Calculating carbon changes in peat soils drained for forestry with four different profile-based methods

Jan Paul Krüger[1], Christine Alewell[1], Kari Minkkinen[2], Sönke Szidat[3] and Jens Leifeld[4]

[1] Environmental Geosciences, University of Basel, Bernoullistrasse 30, 4056 Basel, Switzerland

[2] Department of Forest Science, University of Helsinki, P.O. Box 27, Helsinki FI-00014, Finland

[3] Department of Chemistry and Biochemistry & Oeschger Centre for Climate Change Research, University of Bern, Freiestrasse 3, 3012 Bern, Switzerland

[4] Climate/Air Pollution Group, Agroscope, Reckenholzstrasse 191, 8046 Zürich, Switzerland

Correspondence to:

Jan Paul Krüger (janpaul.krueger@unibas.ch)

Jens Leifeld (jens.leifeld@agroscope.admin.ch)

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Abstract

Boreal peatlands are an important carbon (C) sink. The effect of drainage for forestry on the soil C balance in those peatlands is a controversial debate. The Lakkasuo peatland, central Finland, comprise a minerotrophic and an ombrotrophic part, both partially drained for forestry. A pair-wise comparison was conducted and four different profile-based methods were applied to calculate the soil C balance. The first two methods used differences in ash content (I) between the upper and lower part of the profile and (II) between the drained and natural site of the peatland, respectively. The third method (III) used radiocarbon dated samples to calculate C accumulation rates at the natural site and compared these to the current C-stocks at the drained sites. The fourth method (IV) used radiocarbon dated samples to define a 1000-year layer in the profiles for comparing the C-stocks above this layer. Stable carbon isotope depth profiles, used for a qualitative assessment of the peatland status, identify both undrained site as undisturbed. All four methods indicate a C loss at the minerotrophic drained site but of different magnitude (0.057-0.272 kg C m^{-2} yr^{-1}). At the ombrotrophic drained site both radiocarbon methods (III and IV) indicate a C gain (0.139-0.179 kg C m^{-2} yr^{-1}) whereas methods I and II suggest a C loss (0.084-0.270 kg C m^{-2} yr^{-1}). Method IV is considered the most stringent and robust one. Yet, the comparison of profile-based methods for C balance assessment suggests them to be applicable depending on site-specific conditions of nutrient status and presence of a natural reference site.

1. Introduction

Boreal peatlands are an important long-term terrestrial carbon (C) sink. In their soils, they store an amount of C equivalent to almost half of the current carbon content of the atmosphere (Strack et al., 2008; Yu et al., 2011; Jungkunst et al., 2012). A substantial proportion of boreal peatlands has been drained for forestry with a total area of more than 100,000 km^2 in Fennoscandia and Russia (Minkkinen et al., 2008). In Finland, more than half of the peatlands have been drained during the 20th century, mainly for forestry use (Laine et al., 2006). Peatland drainage for agriculture usually changes a peatland from a C sink into a C source (IPCC, 2013). However, the impact of draining boreal peatlands for forestry on the soil's C balance is controversial. Several studies demonstrate that boreal peatlands drained for forestry are still C sinks, because of an increased wood, root and litter production, which compensate the increased soil respiration of the aerated peat (Minkkinen et al., 1999, 2002; Lohila et al., 2011; Meyer et al., 2013; Ojanen et al., 2013). In contrast, other authors found net ecosystem C losses mainly caused by increased C emissions from degrading peat (Martikainen et al., 1995; Silvola et al., 1996) whereby these peatlands may lose their C sink function (Minkkinen et al., 2007; Ojanen et al., 2010). This raised the question whether a drained boreal peatland is a C sink or C source.

Several approaches exist to determine the soil C balance of peatlands. Simola et al. (2012) broadly divided the different approaches to determine the soil C balance of peatlands into process and inventory studies. Process studies investigate the gas exchange of the soil or the whole ecosystem (Silvola et al., 1996; Lindroth et al., 1998; Alm et al., 1999; von Arnold et al., 2005; Minkkinen et al., 2007; Lohila et al., 2011; Meyer et al., 2013; Ojanen et al., 2013; Hommeltenberg et al., 2014) while inventory studies examine the long-term changes in C-stocks (Minkkinen and Laine, 1998; Minkkinen et al., 1999). Changes in soil C balance via inventories can be studied in two ways: (i) a study site is resampled over decades and C-stocks between present-day and historical situation are compared (Pitkänen et al., 2011; Simola et al., 2012) or (ii) peat profiles of paired undrained and drained parts of a peatland are compared (Minkkinen et al., 1999; Pitkänen et al., 2013), following a space-by-time approach. Process studies are time and cost consuming and the results are usable only for one or several years. Furthermore, these results depend on the climatic circumstances during the measuring period and could indicate special conditions. In contrast, inventory studies examine the long-term C balance of peatlands, whereas the drainage history has to be well documented. A few inventory studies exist and here we want to extend the range of inventory studies and compared four different profile-based methods in a minerotrophic and ombrotrophic part of a well-studied peatland complex in central Finland.

The Lakkasuo peatland complex, central Finland, hosts both a bog and a fen ecosystem, each with adjacent drained-undrained parts. Four different profile-based methods were applied to calculate the C balance of the peatland soils: (I) a combined method with subsoil as reference, (II) a combined method with natural site as reference, (III) a C accumulation method and (IV) a cumulative C-stock comparison method. The combined methods use differences in ash content of the degraded upper part of the peatland either to the assumed natural horizons of the deeper subsoil at the same site (combined method with subsoil as reference) (Krüger et al., 2015b) or to the adjacent undisturbed site (combined method with natural site as reference). This is the first study where a natural situation, formed in the same peatland, is used as reference for the combined method. In addition, two radiocarbon methods using ^{14}C age dated samples are taken to estimate the soil C balance: The C accumulation method relies on the premise of linear C accumulation rates at the natural sites. ^{14}C age dated samples at the reference site are taken to calculate the natural accumulation rates. The former C-stock at the degraded site prior to drainage is calculated with the accumulation rates of the reference sites and then compared to the measured cumulative C-stock of the degraded site. In the fourth method, the cumulative C-stock, both at the drained and natural site, above a peat layer of the same radiocarbon age was compared. The differences between the drained and natural site of the latter method give the soil C loss or gain of the drained sites relative to the undisturbed situation. As previous studies have shown that expected natural peatlands sites are affected by drainage activities of the surrounding area (Krüger et al., 2015b) $\delta^{13}C$ depth profiles were used as an indicator for a qualitative assessment of the natural status of the reference sites. In this approach, a uniform $\delta^{13}C$ depth profile indicates water-saturated conditions within a natural peatland (Alewell et al., 2011; Krüger et al., 2014, 2015b).

The objectives of the present study were (I) to use $\delta^{13}C$ depth profile as a qualitative indicator for the natural status of the undrained sites, and (II) to examine the effect of peatland drainage for forestry on the soil C balance of a minerotrophic as well as an ombrotrophic peatland site by four different profile-based methods.

2. Material and Methods

2.1 Study site

Peat samples were taken in the eccentric peatland complex Lakkasuo (61°48'N, 24°19'E), central Finland. The mean annual temperature is 3 °C, and the mean annual precipitation is 700 mm (Minkkinen et al., 1999). The peatland complex is divided into two parts. The southern part is nutrient poor with ombrotrophic conditions and the northern part is nutrient richer with minerotrophic conditions. Approximately half of the peatland (eastern part) was drained in 1961 for forestry, using ditches with depth of 70 cm and spacing of 40–60 m. This spatial arrangement allows for a pair-wise comparison between an ombrotrophic natural (On) and an ombrotrophic drained (Od) as well as a minerotrophic natural (Mn) and a minerotrophic drained (Md) part. At the natural ombrotrophic part of the peatland the water table is at about 13 cm depth and at the ombrotrophic drained site at about 26 cm depth (Minkkinen et al., 1999). A greater change has been detected at the minerotrophic part of the peatland, where the water table has decreased from close to the surface at the natural site to around 36 cm depth at the drained site (Minkkinen et al., 1999). Drainage has changed the ground vegetation composition from dominating Sphagna to forest mosses (Table 1) (Minkkinen et al., 1999). A detailed description of the vegetation composition and other peatland characteristics is given in Laine et al. (2004).

2.2. Soil sampling and analyses

In September 2013 three volumetric peat cores per site were collected in the Lakkasuo peatland complex at the four different sites. The drained and natural sites of each nutrient status pair is about 50 m. Each site is represented by three independent peat cores which were taken in a radius of about 10 m. Peat cores were taken neither from hummocks nor hollows samples were taken at a medium stage of small scale topography. All cores were taken in a minimum distance to the drainage channel. In the upper 50 cm peat samples were taken with a box sampler (8 ⁄ 8 cm) and in deeper parts down to approximately one meter with a Russian peat corer (Eijkelkamp, Netherlands). The peat cores were stored in plastic shells, wrapped in plastic foil and transported to the lab the same day. The cores were cut into 2 cm sections and dried at 40 °C for 72 h in a drying oven. All samples were ground and homogenised in a vibrating ball mill (MM 400, Retsch, Germany). Stable carbon isotopes as well as C and N content were measured with combined mass spectrometer with a SL elemental analyser (Integra2, Sercon, UK) following standard processing techniques. Stable carbon isotope ratios are reported as $\delta^{13}C$ in [‰] relative to the V-PDB standard. The instrumental standard deviation is 0.1% for $\delta^{13}C$. The volumetric sampling of the peat enabled the determination of the soil bulk density. The C-stocks were calculated by C content and bulk density for depth increments of each single core.

Peat ash content was determined by thermogravimetry (prepAsh, Precia, Switzerland), using 0.5-1.0 g sample material. The sample was heated to 600 °C in air until no significant mass change (constant mass) could be measured (see detailed description of the method by Leifeld et al. (2011a)). The material remaining after heating is defined as the ash content of the sample.

Radiocarbon (^{14}C) content was measured with accelerator mass spectrometry (AMS) at the Laboratory for the Analysis of Radiocarbon with AMS (LARA) at the University of Bern (Szidat et al., 2014). For each site, two depths (at around 50 and 90 cm depth, see supplement) were selected for radiocarbon dating and samples at these depths were measured for each individual core. We selected the radiocarbon samples after the interpretation of the $\delta^{13}C$ depth profiles with the strongest effect of peatland drainage in the first 40-50 cm. The depths were chosen as they should be in catotelm of the peat profile and the influence of young, recently accumulated peat material on the peat age should be negligible. The ground and homogenised material was combusted, transformed into solid targets using an automated graphitisation equipment (AGE) (Nemec et al., 2010), and measured with the MIni Carbon DAting System MICADAS (Synal et al., 2007). ^{14}C ages were calibrated using the IntCal13 dataset (Reimer et al., 2013). Samples with bomb signature were calibrated using the Bomb13 NH1 dataset (Hua et al., 2013). Radiocarbon ages are presented for each site and selected depth as means (n = 3) with 1 SD in cal. years AD or cal. years BC. Results of the individual measurements are shown in Table S1.

2.3. Methods for calculating the C balance of peatland soils

2.3.1. Soil C balance calculated by the combined method with subsoil as reference (combined method-subsoil) (I)

The method of Krüger et al. (2015b) combines two previously published methods which were based on changes in bulk density (Leifeld et al., 2011b) and changes in ash content (Rogiers et al., 2008; Leifeld et al., 2011a) in peat profiles. The so-called combined method (Krüger et al., 2015b) estimates the physical primary subsidence due to compaction, and the chemical secondary subsidence due to the oxidative loss of organic matter (Ewing and Vepraskas, 2006). As the physical primary subsidence has no effect on the C balance this part of the method was left out of this methods section but is described in detail in Krüger et al. (2015b).

The integrated calculation of carbon change of the peatland since the beginning of drainage is based on the simplified assumption of a constant ratio between carbon to ash content during accumulation of peat and that ash content before drainage was the same at all depths. After drainage, the previously waterlogged peat oxidizes and carbon is lost as CO_2 (Rogiers et al., 2008). Additionally, it was assumed that ash from the oxidized peat remains in the respective horizons and accumulates in the upper layer and that the ash content in the permanent water saturated subsoil is not affected by drainage. The ash content of the deeper horizons (70-94 cm depth) of each individual core is taken as a reference value (Leifeld et al., 2011a). The carbon change was calculated separately for each core.

The chemical secondary subsidence S is calculated from the pre-drainage thickness ST_{0i} [m] (Krüger et al., 2015b):

$ST_{0i} = ST_i \times F_{ashi}/F_{ashr}$ (1)

with ST_i the thickness of layer i [m], F_{ashi} the ash concentration of layer i, F_{ashr} the ash concentration of the reference layer.

$S = ST_{0i} - ST_i$ (2)

Before drainage, any layer with the respective thickness ST_{0i} contained the same amount of carbon per soil volume as the contemporary undisturbed reference layers ST_r in the deeper soil profile. The amount of soil carbon in any single layer C_{di} [kg m^2] lost by oxidation is given as

$C_{di} = S \times C_r/ST_r$ (3)

with C_r the soil carbon stock of the reference layer [kg m^{-2}], ST_r the thickness of the reference layer [m] and the volumetric loss due to peat oxidation S [m]. The deeper layers of the drained sites were used as a reference (Table 2) similar to the approach taken in previous studies (Rogiers et al., 2008; Krüger et al., 2015b).

2.3.2. Soil C balance calculated by the combined method with natural site as reference (combined method-natural) (II)

The combined method with the natural site as a reference uses the same Eqs. (1)-(3) above, but takes the mean values from all three cores (n = 3) of the corresponding natural site as reference instead of the subsoil horizons of the drained site. Hence, the reference values of F_{ashr}, C_r and ST_r in Eqs. (1) and (3) are mean values of the whole profile from the corresponding natural site. The C balance was calculated separately for each core at the drained sites.

2.3.3. Soil C balance calculated by C accumulation rates of the natural site (C accumulation method) (III)

In this method the C change of the drained sites is calculated from the mean C accumulation rates of the natural sites as inferred from ^{14}C dating (Krüger et al., 2015a). Accumulation rates of C were calculated by a linear regression of three points: two age dated samples in the catotelm and the uppermost horizon assuming as recent. The C accumulation in peatlands has been reported to be non-linear, because of decomposition in the acrotelm (Clymo, 1984; Clymo and Bryant, 2008). However, our calculated mean linear C accumulation rates of the natural parts Mn and On of the Lakkasuo peatland are quite similar to the C accumulation rates of the same peatland from Minkkinen et al. (1999) and to mean C accumulation rates of this region for bogs and fens in Finland from Turunen et al. (2002). Hence, the linear calculated C accumulation rates were used for this method. The age of samples in a defined depth as well as the corresponding C-stock above this depth was used to calculate the C balance of the peat soil. The $C_{stock\text{-}natural}$ of the drained site was calculated by the year of sampling (Age_s) minus the age in the depth (Age_d) of the drained site multiplied by the calculated yearly C accumulation rates (C_{acc}) of the natural site. The $C_{stock\text{-}natural}$ gives the expected C-stock for the drained site but under non-disturbed conditions. The cumulative C-stock (kg C m^2) down to the corresponding depth ($C_{stock\text{-}drained}$) of the drained site was subtracted from $C_{stock\text{-}natural}$, whereby the difference to the expected C-stock gives the net C loss or gain from drainage ($C_{balance}$). The C-stock ($C_{stock\text{-}drained}$) above the ^{14}C dated sample in 49 cm depth at the drained sites was used for the calculation. In all cases the radiocarbon age for Age_d was taken at 49 cm depth.

$$C_{stock\text{-}natural} = (Age_s - Age_d) \times C_{acc} \quad (4)$$

$$C_{balance} = C_{stock\text{-}natural} - C_{stock\text{-}drained} \quad (5)$$

2.3.4. Soil C balance calculated by differences in the C-stock above a 1000-year layer (cumulative C-stock comparison) (IV)

In this method soil C change (kg C m^2) is estimated by comparing the C-stocks of natural and drained sites above a layer of the same ^{14}C age (here 1000-year layer). The age-depth modelling software Bacon (Blaauw and Christen, 2011) was used to identify the depth of the 1000-year layer (Fig. S1). The 1000-year layer depth was calculated separately by the model for each core with two ^{14}C age dated layers. For the minerotrophic as well as the ombrotrophic sites the cumulative C-stock above the 1000-year layer was calculated. This method requires at least two dated samples at different depths in the profile, which is then inter- or extrapolated to find the 1000-year layer. The method is comparable to the method by Laine et al. (1992) who used a synchronous charcoal layer of drained and undrained parts of the same peatland to calculate the effect of drainage for forestry on the soil C stores. The difference between the mean C-stock above the 1000-year layer at the natural site (n = 3) and that of the drained site (n = 3) gives the C loss or C gain (kg C m^2) at the drained site compared to the natural one. The 1000-year layer was used for the comparison, because this layer is represented roughly within the first meter core of the four studied sites.

All carbon changes are displayed as kg C m^2 and change rates as kg C m^2 yr^{-1} by dividing the carbon change by the number of years passed since the peatland was drained. Values of C balances are presented as means with standard error including error propagation when using the natural site as reference.

3. Results and discussion

3.1. Qualitative indicator of peatland drainage: stable carbon isotope depth profiles

For a preceding analysis of the natural status of the reference sites the approach of stable carbon isotope depth profiles as a qualitative indicator for peatland degradation was used (Alewell et al., 2011; Krüger et al., 2014, 2015b). This was to verify if the undrained sites of the Lakkasuo peatland are without anthropogenic influence and thus suitable as reference sites for the profile-based methods.

Both, the minerotrophic and the ombrotrophic natural site, show a uniform $\delta^{13}C$ profile (Fig. 1). Such a pattern is indicative for low decomposition rates and thus little fractionation of stable carbon isotopes (Clymo and Bryant, 2008; Alewell et al., 2011; Krüger et al., 2014). Mean $\delta^{13}C$ values at Mn are consistently at about -29‰ in the upper 14 cm and represent the isotopic signature of the living vegetation. Below 14 cm, values are more or less stable at about 28‰. The $\delta^{13}C$ depth profile at site On shows a uniform depth pattern throughout the whole profile (mean values between -27 and -26‰). The differences between Mn and On resulted most likely from a different vegetation at these sites leading to different isotopic signatures (Ménot and Burns, 2001; Skrzypek et al., 2008). Thus, $\delta^{13}C$ depth profiles of the natural sites have a pattern similar to the one expected from the theoretical concept for natural peatlands (Alewell et al., 2011; Krüger et al., 2014) and are considered suitable as reference sites.

At both of the drained sites mean $\delta^{13}C$ values increase from 30‰ to 26‰ in the upper 20-30 cm of the profile (Fig. 1). Increasing $\delta^{13}C$ values with depth of up to 4-5‰ are a sign of aerobic decomposition of organic matter (Nadelhoffer and Fry, 1988; Alewell et al., 2011; Krüger et al., 2014). Concerning the minerotrophic drained site the age of the peat, based on the radiocarbon analyses, is much older than the drainage onset at this depth indicating that the increase in stable isotope signature is caused by aerobic decomposition and not by a vegetation change. Further down in the profile the mean $\delta^{13}C$ values at the minerotrophic drained site are higher than at the natural site possibly indicating a slight effect of drainage even in the subsoil. However, at the ombrotrophic drained site the development of a secondary (raw) humus layer in the upper 10-15 cm of the profile can influence the $\delta^{13}C$ signal of the soil. Nevertheless, the $\delta^{13}C$ values between 20 and 40 cm depth of the profile are much higher at the drained site, again indicating aerobic decomposition of the organic matter. Further down in the profile of the drained site (40-100 cm depth), mean $\delta^{13}C$ values vary only little and indicate no effect of topsoil drainage on isotopic fractionation in these still water-saturated horizon. The latter is congruent with the results from Alewell et al. (2011) and Krüger et al. (2014). The $\delta^{13}C$ profiles of the drained sites indicate an effect of drainage activities in both upper parts and smaller effects in the deeper parts of the minerotrophic drained site whereas at the ombrotrophic drained site no effect in the deeper parts could be determined.

3.2. C-stock changes in peat soils drained for forestry

3.2.1. Combined method-subsoil and combined method-natural (I and II)

The combined methods, both with subsoil as well as with the natural site as reference, indicate a C loss at the Md as well as at the Od site (Fig. 2). At both sites highest loss rates were calculated with the combined method taking subsoil as reference (0.272 ± 0.034 kg C m^{-2} yr^{-1} for Md and 0.270 ± 0.108 kg C m^{-2} yr^{-1} for Od). The combined method with the natural site as reference resulted in lower calculated C loss rates (0.140 ± 0.150 kg C m^{-2} yr^{-1} for Md and 0.084 ± 0.194 kg C m^{-2} yr^{-1} for Od). C balance calculations by any of the two combined methods are uncertain in these shallow drained ecosystems owing to only small differences in ash content (Fig. S2), which result in non-significant differences in ash content between natural and drained sites. These methods are better applicable in more severely degraded peatlands with a stronger enrichment in ash. Furthermore, the combined methods might be in general more suitable for bogs, where the input of minerals is solely atmospheric. In fens, by contrast, inputs might not be exclusively atmospheric and other sources (e.g. transport with lateral groundwater flow) may influence the ash contents in minerotrophic peatlands. The influence of the ash profile by other sources than the atmosphere is displayed in the Mn profile where an ash peak is found in the first 20 cm of the profile similar to the Md profile (Fig. S2). The enrichment of ash in an undisturbed peat profile emphasizes that application of methods I and II is, at least in fens, fraught with uncertainty (Table 2).

3.2.2. C accumulation method (III)

Our calculated mean C accumulation rates for Mn and On are 0.020 (±0.001) kg C m^{-2} yr^{-1} and 0.024 (±0.002) kg C m^{-2} yr^{-1}, respectively. The mean C accumulation rates are approximately the same as the C accumulation rates by Minkkinen et al. (1999) of the minerotrophic and ombrotrophic part of Lakkasuo peatland with 0.021 kg C m^{-2} yr^{-1} and 0.026 kg C m^{-2} yr^{-1}, respectively. Furthermore, these accumulation rates of the natural parts of the Lakkasuo peatland are very close to mean C accumulation rates for fens (0.019 kg C m^{-2} yr^{-1}) and bogs (0.029 kg C m^{-2} yr^{-1}) in Finland reported by Turunen et al. (2002). The C accumulation approach reveals C losses of 0.069 ± 0.004 kg C m^{-2} yr^{-1} at Md and C gains of 0.139 ± 0.019 kg C m^{-2} yr^{-1} at Od (Fig. 2). This method is quite sensitive to differences in C accumulation rates as these values could vary spatial and temporally resulting in different amounts of C loss or C gain. For this approach it is necessary to take the C accumulation rates temporally close to the investigation period (drainage period) as the C accumulation is varying over time (Loisel et al., 2014).

3.2.3. Cumulative C-stock comparison method (IV)

The calculated C balance from the cumulative C-stock comparison method reveals a C loss of 0.057 ± 0.030 kg C m^{-2} yr^{-1} at Md and a C gain of 0.179 ± 0.083 kg C m^{-2} yr^{-1} at Od (Fig. 2). The results from the minerotrophic part are not significantly different from the rates calculated with the C accumulation approach. At the ombrotrophic site, results are also in the same range as those of the C accumulation method. The cumulative C-stock comparison method (IV) allows for determining a layer of same age. Unlike method III, the reference here is defined by age, not by depth. Depth as a reference in peatlands can be affected by compaction and different growth rates of the peat and is therefore less appropriate as a benchmark. Therefore, method IV is considered to be the most robust in terms of estimating differences in C accumulation or loss among sites.

3.2.4. Comparison of C balances to previous studies applying profile-based methods

For the Lakkasuo peatland Minkkinen et al. (1999), using changes in C-stock of volumetric peat samples defined by synchronous peat layers based on charcoal and pollen analyses, reported an annual C loss of 0.060 kg C m^{-2} yr^{-1} for Md and an annual C gain of 0.070 kg C m^{-2} yr^{-1} for Od. Calculated C changes of both ^{14}C approaches (method III and method IV) at the minerotrophic drained site are within the range of the values from Minkkinen et al. (1999). In contrast, our results using the combined methods at site Od are different to Minkkinen et al. (1999) (C loss instead of C gain). However, two other approaches from Finland, re-sampling and pairwise full peat column inventories, revealed a C loss of bogs and fens drained for forestry and of a bog drained for forestry of 0.150 kg C m^{-2} yr^{-1} (Simola et al., 2012) and 0.131 kg C m^{-2} yr^{-1} (Pitkänen et al., 2013), respectively. These results are in the range of our C losses calculated for Od by the two combined methods (0.084 kg C m^{-2} yr^{-1} and 0.270 kg C m^{-2} yr^{-1}). This shows that in general drained ombrotrophic peatlands in the boreal region does not necessarily maintain their C sink function.

3.2.5. Influencing parameters on C balances and comparison to gas flux measurements

According to our data, drainage of a nutrient-rich fen results in higher C losses or smaller C gains compared to the bog. Soil fertility plays a crucial role in modifying the impact of drainage for forestry on the greenhouse gas (GHG) balances in managed peatlands (IPCC, 2013). The minerotrophic part of the Lakkasuo peatland showed a higher increase in the annual CO_2 emissions of the drained peat compared to the ombrotrophic site (Martikainen et al., 1995; Silvola et al., 1996). Other studies from Finland confirm the influence of the nutrient status on the soil C balance in drained peatlands (Minkkinen and Laine, 1998; Minkkinen et al., 1999; Ojanen et al., 2013, 2014) and show higher C losses at nutrient-rich compared to nutrient-poor sites. Furthermore, at drained nutrient-poor sites root as well as moss production is higher than at drained nutrient-rich sites (Minkkinen et al., 2008), thereby providing higher organic matter inputs to soil. Additionally, soil temperature at the peat surface is lower in long-term drained peatlands compared to the natural ones which may have an additional effect on decomposition processes Minkkinen et al., 1999). The drainage at the ombrotrophic site resulted in a small water table draw-down leading to a slight increase in the CO_2 emissions which are compensated by an increase in the primary production resulting in enhanced carbon accumulation rates after drainage. Additionally, increased litter input by trees is mixed with the mosses at nutrient-poor sites that together often forms a secondary (raw) humus layer on top of the peat (Minkkinen et al., 2008). This increased input, when not counterbalanced by a significantly increase in decomposition, favours C accumulation at the drained nutrient-poor sites (Minkkinen et al., 2008). However, lowering of the water table by 15-30 cm would result in a release of carbon because under these conditions the soil carbon emissions are assumed to be greater than the primary production of the forested peatland (Silvola et al., 1996). All these factors foster C accumulation in the drained bog, whereas increased decomposition at the drained fen leads to a C loss. Furthermore, peat ages in both depths are much older at the drained parts compared to the natural ones indicating that the drainage activities have effects even in the deeper parts of the peat profile.

Net CO_2 flux rates in peatlands drained for forestry are highly variable (Silvola et al., 1996; Lohila et al., 2011; Meyer et al., 2013; Hommeltenberg et al., 2014). Several studies reported that such drained forests are still a C sink (Lohila et al., 2011) whereas others reported them to be a C source (Lindroth et al., 1998). Lohila et al. (2011) reported a C accumulation of 0.065 kg C m^{-2} yr^{-1} in a forestry drained peat soil in southern Finland as measured by eddy covariance (EC). Also with EC, Hommeltenberg et al. (2014) detected a stronger C sink in a bog drained for forestry (0.130-0.300 kg C m^{-2} yr^{-1}) than in a natural bog forest (0.053–0.073 kg C m^{-2} yr^{-1}). Furthermore, some studies determined a C balance of boreal drained peatlands close to zero (Dunn et al., 2007; Ojanen et al., 2014). These studies emphasize that further analysis by profile-based studies, besides flux measurements, on the C balance of drained peatlands for forestry in the boreal region are needed to determine whether and under which conditions these ecosystems function as a C sink or source.

4. Conclusions

A comparison of four applied profile-based methods revealed that the combined methods are applicable only on (strongly degraded) bogs and not on fens because fens also receive their nutrients from the groundwater. In contrast, both radiocarbon methods are suitable independent of the peatland type. Moreover, the cumulative C-stock comparison method (IV) seems more robust as it uses a layer of same age and not depth and is therefore not affected by compaction. However, all applied methods, except the combined method with subsoil as reference, require a natural site of the same peatland as reference. Hence, the site conditions co-determine which method for estimating the C balance has to be chosen.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.foreco.2016.09.006.

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Table 1. Site characteristics of the natural and drained parts of the Lakkasuo peatland in 1991 (Minkkinen et al., 1999).

	Minerotrophic		Ombrotrophic	
	Natural (Mn)	Drained (Md)	Natural (On)	Drained (Od)
Stand volume (m^3 ha^{-1})	0	111	5	16
Coverage Sphagna (%)	82	5	83	21
Coverage forest mosses (%)	0	58	0.4	32
Subsidence 30 years after drainage (cm)		23		-10
Water table median (cm)	2	36	13	26
Peat C store (kg C m^{-2})	70.9	68.0	77.6	79.0
Average C accumulation rate (g C m^{-2} yr^{-1})	21		26	
Bulk density (kg m^{-3})[a]	65	108	37	47
pH[a]	3.7	3.3	2.7	2.7
C (%)[a]	49.6	51.7	44.4	45.4
N (%)[a]	1.9	2.1	0.5	0.5

[a] 0–20 cm depth.

Table 2. Approaches, assumptions, analyses and required reference sites of the four different profile-based methods for calculating the soil carbon balance at the Lakkasuo peatland.

	Approach	Reference site	Analyses	Assumptions
Method (I)[a] combined method – subsoil	Differences in ash content between degraded upper part and undisturbed subsoil	Subsoil[A]	Ash content, bulk density, C%	Homogeneous ash input over time
Method (II) combined method - natural	Differences in ash content between degraded upper part and adjacent natural site	Natural site	Ash content, bulk density, C%	Spatial homogeneous ash input
Method (III)[b] C accumulation method	Comparison of C-stock calculated by C accumulation rates and age dated sample to cumulative C-stock	Natural site[B]	^{14}C, bulk density, C%	Constant C accumulation rates
Method (IV) cumulative C-stock comparison method	Comparison between the cumulative C-stock of drained and natural site above a layer of the same age	Natural site	^{14}C, bulk density, C%, age depth model	Same spatial C accumulation rates

[A] Needs an undisturbed subsoil as a reference. Input of, for instance, sand is problematic for this method. Probably only applicable on bogs, because fens receive their nutrients and water also from surrounding mineral soils.
[B] Could also use the C accumulation rates by comparable natural sites from the same region.
[a] Krüger et al. (2015b).
[b] Krüger et al. (2015a).

Figure captions

Fig. 1. Mean (±SE) of $\delta^{13}C$ values in depth profiles (n = 3) of the four study sites.

Fig. 2. Mean (±SD) annual soil C changes (kg C m^{-2} yr^{-1}) of the drained sites at Lakkasuo peatland based on the four different profile-based methods since the onset of drainage in the year 1961 (negative values indicate C loss from the soil and positive values a C gain).

Figures

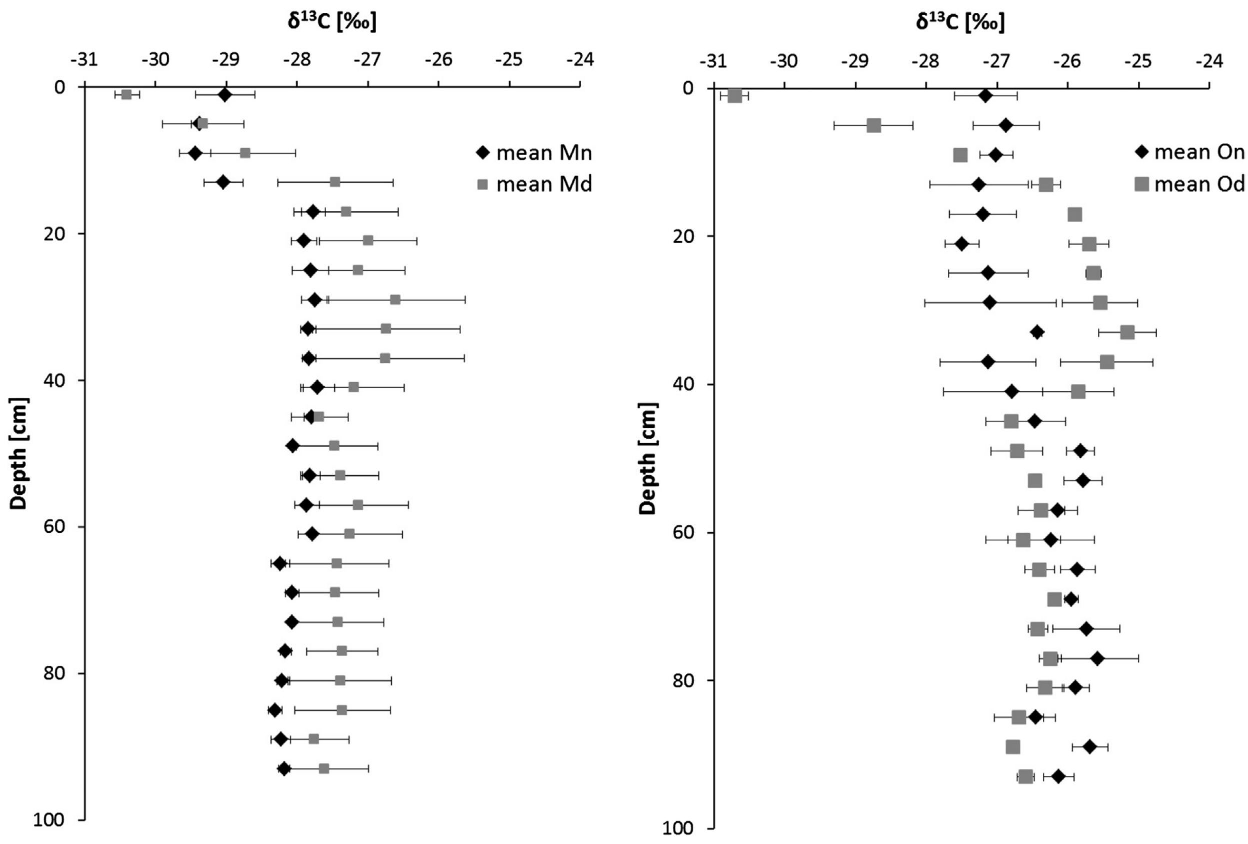

Figure 1

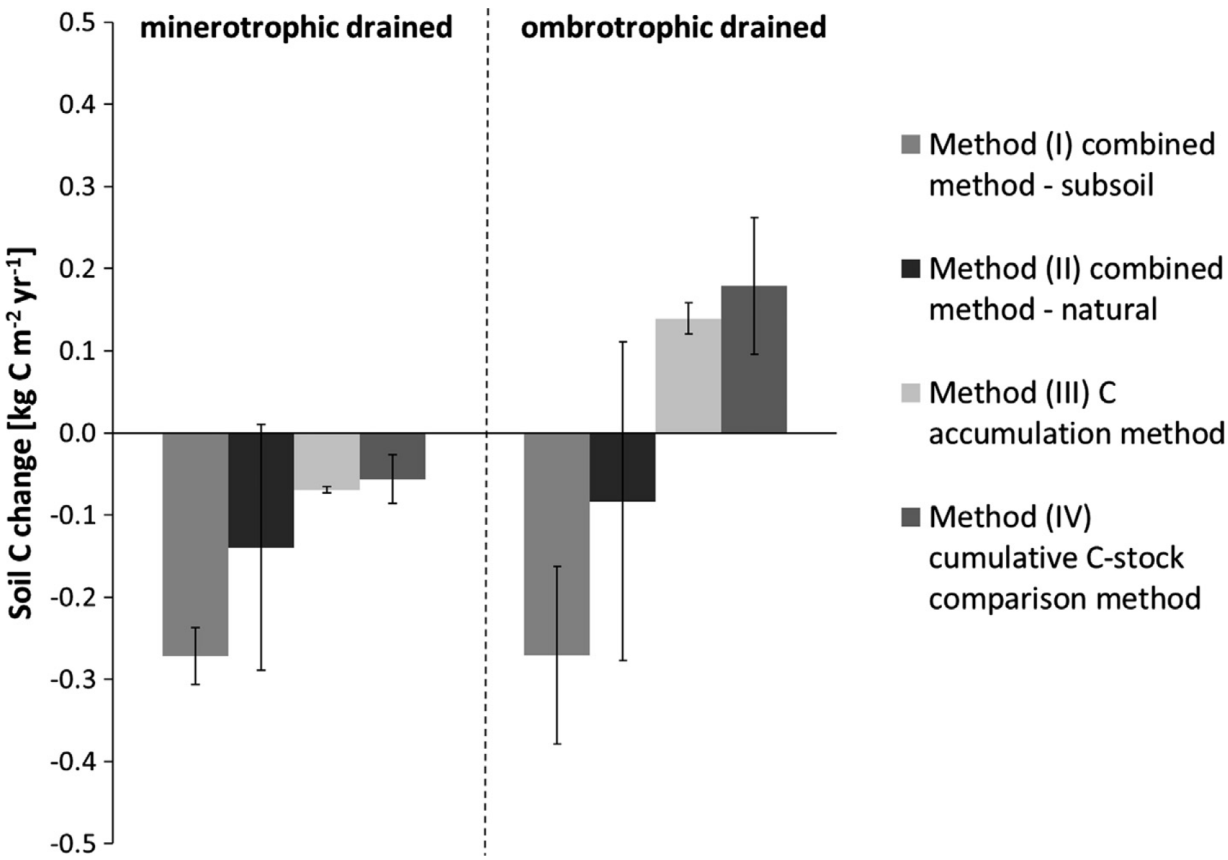
minerotrophic drained
ombrotrophic drained
Soil C change [kg C m-2 yr-1]
0.5
0.4
0.3
0.2
0.1
0.0
-0.1
-0.2
-0.3
-0.4
-0.5
Method (I) combined method - subsoil
Method (II) combined method - natural
Method (III) C accumulation method
Method (IV) cumulative C-stock comparison method

Figure 2