing ecosystem and soil respiration: Review and key challenges of tower-based and soil measurements, Agric. For. Meteorol., 249, 434–443, , 2018.

Basiliko, N., Stewart, H., Roulet N. T., and Moore, T. R.: Do Root Exudates Enhance Peat Decomposition? Geomicrobiol. J., 29(4), 374–378, https://doi.org/10.1080/01490451.2011.568272, 2012.

Bhuiyan, M. R., Minkkinen, K., Helmisaari, H.-S., Ojanen, P., Penttilä, T., and Laiho, R.: Estimating fine-root production by tree species and understorey functional groups in two contrasting peatland forests. Plant Soil, 412(1-2), 299–316, https://doi.org/10.1007/s11104-016-3070-3, 2017.

Bond-Lamberty, B., Wang, C., and Gower, S. T.: A global relationship between the heterotrophic and autotrophic components of soil respiration? Global Change Biology, 10: 1756–1766, https://doi.org/10.1111/j.1365-2486.2004.00816.x, 2004.

Braekke, F. H.: Nutrient relationships in forest stands: effects of drainage and fertilization on surface peat layers. Forest Ecol. Manag., 21, 269–284, https://doi.org/10.1016/0378-1127(87)90048-X, 1987.

Braekke, F. H. and Finér L.: Fertilization effects on surface peat of pine bogs. Scand. J. For. Res., 6, 433–449, https://doi.org/10.1080/02827589109382681, 1991.

~~Braekke, F. H.: Nutrient relationships in forest stands: effects of drainage and fertilization on surface peat layers. Forest Ecol. Manag., 21, 269–284, https://doi.org/10.1016/0378-1127(87)90048-X, 1987.~~

Brumme, R., Borker, W., and Finke, S.: Hierarchical control on nitrous oxide emissions in forest ecosystems. Global Biogeochem. Cyc., 13, 1137–1148, https://doi.org/10.1029/1999GB900017, 1999.

Byrne, K. A. and Farrell, E. P.: Carbon dioxide emissions in blanket peatland in Ireland. Forestry, 78, 217–227, https://doi.org/10.1093/forestry/cpi020, 2005.

Christiansen, J. R., Korhonen, J. F. J., Juszczak, R., and Giebels, M.: Assessing the effects of chamber placement, manual sampling and headspace mixing on CH_4 fluxes in a laboratory experiment. Plant Soil, 343: 171–185, https://doi.org/10.1007/s11104-010-0701-y, 2011.

Christiansen, J. R., Vesterdal, L., and Gundersen, P.: Nitrous oxide and methane exchange in two small temperate forest catchments – effects of hydrological gradients and implications for global warming potentials of forest soils. Biogeochemistry, 107, 437–454, https://doi.org/10.1007/s10533-010-9563-x, 2012.

Coles, J. R. P. and Yavitt, J. B.: Linking Belowground Carbon Allocation to Anaerobic CH_4 and CO_2 production in a Forested Peatland, New York State. Geomicrobiol. J., 21, 445–455, https://doi.org/10.1080/01490450490505419, 2004.

Danevčič, T., Mandic-Mulec, I., Stres, B., Stopar, D., and Hacin, J.: Emissions of CO_2, CH_4 and N_2O from Southern European peatlands. Soil Biol. Biochem., 42, 1437–1446, https://doi.org/10.1016/j.soilbio.2010.05.004, 2010.

Dise, N. B.: Winter fluxes of methane from Minnesota peatlands. Biogeochemistry, 17, 71–83, https://doi.org/10.1007/BF00002641, 1992.

Eickenscheidt, T., Heinichen, J., Augustin, J., Freibauer, A., and Drösler, M.: Nitrogen mineralization and gaseous nitrogen losses from waterlogged and drained organic soils in a black alder (*Alnus glutinosa* (L.) Gaertn.) forest. Biogeosciences, 11, 2961–2976, https://doi.org/10.5194/bg-11-2961-2014, 2014.

Ernfors, M., von Arnold, K., Stendahl, J., Olsson, M., and Klemedtsson, L.: Nitrous oxide emissions from drained organic forest soils - an up-scaling based on C:N ratios. Biogeochemistry, 89, 29–41, https://doi.org/10.1007/s10533-008-9190-y, 2008.

Ernfors, M., Rütting T, and Klemedtsson, L.: Increased nitrous oxide emissions from a drained organic forest soil after exclusion of ectomycorrhizal mycelia. Plant Soil, 343, 161–170, https://doi.org/10.1007/s11104-010-0667-9, 2011.

~~Ernfors, M., von Arnold, K., Stendahl, J., Olsson, M., and Klemedtsson, L.: Nitrous oxide emissions from drained organic forest soils - an up-scaling based on C:N ratios. Biogeochemistry, 89, 29–41, https://doi.org/10.1007/s10533-008-9190-y, 2008.~~

Foken T., Leuning R., Oncley, S. R., Mauder, M., and Aubinet M.: Corrections and data quality control. In: Aubinet, M., Vesala, T., and Papale, D. (eds.), Eddy covariance: A practical guide to measurement and data analysis, Springer Atmospheric Sciences, Springer, Dordrecht, Heidelberg, London, New York, pp. 85–131, https://doi.org/10.1007/978-94-007-2351-1, 2012.

Glenn, S., Heyes, A., and Moore, T.: Carbon dioxide and methane fluxes from drained peat soils, Southern Quebec. Global Biogeochem. Cy., 7, 247–257, https://doi.org/10.1029/93GB00469, 1993.

Hargreaves, K. J., Milne, R., and Cannell, M. G. R.: Carbon balance of afforested peatland in Scotland, Forestry, 76, 299–317, https://doi.org/10.1093/forestry/76.3.299, 2003.

Holz, M., Aurangojeb, M., Kasimir, Å., Boeckx, P., Kuzyakov, Y., Klemedtsson, L., and Rütting, T.: Gross Nitrogen Dynamics in the Mycorrhizosphere of an Organic Forest Soil. Ecosystems 19(2), 284–295, https://doi.org/10.1007/s10021-015-9931-4, 2016.

Hommeltenberg, J., Schmid, H. P., Drösler, M., and Werle, P.: Can a bog drained for forestry be a stronger carbon sink than a natural bog forest? Biogeosciences, 11, 3477–3493, https://doi.org/10.5194/bg-11-3477-2014, 2014.

Hutchinson, J. N.: The record of peat wastage in the east-Anglian fenlands at Holme post, 1848–1978 AD. J. Ecol., 68, 229–249, https://doi.org/10.2307/2259253, 1980.

Huttunen, J. T., Nykänen, H., Martikainen, P. J., and Nieminen, M.: Fluxes of nitrous oxide and methane from drained peatlands following forest clear-felling in southern Finland. Plant Soil, 255, 457–462, https://doi.org/10.1023/A:1026035427891, 2003.

IPCC: 2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands, Hiraishi, T., Krug, T., Tanabe, K., Srivastava, N., Baasansuren, J., Fukuda, M., and Troxler, T. G. (eds). Published: IPCC, Switzerland. 353 p., https://www.ipcc-nggip.iges.or.jp/public/wetlands/, 2014.

Jovani-Sancho, J., Cummins, A., and Byrne, K. A.: Collar insertion depth effects on soil respiration in afforested peatlands. Biol. Fert. Soils, 53, 677–689, https://doi.org/10.1007/s00374-017-1210-4, 2017.

Kareksela, S., Haapalehto, T., Juutinen, R., Matilainen, R., Tahvanainen, T., and Kotiaho, J.: Fighting carbon loss of degraded peatlands by jump-starting ecosystem functioning with ecological restoration. Sci. Total Environ., 537, 268–270, https://doi.org/10.1016/j.scitotenv.2015.07.094, 2015.

Klemedtsson, L., Ernfors, M., Björk, R. G., Weslien, P., Rütting, T., Crill, P., and Sikström, U.: Reduction of greenhouse gas emissions by wood ash application to a *Picea abies* (L.) Karst. forest on a drained organic soil. Eur. J. Soil Sci., 61, 734–744, https://doi.org/10.1111/j.1365-2389.2010.01279.x, 2010.

Kolka, R. K., Grogal, D. F., Verry, E. S., and Nater, E. A.: Mercury and organic carbon relationships in steams draining forested upland/peatland watersheds. J. Environ. Qual,, 28, 766–775, https://doi.org/10.2134/jeq1999.00472425002800030006x, 1999.

Komulainen, V.-M., Nykänen, H., and Martikainen, P. J., Laine, J.: Short-term effect of restoration on vegetation change and methane emissions from peatlands drained for forestry in southern Finland. Can. J. Forest Res., 28(3), 402–411, https://doi.org/10.1139/x98-011, 1998.

Komulainen, V.-M., Tuittila, E.-S., Vasander, H., and Laine, J.: Restoration of drained peatlands in southern Finland: initial effects on vegetation change and CO_2 balance. J. Appl. Ecol., 36, 634–648, https://doi.org/10.1046/j.1365-2664.1999.00430.x, 1999.

Korkiakoski, M., Tuovinen, J-.P., Aurela, M., Koskinen, M., Minkkinen, K., Ojanen, P., Penttilä, T., Rainne, J., Laurila, T., and Lohila, A.: Methane exchange at the peatland forest floor – automatic chamber system exposes the dynamics of small fluxes. Biogeosciences, 14, 1947–1967, https://doi.org/10.5194/bg-14-1947-2017, 2017.

Kortelainen, P., Saukkonen, S., and Mattsson, T.: Leaching of nitrogen from forested catchments in Finland. Global Biogeochem. Cy., 11, 627–638, https://doi.org/10.1029/97GB01961, 1997.

Kortelainen, P., Mattsson, T., Finér, L., Ahtiainen, M., Saukkonen, S., and Sallantaus, T.: Controls on the export of C, N, P and Fe from undisturbed boreal catchments, Finland. Aquat. Sci., 68, 453–468, https://doi.org/10.1007/s00027-006-0833-6, 2006.

~~Kortelainen, P., Saukkonen, S., and Mattsson, T.: Leaching of nitrogen from forested catchments in Finland. Global Biogeochem. Cy., 11, 627–638, https://doi.org/10.1029/97GB01961, 1997.~~

Koskinen, M., Minkkinen, K., Ojanen, P., Kamarainen, M., Laurila, T., and Lohila, A.: Measurements of CO_2 exchange with an automated chamber system throughout the year: challenges in measuring night-time respiration on porous peat soil. Biogeosciences, 11, 347–363, https://doi.org/10.5194/bg-11-347-2014, 2014.

Krüger, J. P., Alewell, C., Minkkinen, K., Szidat, S., and Leifeld, J.: Calculating carbon changes in peat soils drained for forestry with four different profile-based methods. Forest Ecol. Manag., 381, 29–36, https://doi.org/10.1016/j.foreco.2016.09.006, 2016.

Kuzyakov, Y., Friedel, J. K., and Stahr, K.: Review of mechanisms and quantification of priming effects. Soil Biol. Biochem., 32, 1485–1498, https://doi.org/10.1016/S0038-0717(00)00084-5, 2000.

Lai, D. Y. F., Roulet, N. T., Humphreys, E. R., Moore, T. R., and Dalva, M.: The effect of atmospheric turbulence and chamber deployment period on autochamber CO_2 and CH_4 flux measurements in an ombrotrophic peatland. Biogeosciences, 9, 3305–3322, https://doi.org/10.5194/bg-9-3305-2012, 2012.

Laiho, R. and Pearson, M.: Surface peat and its dynamics following drainage - do they facilitate estimation of carbon losses with the C/ash method? Mires Peat, 17, Article 08, 1–19, https://doi.org/10.19189/MaP.2016.OMB.247, 2016.

Laine, J., Minkkinen, K., Sinisalo, J., Savolainen, I., and Martikainen, P. J.: Greenhouse impact of a mire after drainage for forestry. In: Northern Forested Wetlands, Ecology and Management, (eds) C. C. Trettin, M. F. Jurgensen, D. F. Grigal, M. R. Gale, and J. K. Jeglum, Boca Raton, FL, USA: CRC Lewis Publishers., pp. 437–447, https://doi.org/10.1201/9780203745380-31, 1996.

Launiainen, S., Rinne, J., Pumpanen, J., Kulmala, L., Kolari, P., Keronen, P., Siivola, E., Pohja, T., Hari, P., and Vesala, T.: Eddy covariance measurements of CO_2 and sensible and latent heat fluxes during a full year in a boreal pine forest trunk-space. Boreal Environ. Res., 10, 569–588, www.borenv.net/BER/pdfs/ber10/ber10-569.pdf, 2005.

Laurila, T., Lohila, A., Aurela, M., Tuovinen, J.-P., Thum, T., Aro, L., Laine, J., Penttilä, T., Minkkinen, K., Riutta, T., Rinne, J., Pihlatie, M., and Vesala, T.: Ecosystem-level carbon sink measurements on forested peatlands. In: Greenhouse Impacts of the Use of Peat and Peatlands in Finland. S. Sarkkola (ed.), Ministry of Agriculture and Forestry 11a/2007, pp. 38–40, http://urn.fi/URN:978-952-453394-2, 2007.

Linkosalmi, M., Pumpanen, J., Biasi, C., Heinonsalo, J., Laiho, R., Lindén, A., Palonen, V., Laurila, T., and Lohila, A.: Studying the impact of living roots on the decomposition of soil organic matter in two different forestry-drained peatlands. Plant Soil, 396(1-2), 59–72, https://doi.org/10.1007/s11104-015-2584-4, 2015.

Lohila, A., Laurila, T., Aro, L., Aurela, M., Tuovinen, J.-P., Laine, J., Kolari, P., and Minkkinen, K.: Carbon dioxide exchange above a 30-year-old Scots pine plantation established on organic-soil cropland. Boreal Environ. Res.., 12, 141–157, www.borenv.net/BER/pdfs/ber12/ber12-141.pdf, 2007.

Lohila, A., Minkkinen, K., Aurela, M., Tuovinen, J.-P., Penttilä, T., and Laurila, T.: Greenhouse gas flux measurements in a forestry-drained peatland indicate a large carbon sink. Biogeosciences, 8, 3203–3218, https://doi.org/10.5194/bg-8-3203-2011, 2011.

Lupikis, A. and Lazdins, A.: Soil carbon stock changes in transitional mire drained for Forestry in Latvia: a case study. Res. Rural Dev., 1, 55–61, https://doi.org/10.22616/rrd.23.2017.008, 2017.

Mäkiranta, P., Hytönen, J., Aro, L., Maljanen, M., Pihlatie, M., Potila, H., Shurpali, N. J., Laine, J., Lohila, A., Martikainen, P. J., and Minkkinen, K.: Soil greenhouse gas emissions from afforested organic soil croplands and peat extraction peatlands. Boreal Environ. Res., 12, 159–175, www.borenv.net/BER/pdfs/ber12/ber12-159.pdf, 2007.

Maljanen, M., Hytönen, J., and Martikainen, P. J.: Fluxes of N_2O, CH_4 and CO_2 on afforested boreal agricultural soils. Plant Soil, 231, 113–121, https://doi.org/10.1023/A:1010372914805, 2001.

Maljanen, M., Liikanen, A., Silvola, J., and Martikainen, P. J.: Methane fluxes on agricultural and forested boreal organic soils. Soil Use Manage., 19, 73–79, https://doi.org/10.1111/j.1475-2743.2003.tb00282.x, 2003a.

Maljanen, M., Liikanen, A., Silvola, J., and Martikainen, P. J.: Nitrous oxide emissions from boreal organic soil under different land-use. Soil Biol. Biochem., 35, 689–700, https://doi.org/10.1016/S0038-0717(03)00085-3, 2003b.

Maljanen, M., Nykänen, H., Moilanen, M., and Martikainen, P. J.: Greenhouse gas fluxes of coniferous forest floors affected by wood ash fertilization. For. Ecol. Man., 237, 143–149, https://doi.org/10.1111/10.1016/j.foreco.2006.09.039, 2006.

Maljanen, M., Alm, J., Martikainen, P. J., and Repo, T.: Prolongation of soil frost resulting from reduced snow cover increases nitrous oxide emissions from boreal forest soil. Boreal Environ. Res., 15, 34–42, www.borenv.net/BER/pdfs/ber15/ber15-034.pdf, 2010a.

Maljanen, M., Hytönen, J., and Martikainen, P. J.: Cold-season nitrous oxide dynamics in a drained boreal peatland differ depending on land-use practice. Can. J. Forest Res., 40, 565–572, https://doi.org/10.1139/X10-004, 2010b.

Maljanen, M., Sigurdsson, B. D., Guðmundsson, J., Óskarsson, H., Huttunen, J. T., and Martikainen, P. J.: Greenhouse gas balances of managed peatlands in the Nordic countries – present knowledge and gaps. Biogeosciences, 7, 2711–2738, https://doi.org/10.5194/bg-7-2711-2010, 2010c.

~~Maljanen, M., Hytönen, J., and Martikainen, P. J.: Fluxes of N_2O, CH_4 and CO_2 on afforested boreal agricultural soils. Plant Soil, 231, 113–121, https://doi.org/10.1023/A:1010372914805, 2001.~~

~~Maljanen, M., Liikanen, A., Silvola, J., and Martikainen, P. J.: Nitrous oxide emissions from boreal organic soil under different land-use. Soil Biol. Biochem., 35, 689–700, https://doi.org/10.1016/S0038-0717(03)00085-3, 2003b.~~

~~Maljanen, M., Liikanen, A., Silvola, J., and Martikainen, P. J.: Methane fluxes on agricultural and forested boreal organic soils. Soil Use Manage., 19, 73–79, https://doi.org/10.1111/j.1475-2743.2003.tb00282.x, 2003a.~~

Maljanen, M., Shurpali, N., Hytönen, J., Mäkiranta, P., Aro, L., Potila, H., Laine, J., Li, C., and Martikainen, P. J.: Afforestation does not necessarily reduce nitrous oxide emissions from managed boreal peat soils. Biogeochemistry, 108, 199–218, https://doi.org/10.1007/s10533-011-9591-1, 2012.

Maljanen, M., Liimatainen, M., Hytönen, J., Martikainen, P. J.: The effect of granulated wood-ash fertilization on soil properties and greenhouse gas (GHG) emissions in boreal peatland forests. Boreal Environ. Res., 19, 295–309, www.borenv.net/BER/pdfs/ber19/ber19-295.pdf, 2014.

~~Maljanen, M., Nykänen, H., Moilanen, M., and Martikainen, P. J.: Greenhouse gas fluxes of coniferous forest floors affected by wood ash fertilization. For. Ecol. Man., 237, 143–149, https://doi.org/10.1111/10.1016/j.foreco.2006.09.039, 2006.~~

~~Maljanen, M., Shurpali, N., Hytönen, J., Mäkiranta, P., Aro, L., Potila, H., Laine, J., Li, C., and Martikainen, P. J.: Afforestation does not necessarily reduce nitrous oxide emissions from managed boreal peat soils. Biogeochemistry, 108, 199–218, https://doi.org/10.1007/s10533-011-9591-1, 2012.~~

~~Maljanen, M., Sigurdsson, B. D., Guðmundsson, J., Óskarsson, H., Huttunen, J. T., and Martikainen, P. J.: Greenhouse gas balances of managed peatlands in the Nordic countries – present knowledge and gaps. Biogeosciences, 7, 2711–2738, https://doi.org/10.5194/bg-7-2711-2010, 2010c.~~

Mander, Û., Lõhmus, K., Teiter, S., Uri, V., and Augustin, J.: Gaseous nitrogen and carbon fluxes in riparian alder stands. Boreal Environ. Res., 13, 231–241, www.borenv.net/BER/pdfs/ber13/ber13-231.pdf, 2008.

Martikainen, P. J., Nykänen, H., Crill, P., and Silvola, J.: The effect of changing water table on methane fluxes at two Finnish mire sites. Suo, 43, 237–240, http://www.suo.fi/article/9712, 1992.

Martikainen, P. J., Nykänen, H., Crill, P., and Silvola, J.: Effect of a lowered water table on nitrous oxide fluxes from northern peatlands. Nature, 366, 51–53, https://doi.org/10.1038/366051a0, 1993.

Martikainen, P. J., Nykänen, H., Alm, J., and Silvola, J.: Change in fluxes of carbon dioxide, methane and nitrous oxide due to forest drainage of mire sites of different trophy. Plant Soil, 168, 571–577, https://doi.org/10.1007/BF00029370, 1995a.

~~Martikainen, P. J., Nykänen, H., Crill, P., and Silvola, J.: Effect of a lowered water table on nitrous oxide fluxes from northern peatlands. Nature, 366, 51–53, https://doi.org/10.1038/366051a0, 1993.~~

~~Martikainen, P. J., Nykänen, H., Crill, P., and Silvola, J.: The effect of changing water table on methane fluxes at two Finnish mire sites. Suo, 43, 237–240, http://www.suo.fi/article/9712, 1992.~~

Martikainen, P. J., Nykänen, H., Regina, K., Lehtonen, M., and Silvola, J.: Methane fluxes in a drained and forested peatland treated with different nitrogen compounds, in: Northern Peatlands in Global Climatic Change. Laiho, R., Laine, J. and Vasander, H. (eds). Proceedings of the International Workshop Held in Hyytiälä, Finland. Helsinki, pp. 105–109, 1995b.

Mattsson, T., Finér, L., Kortelainen, P., and Sallantaus, T.: Brookwater quality and background leaching from unmanaged forested catchments in Finland. Water Air Soil Poll., 147, 275–297, https://doi.org/10.1023/A:1024525328220, 2003.

McNamara, N. P., Black, H. I. J., Piearce, T. G., Reay, D. S., and Ineson, P.: The influence of afforestation and tree species on soil methane fluxes from shallow organic soils at the UK Gisburn Forest Experiment. Soil Use Manage., 24, 1–7, https://doi.org/10.1111/j.1475-2743.2008.00147.x, 2008.

Meyer, A., Tarvainen, L., Nousratpour, A., Björk, R. G., Ernfors, M., Grelle, A., Kasimir Klemedtsson, Å., Lindroth, A., Räntfors, M., Rütting, T., Wallin, G., Weslien, P., and Klemedtsson, L.: A fertile peatland forest does not constitute a major greenhouse gas sink. Biogeosciences, 10, 7739–7758, https://doi.org/10.5194/bg-10-7739-2013, 2013.

Minkkinen, K. and Laine, J.: Effect of forest drainage on the peat bulk density of pine mires in Finland. Can. J. For. Res., 28, 178–186, https://doi.org/10.1139/x97-206, 1998a.

Minkkinen, K. and Laine, J.: Long-term effect of forest drainage on the peat carbon stores of pine mires in Finland. Can. J. For. Res., 28, 1267–1275, https://doi.org/10.1139/x98-104, 1998b.

Minkkinen, K. and Laine, J.: Vegetation heterogeneity and ditches create spatial variability in methane fluxes from peatlands drained for forestry. Plant Soil, 285, 289–304, https://doi.org/10.1007/s11104-006-9016-4, 2006.

Minkkinen, K., Laine, J., Shurpali, N. J., Mäkiranta, P., Alm, J., and Penttilä, T.: Heterotrophic soil respiration in forestry-drained peatlands. Boreal Environ. Res., 12, 115–126, www.borenv.net/BER/pdfs/ber12/ber12-115.pdf, 2007b.

Minkkinen, K., Penttilä, T., and Laine, J.: Tree stand volume as a scalar for methane fluxes in forestry-drained peatlands in Finland. Boreal Environ. Res., 12, 127–132, www.borenv.net/BER/pdfs/ber12/ber12-127.pdf, 2007a.

Minkkinen, K., Vasander, H., Jauhiainen, S., Karsisto, M., and Laine, J.: Post-drainage changes in vegetation composition and carbon balance in Lakkasuo mire, Central Finland. Plant Soil, 207, 107–120, https://doi.org/10.1023/A:1004466330076, 1999.

Moilanen, M., Hytönen, J., and Leppälä, M.: Application of wood ash accelerates soil respiration and tree growth on drained peatland. Eur. J. Soil Sci., 63, 467–475, https://doi.org/10.1111/j.1365-2389.2012.01467.x, 2012.

Moore, T.R. and Knowles, R.: Methane emissions from fen, bog and swamp peatlands in Quebec. Biogeochemistry, 11, 45–61, https://doi.org/10.1007/BF00000851, 1990.

Munger, J. W., Loescher, H. W., and Luo, H.: Measurement, Tower, and Site Design Considerations. In: Eddy Covariance - A Practical Guide to Measurement and Data Analysis. Aubinet, M., Vesala, T., and Papale, D. (eds). Springer, Dordrecht. pp. 21–58, https://doi.org/10.1007/978-94-007-2351-1, 2012.

Mustamo, P., Maljanen, M., Hyvärinen, M., Ronkainen, A.-K., and Kløve, B.: Respiration and emissions of methane and nitrous oxide from a boreal peatland complex comprising different land-use types. Boreal Environ. Res., 12, 405–426, www.borenv.net/BER/pdfs/ber21/ber21-405.pdf, 2016.

Nieminen, M., Koskinen, M., Sarkkola, S., Laurén, A., Kaila, A., Kiikkilä, O., Nieminen, T.M., and Ukonmaanaho, L.: Dissolved organic carbon export from harvested peatland forests with differing site characteristics. Water Air Soil Poll., 225, 181, https://doi.org/10.1007/s11270-015-2444-0, 2015.

Nykänen, H., Alm, J., Silvola, J., Tolonen, K., and Martikainen, P. J.: Methane fluxes on boreal peatlands of different fertility and the effect of long term experimental lowering of the water table on flux rates. Global Biogeochem. Cy., 12, 53–69, https://doi.org/10.1029/97GB02732, 1998.

Ojanen, P., Lehtonen, A., Heikkinen, J., Penttilä, T., and Minkkinen, K.: Soil CO_2 balance and its uncertainty in forestry-drained peatlands in Finland. Forest Ecol. Manag., 325, 60–73, https://doi.org/10.1016/j.foreco.2014.03.049, 2014.

Ojanen, P., Minkkinen, K., Alm, J., and Penttilä, T.: Soil – atmosphere CO_2, CH_4 and N_2O fluxes in boreal forestry-drained peatlands. Forest Ecol. Manag., 260, 411–421, https://doi.org/10.1016/j.foreco.2010.04.036, 2010.

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

Ojanen, P., Minkkinen, K., and Penttilä, T.: The current greenhouse gas impact of forestry-drained boreal peatlands. Forest Ecol. Manag., 289, 201–208, https://doi.org/10.1016/j.foreco.2012.10.008, 2013.

Ojanen, P., Minkkinen, K., Alm, J., and Penttilä, T.: Corrigendum to "Soil–atmosphere CO_2, CH_4 and N_2O fluxes in boreal forestry-drained peatlands" [For. Ecol. Manage., 260, 411–421, 2010], https://doi.org/10.1016/j.foreco.2018.01.020, 2018.

~~Ojanen, P., Minkkinen, K., Alm, J., and Penttilä, T.: Soil – atmosphere CO_2, CH_4 and N_2O fluxes in boreal forestry-drained peatlands. Forest Ecol. Manag., 260, 411–421, https://doi.org/10.1016/j.foreco.2010.04.036, 2010.~~

~~Ojanen, P., Minkkinen, K., and Penttilä, T.: The current greenhouse gas impact of forestry-drained boreal peatlands. Forest Ecol. Manag., 289, 201–208, https://doi.org/10.1016/j.foreco.2012.10.008, 2013.~~

~~Ojanen, P., Minkkinen, K., Lohila, A., Badorek, T., and Penttilä, T.: Chamber measured soil respiration: A useful tool for estimating the carbon balance of peatland forest soils? Forest Ecol. Manag., 277, 132–140. https://doi.org/10.1016/j.foreco.2012.04.027, 2012.~~

Oleszczuk, R., Regina, K., Szajdak, L., Höper, H., and Maryganova, V.: Impacts of agricultural utilization of peat soils on the greenhouse gas balance. In: Strack, M. (ed.), Peatlands and Climate Change. Saarijärven Offset Oy, Finland. pp. 70–97, http://www.peatsociety.org/peatlands-and-peat/peatlands-and-climate-change, 2008.

Pihlatie, M., Rinne, J., Lohila, A., Laurila, T., Aro, L., and Vesala, T.: Nitrous oxide emissions from an afforested peat field using eddy covariance and enclosure techniques. In: J. Päivänen et al. (eds.), Proceedings of 12th International Peat Congress, Tampere, Finland 6–11 Jun 2004, Vol 2, pp. 1010–1014, 2004.

Pitkänen, A., Turunen, J., Tahvanainen, T., and Simola, H.: Carbon storage change in a partially forestry-drained boreal mire determined through peat column inventories. Boreal Environ. Res., 18, 223–234, www.borenv.net/BER/pdfs/ber18/ber18-223.pdf, 2013.

Pumpanen, J., Kolari, P., Ilvesniemi, H., Minkkinen, K., Vesala, T., Niinistö, S., Lohila, A., Larmola, T., Morero, M., Pihlatie, M., Janssens, I., Yuste, J. C., Grünzweig, J. M., Reth, S., Subke, J. A., Savage, K., Kutsch, W., Østreng, G., Ziegler, W., Anthoni, P., Lindroth, A., and Hari, P.: Comparison of different chamber techniques for measuring soil CO_2 efflux. Agr. Forest Meteorol., 123, 159–176, https://doi.org/10.1016/j.agrformet.2003.12.001, 2004.

Rantakari, M., Mattsson, T., Kortelainen, P., Piirainen, S., Finér, L., and Ahtiainen, M.: Organic and inorganic carbon concentrations and fluxes from managed and unmanaged boreal first-order catchments. Sci. Total Environ., 408, 1649–1658, https://doi.org/10.1016/j.scitotenv.2009.12.025, 2010.

Regina, K., Nykänen, H., Maljanen, M., Silvola, J., and Martikainen, P. J.: Emissions of N_2O and NO and net nitrogen mineralization in a boreal forested peatland treated with different nitrogen compounds. Can. J. For. Res., 28, 132–140, https://doi.org/10.1139/x97-198, 1998.

Regina, K., Nykänen, H., Silvola, J., and Martikainen, P. J.: Fluxes of nitrous oxide from boreal peatlands as affected by peatland type, water table level and nitrification capacity. Biogeochemistry, 35, 401–418, https://doi.org/10.1007/BF02183033, 1996.

Reichstein, M., Falge, E., Baldocchi, D., Papale, D., Aubinet, M., Berbigier, P., Bernhofer, C., Buchmann, N., Gilmanov, T., and Granier, A.: On the separation of net ecosystem exchange into assimilation and ecosystem respiration: review and improved algorithm. Global Change Biol., 11, 1424–1439, https://doi.org/10.1111/j.1365-2486.2005.001002.x, 2005.

Saari, P., Saarnio, S., Kukkonen, J. V. K., Akkanen, J., Heinonen, J., Saari, V., and Alm, J.: DOC and N_2O dynamics in upland and peatland forest soils after clear-cutting and soil preparation. Biogeochemistry, 94, 217–231, https://doi.org/10.1007/s10533-009-9320-1, 2009.

Sallantaus, T.: Leaching in the material balance of peatlands – preliminary results. Suo, 43, 253–258, http://www.suo.fi/article/9716, 1993.

Salm, J.-O., Maddison, M., Tammik, S., Soosaar, K., Truu, J., and Mander, Ü.: Emissions of CO_2, CH_4 and N_2O from undisturbed, drained and mined peatlands in Estonia. Hydrobiologia, 692: 41–55, https://doi.org/10.1007/s10750-011-0934-7, 2012.

Sarkkola, S., Koivusalo, H., Laurén, A. Kortelainen, P., Mattsson, T., Palviainen, M., Piirainen, S., Starr, M., and Finér, L.: Trends in hydrometeorological conditions and stream water organic carbon in boreal forested catchments. Sci. Total Environ., 408, 92–101, https://doi.org/10.1016/j.scitotenv.2009.09.008, 2009.

Sikström, U., Björk, R. G., Ring, E., Ernfors, M., Jacobson, S., Nilsson, M., and Klemedtsson, L.: Tillförsel av aska i skog på dikad torvmark i södra Sverige. Effekter på skogsproduktion, flöden av växthusgaser, torvegenskaper, markvegetation och grundvattenkemi. VÄRMEFORSK Service AB, Stockholm, 75 pp., 2009.

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

Simola, H., Pitkänen, A., and Turunen, J.: Carbon loss in drained forestry peatlands in Finland, estimated by re-sampling peatlands surveyed in the 1980s. Eur. J. Soil Sci., 63, 798–807, https://doi.org/10.1111/j.1365-2389.2012.01499.x, 2012.

Subke, J.-A., Inglima, I., and Cotrufo, M. F.: Trends and methodological impacts in soil CO_2 efflux partitioning: A meta-analytical review. Global Change Biol., 12, 921–943, https://doi.org/10.1111/j.1365-2486.2006.01117.x, 2006.

Uri, V., Kukumägi, M., Aosaar, J., Varik, M., Becker, H., Morozov, G., and Karoles, K.: Ecosystems carbon budgets of differently aged downy birch stands growing on well-drained peatlands. Forest Ecol. Manag., 399, 82–93, https://doi.org/10.1016/j.foreco.2017.05.023, 2017.

von Arnold, K., Hånell, B., Stendahl, J., and Klemedtsson, L.: Greenhouse gas fluxes from drained organic forestland in Sweden. Scand. J. For. Res., 20, 400–411, https://doi.org/10.1080/02827580500281975, 2005c.

von Arnold, K., Nilsson, M., Hånell, B., Weslien, P., and Klemedtsson, L.: Fluxes of CO_2, CH_4 and N_2O from drained organic soils in deciduous forests. Soil Biol. Biochem., 37, 1059–1071, https://doi.org/10.1016/j.soilbio.2004.11.004, 2005a.

von Arnold, K., Weslien, P., Nilsson, M., Svensson, B. H., and Klemedtsson, L.: Fluxes of CO_2, CH_4 and N_2O from drained coniferous forests on organic soils. Forest Ecol. Manage., 210, 239–254, https://doi.org/10.1016/j.foreco.2005.02.031, 2005b.

Väisänen, S. E., Silvan, N. R., Ihalainen, A. V. J., and Soukka, R. M.: Peat production in high-emission level peatlands – key to reduce climatic impacts? Energ. Environ., 24, 757–778, https://doi.org/10.1260/0958-305X.24.5.757, 2013.

Wang, X., Wang, C., and Bond-Lamberty, B.: Quantifying and reducing the differences in forest CO2-fluxes estimated by eddy covariance, biometric and chamber methods: A global synthesis. Agric. For. Meteorol., 247, 93–103, https://dx.doi.org/10.1016/j.agrformet.2017.07.023, 2018.

Weslien, P., Kasimir Klemedtsson, Å., Börjesson, G., and Klemedtsson, L.: Strong pH influence on N_2O and CH_4 fluxes from forested organic soils. Eur. J. Soil Sci., 60, 311–320, https://doi.org/10.1111/j.1365-2389.2009.01123.x, 2009.

Yamulki, S., Anderson, R., Peace, A., and Morison, J. I. L.: Soil CO_2, CH_4 and N_2O fluxes from an afforested lowland raised peatbog in Scotland: implications for drainage and restoration. Biogeosciences, 10, 1051–1065, https://doi.org/10.5194/bg-10-1051-2013, 2013.