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Supplement of

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

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S1. Data materials

Reference numbers used in Table S1 and S2; (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 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)
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 publication.	Uri et al., 2017 / (46)

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 (IV)	NEE; NPP_{tr}; G_{rs}; S_{rs}; L_{Ars}; Di	-	Trenched plots included. Two calculus approaches in the publication.	Meyer et al., 2013 / (27)

				Assumed equal annual production and decomposition of litter from both leaves and roots. Whole year flux monitoring.	
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 = 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 decomposition on the soil surface.
$FR_{in/t.o}$ = Fine root production and decomposition.
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)
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 likely retained on the soil surface.	McNamara et al., 2008 / (26)
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 retained on the soil surface.	Väisänen et al., 2013 / (49)
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 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).

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