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Northern peatland carbon stocks and dynamics: a review

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Abstract

Here I review different approaches and associated uncertainties of estimates in the literature of carbon stocks and found that there is most likely 500 (±100 range) gigatons of carbon (Gt C) in northern peatlands. The greatest uncertainty for all the approaches is the lack or insufficient representation of data, including depth, bulk density and carbon accumulation data, especially from the world's large peatlands. Several ways to improve estimates of peat carbon stocks were also discussed in this paper. Changes in peatland carbon stocks over time, estimated using *Sphagnum* (peat moss) spore data and down-core peat accumulation records, show different patterns during the Holocene. Considering long-term peat decomposition using peat accumulation data allows estimates of net carbon sequestration rates by peatlands, or net ecosystem carbon balance (NECB), which indicates more than half of peat carbon (> 270 Gt C) was sequestrated before 7000 yr ago during the Holocene. Contemporary carbon flux studies at 5 peatland sites show much larger NECB during the last decade (32 ± 7.8 (S.E.) $g\,C\,m^{-2}\,yr^{-1}$) than during the last 7000 yr ($\sim 11\,g\,C\,m^{-2}\,yr^{-1}$) as modeled from peat records across northern peatlands. This discrepancy highlights the urgent need for carbon accumulation data and process understanding, especially at decadal and centennial timescales, that would bridge current knowledge gaps and facilitate comparisons of NECB across all timescales.

1 Introduction

Northern peatlands developed mostly after the last deglaciation in the circum-Arctic region and represent one of the largest carbon pools in the biosphere. Their dynamics have played an important role in the global carbon cycle during the Holocene (Gorham, 1991; Yu, 2011), and it has become essential to include peatlands in the modeling and analysis of the global carbon cycle to constrain the changes in other carbon reservoirs (Brovkin et al., 2002; Kleinen et al., 2010; Menviel and Joos, 2012) and in the

discussion of relative roles of anthropogenic and natural processes (Ruddiman et al., 2011). However, there are very different estimates of peat carbon stocks in the literature (e.g., Gorham, 1991; Turunen et al., 2002). Also, little is known about the sequestration history of peatland carbon stocks. Documenting and understanding the total carbon stocks and their accumulation histories will help project and understand possible surprise and changes of peatlands in the future (Moore, 2002; Frolking et al., 2011; Yu et al., 2011).

Here I provide a brief review of published estimates of carbon stocks, their accumulation histories, and comparison of contemporary and paleo carbon fluxes from northern (boreal and subarctic, or circum-Arctic) peatlands. Below in Sect. 2, I present an assessment of approaches, estimates, and uncertainties of carbon stocks. Although the focus of this review is on northern peatlands as a whole, I also comment on some studies with detailed regional analysis of carbon stocks, including Western Canada (including Mackenzie River Basin), Finland and West Siberia. Section 3 discusses peatland changes over time, where I review studies of using basal peat ages for peatland initiation histories, synthesis of carbon accumulation rates, and histories of carbon stocks and modeled net ecosystem carbon balance (NECB). In Sect. 4, I discuss and compare the peat-core derived Holocene carbon sequestration rates with contemporary NECB from several peatland carbon flux sites and emphasize the lack of data and understanding of peatland carbon dynamics at decadal and centennial timescales. In the last Sect. 5, I highlight some future research directions and activities that will facilitate the understanding of peatland carbon dynamics.

2 Total carbon stocks in northern peatlands

2.1 Approaches

Three approaches have been used to estimate carbon stocks in peatlands: peat volume, carbon density and time history approaches (Table 1). All these approaches

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require information on present peatland area. The peat volume approach focuses on estimates of mean peat depth in order to derive the total peat volume (along with peatland area), and then uses bulk density and carbon proportion (carbon concentration) data to convert volume to mass and carbon (e.g., Gorham, 1991). The carbon den-
5 sity approach requires similar data, but focuses on estimating total carbon content of unit area (that is, soil carbon density) and then derives total carbon stocks by multiplying peatland area and soil carbon density (Armentano and Menges, 1986). This is a commonly used approach, also called "paint-by-number" approach, to empirically estimate carbon stocks of other ecosystem types (biomes) and of terrestrial biosphere as
10 a whole (Schlesinger, 1977). Bulk density and carbon concentration data are derived from peat/soil profiles (pedons) to certain depth (oftentimes the top 1 m) to calculate carbon density. The time history approach relies on data from carbon accumulation rates (carbon accumulated in unit area per year as derived from individual peat cores) and peatland areas over time to first calculate carbon stocks at each time interval and
15 then sum up all time intervals for total carbon stocks. The time history approach is the only approach explicitly using multiple ages from individual peatlands (Yu et al., 2010), though Turunen et al. (2002) used mean peat ages for extrapolation of Finnish data to northern peatlands (see below).

All these approaches can be first applied to a peatland region or a type of peatland
20 region, and then sum up data from different peatland types and regions for the total carbon stocks. However, oftentimes due to lack of detailed regional data many studies lumped all regions together for a single estimate of carbon stocks in northern peatlands. For example, Gorham (1991) used area-weighted depth and bulk density data from different major peatland regions to estimate a single mean peat depth and average
25 bulk density for estimating total carbon stocks of northern peatlands using the peat volume approach. In the applications of the carbon density approach, most studies used a single value for carbon density (e.g., Schlesinger, 1977; Lappalainen, 1996), while Armentano and Menges (1986) estimated carbon density values for peatlands in different regions and then summed up for all northern peatlands. Yu et al. (2010) only

presented a single estimate of carbon stocks and history using average accumulation rates and peatland area change at every 1000-yr interval over the Holocene for the entire northern peatlands. Table 1 shows the equations used in different approaches, the required data, and examples from the literature.

2.2 Carbon stock estimates and uncertainties

Several peatland carbon stock estimates have been published using the peat volume approach. Sjörs (1980) provided one of the first estimates of peatland carbon stocks using highly rounded and approximate values for peatland area, depth and bulk density. Sjörs (1980) estimated carbon stocks of 300 Gt C (gigatons of carbon) in northern peatlands (Table 2; Fig. 1). Gorham's (1991) estimate of 455 Gt C is the most widely cited figure for carbon stocks in northern peatlands. This estimate is more than doubled the estimate a year earlier by the same author (Gorham, 1990), mostly owing to the use of the revised and higher values for mean depth of 2.3 m and bulk density of 0.112 g cm^{-3} in Gorham (1991). On the basis of the detailed peatland inventory data from Finland (Mäkilä, 1994), Turunen et al. (2002) indicated that the mean depth and bulk density values used by Gorham (1991) were too high, and they estimated a total carbon stock of 270–370 Gt C in northern peatlands by extrapolating Finnish data. However, peatlands in Finland only represent a carbon stock of 2.3 Gt C – it is much too small a peatland region to be representative of the entire northern peatlands. Bulk density values from other large peatland regions are higher than the mean bulk density of 0.078–0.091 g cm^{-3} from Finland (Mäkilä, 1994; Turunen et al., 2002). For example, in Continental Western Canada a large database of 2167 peat samples from 120 peatland sites suggests a mean bulk density of 0.093 g cm^{-3} (Zoltai et al., 2000; Beilman et al., 2008), while Vitt et al. (2000) reported bulk density values of 0.094 g cm^{-3} for open fens and of 0.105 g cm^{-3} for wooded and shrubby fens. A summary of detailed peat-core analysis data from 14 cores at 12 sites in Continental Western Canada shows a mean bulk density value of 0.122 g cm^{-3} (ranges from 0.068 to 0.176 g cm^{-3}) (Yu, 2006). Also, recent estimates of mean peat depths in some large peatland regions

seem to be similar to the mean depth of 2.3 m used by Gorham (1991). For example, Riley (2011) reported mean peat depths from 1.88 to 2.55 m for bogs and from 1.37 to 2.15 m for fens from the south to north in the Ontario Hudson Bay Lowlands, similar to his earlier estimate of overall mean depth of 2.2 m (Riley, 1994). The Mackenzie River Basin of Northern Canada (overlapping with part of Continental Western Canada), the second largest peatland complex in North America representing a total carbon stock of 13–18 GtC, has an overall mean depth of 2.22 m (Vitt et al., 2005). In a detailed spatial analysis of peatlands in the Southern Mackenzie River Basin, Beilman et al. (2008) reported a mean peat depth of 2.5 m (ranging from 0.5 to 6 m). Also, mean peat depth in West Siberia (the largest peatland basin in the world) is more than 2 m (Sheng et al., 2004). All these recent depth estimates from these large peatland regions are much deeper than Finnish peatlands of 1.1 m used in Turunen et al. (2002). These regions also contain much larger carbon stocks, 16 GtC in the Mackenzie River Basin (Vitt et al., 2005), 48 GtC in Continental Western Canada (Vitt et al., 2000), and 70.2 GtC in West Siberian Lowlands (Sheng et al., 2004). Thus, very likely the estimate of 270–370 GtC in carbon stocks of northern peatlands by Turunen et al. (2002) is an underestimate.

As indicated above, the carbon density approach is one of the common approaches used for scaling up carbon stocks for different biomes based on the average or representative carbon density value. Carbon stock estimates for wetlands or peatlands were often done as part of global soils or ecosystem carbon stock estimates (Schlesinger, 1977; Post et al., 1982; Adams and Faure, 1998). Also, most of the available world's soil survey data are for the top 1 m of soil carbon density (e.g., GSDTG, 2000), so this often results in significant underestimates of carbon density and total carbon stocks (Table 2). The carbon stocks of 234–252 GtC estimated by Lappalainen (1996) is one of the most recent estimates using the carbon density approach in a study focusing only on peatlands, but it is surprisingly low, likely due to the very low soil carbon density value (58.7–63 kg C m^{-2}) used by Lappalainen (1996), which is even lower than the ones only for the top 1 m soils/peat in other studies using the carbon density approach

(Table 2). Another factor for very low estimates in most studies using the carbon density approach is the small peatland area used (e.g., Schlesinger, 1977; Post et al., 1982; Oechel, 1989). The estimate of 466 Gt C by Adams and Faure (1998) is not really an estimate using the carbon density approach (they only indicated a vegetation biomass
5   carbon density of 2 kg C m^{-2}), but they used an assumed rate of peat carbon stock buildup at 46 Gt C kyr^{-1} since the beginning of the Holocene. Another estimate only for part of the peatland domain is from soil survey (pedon/soil profile) data for circum-Arctic permafrost regions by Tarnocai et al. (2009), which estimated carbon stocks of 280 Gt C in peatlands of permafrost regions.

10   The time history approach relies on peatland development histories to estimate total carbon stocks during the Holocene and beyond. Yu et al. (2010) provided a first estimate of peatland carbon stocks using dated carbon accumulation records and the peatland area change over time as derived from basal ages. They calculated mean carbon accumulation rates for each 1000-yr bin during the Holocene from 33 dated peat
15   profiles across northern peatlands (Fig. 2c; Yu et al., 2009). Also, they derived a first approximation of peatland area change over time at 1000-yr intervals (Fig. 2b) using the 1516 basal peat ages across the northern peatland domain (Fig. 2a; MacDonald et al., 2006), under the assumption that the expansion rates of individual peatlands were constant, or peatland area has increased linearly, since their peatland initiation
20   and formation (Yu et al., 2010; Yu, 2011). Yu et al. (2010) estimated a carbon stock of 547 Gt C in northern peatlands, with a range of 473–621 Gt C based on the standard errors of mean carbon accumulation rates.

The major uncertainties for all approaches discussed above are related to the data coverage gaps and representation of available data. Turunen et al. (2002) indicated
25   that the large differences between various estimates using the peat volume approach (Fig. 1; Table 2) were caused by uncertainties in mean peat depth and bulk density values used. Similar uncertainties apply to carbon density values, as they are ultimately based on the values of peat/soil depth, organic matter/carbon concentration, and bulk density used. Also, large errors may be introduced when the data from one peatland

region were extrapolated to the entire northern peatlands, as Turunen et al. (2002) did with detailed peatland data from Finland. Underrepresentation of the world's large peatlands (Yu, 2011) and of shallow peats in peatland margins in existing datasets (Khury and Turunen, 2006) may be another problem. To increase the representation of mean peat depth and bulk density values, data from other large peatland regions, such as West Siberia (Sheng et al., 2004), Continental Western Canada (Vitt et al., 2000), and the Mackenzie River Basin (Vitt et al., 2005) should be integrated and synthesized with detailed data available from Finland (Clymo et al., 1998; Turunen et al., 2002). For the time history approach, the major uncertainties are the history of peatland area change over time as well as the representativity of the carbon accumulation records used. For example, likely peatland expansion is highly nonlinear after initiation, as documented at site-scale studies (Korhola, 1994; Korhola et al., 1996; van Bellen et al., 2011; Loisel et al., in review). Therefore, the assumption of linear peatland expansion used in Yu et al. (2010) might have greatly underestimated the peatland area in their early development history and, as a result, the overall carbon stocks.

In all these studies of carbon stocks in northern peatlands (Table 2), there appears to be a convergence in the total peatland area. Most authors used an area between 3.5 and 4 million km^2, so an average of about 3.7 million km^2 or a rounded value of 4 million km^2, would be a reasonable value to use for Holocene peat carbon stock estimates, especially considering the loss of peatlands through drainage or other disturbances during historical times that have not been considered in some area estimates. This area estimate is similar to the recent estimate of 3.7 million km^2 from detailed tabulation of peatland areas in each country of the world (Joosten and Clarke, 2002). These include peatlands areas of 0.617 million km^2 in Europe, of 1.18 million km^2 in Asian part of Russia, and of 1.86 million km^2 in North America (1.235 million km^2 in Canada, and 0.625 million km^2 in the US) (Joosten and Clarke, 2002; their appendix 1). Maltby and Immirzi (1993) estimated the area of northern peatlands at 4 million km^2, and Bridgham et al. (2006) used 4 million km^2 of global peatland area for their carbon flux calculations. To put the estimates of peatland area in context, estimates for global

wetland (including peatlands) area range from 5.26 million km^2 (Matthews and Fung, 1987) to 9.167 million km^2 (Lehner and Döll, 2004).

For peat carbon stock estimates, it is worth noting that two very different approaches produced surprisingly similar estimates of 455 Gt C using the peat volume approach by Gorham (1991) and of 547 Gt C using the time history approach by Yu et al. (2010). Both converge at a rounded figure of 500 Gt C. In their review on the carbon balance of North American wetlands, Bridgham et al. (2006) found that global peatlands contain from 234 to 679 Gt C, including 178 Gt C in North America, with about 150 Gt C in Canada (Roulet, 2000; Tarnocai et al., 2005). Botch et al. (1995) estimated a carbon pool of 214 Gt C in peatlands of the Russian Federation. Based on these estimates, peatlands in North America and Russia alone would amount to about 400 Gt C. Therefore, considering all the uncertainties in estimating these values (see above), it is probably only justifiable and desirable to state the carbon stocks in northern peatlands with one significant figure (Davidson and Janssesn, 2006; Yu, 2011). As such, northern peatlands most likely contain about 500 ± 100 Gt C (or 20 % uncertainty range). A more precise statement and a comprehensive error analysis of carbon stock estimates in northern peatlands are desirable but still out of reach.

3 Peatland changes over time

Knowledge about historical trajectories of peatland carbon sequestration is needed to evaluate peatlands contribution to the global carbon cycle during the Holocene. The most widely available data sets are basal peat ages that have been used as a proxy of peatland initiation histories. MacDonald et al. (2006) provided the first most comprehensive compilation of basal ages from northern peatlands (Fig. 2a), showing peak peatland initiation in the early Holocene, and Yu et al. (2010) presented the similar first data sets for tropical peatlands and southern (mostly Patagonian) peatlands. Several regional compilations of basal peat ages also have been published, including for Southern Finland (Korhola, 1995), Western Canada (Halsey et al., 1998; Campbell

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et al., 2000), West Siberia (Smith et al., 2004), North America (Gorham et al., 2007), and Alaska (Jones and Yu, 2011). As a first approximation, the basal ages in Mac-Donald et al. (2006) were used to derive peatland area changes over time (Fig. 2b; Yu et al., 2010).

Another aspect of peatland dynamics is carbon accumulation intensity, that is, accumulation rates per unit peatland area. Tolonen and Turunen (1996) compiled a large dataset of basal ages and total amount of carbon from each of 1028 peatland columns in Finland and found a monotonic increasing trend in apparent carbon accumulation rates during the Holocene, from $\sim 15\,\mathrm{g\,C\,m^{-2}\,yr^{-1}}$ in the early Holocene to $\sim 45\,\mathrm{g\,C\,m^{-2}\,yr^{-1}}$ in the late Holocene. They also found that bogs overall have higher accumulation rates than fens, and there are larger data scatter and variability during the late Holocene than in the early Holocene. Tolonen and Turunen (1996) also plotted and compared similar data from 113 boreal and subarctic peatlands in Western Canada, mostly from Zoltai (1991), and found higher accumulation rates in the recent millennia, with the lowest rates around 4000 yr ago, especially from subarctic peatland sites. In both regions, the recent high accumulation rates were caused by autogenic process due to limited decomposition of recent peat (Clymo, 1984; Belyea and Baird, 2006). However, the depressed carbon accumulation around 4000 yr ago might be caused by the initiation (aggradation) of permafrost during neoglacial climate cooling in this region (Zoltai, 1993). The accumulation rates calculated this way using a single basal age are termed long-term apparent rates of carbon accumulation (LORCA) by Tolonen and Turunen (1996). Khury and Turunen (2006) also provided a nice review of some LORCA data and results. As commented recently by Tarnocai et al. (2012) that "basal dates generally provide unreliable estimates for peat or carbon accumulation", as "[p]eatlands affected by fires and/or erosion have reduced amounts of peat material". I also argue that the fundamental problem inherent in LORCA data is their inability of identifying and locating the time intervals when these disturbances and the reduced carbon accumulation occurred in the past. However, it may be possible to make more meaningful use of these large and valuable basal age datasets, if a new approach and

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methodology can be developed in analyzing the data. Some later studies expanded the initial definition of LORCA by also including accumulation rates calculated from multiple age determinations along peat profiles. It has become confusing as both types of accumulation data have different meaning and limitations. So proliferation of these
5 terms and acronyms may not help the understanding and communication of long-term carbon dynamics in peatlands.

An alternative way to derive carbon accumulation rates is based on peat profiles with multiple age determinations and carbon amount measurements. Using this approach we avoid the problems associated with unidentified disturbance-related peat removal or
10 slowdown and subsequent underestimate of overall average peat accumulation rates, as we briefly discussed in Yu et al. (2012). Using this approach we recently compiled a total of 33 peatland sites with multiple ages per site and detailed carbon measurements across the circum-Arctic region (see Fig. 3 for site locations on climate space) to derive a synthesis history of average carbon accumulation rates for northern peat-
15 lands, which shows the highest carbon accumulation in the early Holocene (Fig. 2c; Yu et al., 2009). These records would more precisely show any disturbance-related loss of carbon at 1000-yr intervals as reflected in a decrease in carbon accumulation rates.

The product of peatland area and mean carbon accumulation rates for every 1000-yr interval during the Holocene was used to estimate the net carbon pool (NCP) that
20 is currently stored in peatlands (Fig. 2d; Yu, 2011). By taking into account the loss of peat carbon through decomposition after the production and deposition of peat, Yu (2011) used a decay model to back-calculate the amount of carbon lost and provided an estimate of net carbon balance (NCB) for every 1000-yr interval during the Holocene (Fig. 2d). NCB would represent the carbon sequestration by peatlands at different times
25 in the past before their subsequent and inevitable decomposition, so we argue that NCB is the carbon flux term that should be used to discuss contributions of peatlands to the global carbon cycle (Yu, 2011; Yu et al., 2011). Both NCP and NCB represent the same amount of net carbon accumulated in peatlands (so the same area under these two curves in Fig. 2d), but the main difference is their respective histories of

carbon sequestration at any time in the past. For example, the observed NCP showed a general increasing trend over the Holocene, while the highest NCB occurred in the early Holocene, as the decomposition loss of old peat was calculated and added to earlier NCB. Consequently, cumulative histories of NCP and NCB are also different, with cumulative NCB showing sharp increase in carbon stocks earlier in their accumulation histories than cumulative NCP (Fig. 2e). The cumulative NCB results indicate that northern peatlands sequestered close to 400 Gt C before 5000 yr ago, about 70 % of the current total of 547 Gt C.

In their analysis of soil chronosequence data, Harden et al. (1992) indicated that peak peatland expansion occurred at 8000–4000 yr ago in glaciated North America. Based on global land ecosystem reconstructions, Adams and Faure (1998) provided an estimate of carbon storage on land since the last glacial maximum. They assumed a constant linear rate of peat carbon stock increase over the Holocene at 46 Gt C per 1000 yr for a total peat carbon stock of 466 Gt C (Table 2). Halsey et al. (2000) used the abundance of *Sphagnum* (peat moss) spores as recorded in the North America Pollen Database to map the extent of peatlands in North America. Similarly, Gajewski et al. (2001) scaled up the total carbon stocks of 455 Gt C as estimated by Gorham (1991) throughout the last 21 000 yr on the basis of abundance of *Sphagnum* spores from the Global Pollen Database. Gajewski et al. (2001) found that most peat carbon was accumulated in the late half of the Holocene, with about 350 Gt C accumulated in the last 5000 yr, about 78 % of 455 Gt C total (Fig. 2e). We argue that *Sphagnum* spores approach likely underestimates the extent of peatlands in the early Holocene, at which time peatlands (mostly rich fens) were often dominated by non-*Sphagnum* plants (Gajewski et al., 2001; Yu, 2011; Yu et al., 2012). Gorham (1991) also indicated that northern peatlands accumulate their carbon mostly in the late half of the Holocene. These Holocene histories of carbon sequestration were very different from our recent analysis using the time history approach (Yu et al., 2010), as discussed above. At regional scales, Vitt et al. (2000) showed that about half of total carbon stock (48 Gt C) in peatlands of Continental Western Canada was observed in the last 3000–2000 yr, but

after considering long-term peat decomposition the temporal pattern changed slightly
– a similar general pattern as in Gajewski et al. (2001) for northern peatlands. These
differences have significant implications for understanding peatlands' role in the global
carbon cycle (Yu, 2011; Yu et al., 2011; Ruddiman et al., 2011).

4   Carbon fluxes across timescales

Holocene carbon sequestration histories provide opportunities to assess and under-
stand peatland carbon fluxes over different time scales. "True" instantaneous car-
bon accumulation rates as derived from NCB (Fig. 2d) and peatland areas over time
(Fig. 2b) were plotted on log scale of ages to emphasize the different time scales
(Fig. 4b; Yu et al., 2011). The accumulation rates (NCB) ranged from the highest value
of $38\,\mathrm{g\,C\,m^{-2}\,yr^{-1}}$ at 8000–9000 yr ago to the lowest of $5.6\,\mathrm{g\,C\,m^{-2}\,yr^{-1}}$ at 2000–3000 yr
ago. The Holocene average rate is $19\,\mathrm{g\,C\,m^{-2}\,yr^{-1}}$, but the rates were about half of that
during the later half of the Holocene. For example, the last millennium had a rate of
$10.4\,\mathrm{g\,C\,m^{-2}\,yr^{-1}}$, and the mean rate for the last seven millennia was $11.1\,\mathrm{g\,C\,m^{-2}\,yr^{-1}}$
(Fig. 4b). As the calculations of carbon accumulation rates consider all carbon gains
(photosynthetic uptake) and losses (respiratory, leaching and disturbance-related re-
lease) from peatlands during their histories, we argue that these rates are conceptually
equivalent to the net ecosystem carbon balance (NECB) as from contemporary car-
bon flux studies in peatlands and other ecosystem types (Chapin et al., 2006; Olefeldt
et al., 2012). However, the time periods used for the NECB measurements or calcu-
lations need to be specified when describing NECB as a functioning property of peat-
land ecosystems, as long-term carbon accumulation rates and contemporary NECB
measurements integrate over very different lengths of time. In other words, we do not
know how many years would be needed for contemporary NECB to approach a stabi-
lized mean value, or what is the likely variability at centennial, decadal and interannual
timescales for each 1000-yr interval of integrated carbon accumulation rates (NCB).

How do these long-term Holocene carbon sequestration rates derived from peat-core records compare with contemporary C flux measurements? To my knowledge, there are five peatland sites that have measurements for all carbon flux terms over multiple years, including CO_2 uptake by photosynthesis and release by ecosystem res-piration, CH_4 emissions, and dissolved organic carbon (DOC) discharges from peat-lands (Table 3; Roulet et al., 2007; Nilsson et al., 2008; Dinsmore et al., 2010; Koehler et al., 2011; Olefeldt et al., 2012). When plotted on the temperature-precipitation cli-mate space, all these sites are located near the warm fringe of the boreal peatland domain, although spanning essentially the entire precipitation range (Fig. 3). There are large interannual variations at most of these sites with long records, including the largest observed carbon sink of $101\,g\,C\,m^{-2}\,yr^{-1}$ at Auchencorth Moss, Scotland in 2007 (Dinsmore et al., 2010) and the great carbon source to the atmosphere of $-13.8\,g\,C\,m^{-2}\,yr^{-1}$ at Mer Bleue, Ontario (Roulet et al., 2007). Most variability at inter-annual timescale was caused by weather and resultant changes in temperature and peatland hydrology. Obviously, due to the large interannual variability, NECB measure-ments from any particular year or multiple years may not represent the carbon se-questration capacity for a particular peatland over long timescales. The overall mean of a total of 18 yr of measurements from these five peatland sites is $32.3\,g\,C\,m^{-2}\,yr^{-1}$ (with a standard error of the mean at $7.8\,g\,C\,m^{-2}\,yr^{-1}$), shown as a solid circle in Fig. 4a. This mean NECB, or carbon accumulation rate, of $32.3\,g\,C\,m^{-2}\,yr^{-1}$ from contemporary car-bon flux measurements is about three-fold higher than the rates in the last millennium ($10.4\,g\,C\,m^{-2}\,yr^{-1}$) or the mean rate over the last seven millennia ($11.1\,g\,C\,m^{-2}\,yr^{-1}$), but similar to the rate during the Holocene thermal maximum in the early Holocene (Fig. 4b). Also, when comparing the contemporary NECB at individual sites with the carbon accumulation rates at the nearest long-term sites (Fig. 3) I found that NECB is about 2 to 7 times higher than Holocene average carbon accumulation rates (Yu et al., 2009; their Table 1). However, it is interesting to note that a first direct compara-tive study at Mer Bleue showed no statistical difference between contemporary NECB

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and carbon accumulation rates estimated for the last 3000 yr from peat-core analysis (Roulet et al., 2007).

If the derived Holocene NCB and "true" carbon accumulation rates are robust and representative and if the measured contemporary NECB are representative of these ecosystems, then what could have contributed to the much higher NECB at these flux sites over the recent decade? We speculated that the environmental conditions at the present may no longer be "natural", owing to recent global changes, including climate warming, elevated CO_2 concentration and subsequent CO_2 fertilization effect, and increased nitrogen deposition (Yu et al., 2011). I added two additional sites (Auchencorth Moss, and Stordalen) in the synthesis here, compared to an earlier analysis (Yu et al., 2011), and the updated mean value of $32.3\,\mathrm{g\,C\,m^{-2}\,yr^{-1}}$ is higher than the earlier mean of $25\,\mathrm{g\,C\,m^{-2}\,yr^{-1}}$ from three sites (Yu et al., 2011), suggesting again the high interannual and between-site variability of contemporary NECB measurements. Alternatively, these contemporary study sites are not representative of most peatlands in these regions, as researchers tend to select more productive and less-disturbed sites for eddy covariance tower and other flux measurements. For example, fires and possibly flooding have been frequent disturbances in peatlands during the Holocene that often cause large carbon loss from ecosystems and reduce net carbon accumulation rates, and these carbon losses were implicitly accounted for in our Holocene NCB calculations. However, these disturbances were likely prevented or suppressed during the period of carbon flux measurements at these flux study sites. Furthermore, the positions of these sites in the climate space indicate that all these flux sites represent peatlands under the warmest climates with similar precipitation, while the sites used for peat-core derived estimates of Holocene NCB were more widely distributed in the northern peatland climate domain (Fig. 3). If the NECB is indeed higher at the warm fringe than under a cold climate, then this observation suggests that temperature is a dominant control on peatland carbon balance at this spatial scale. This suggestion appears to be supported by peatland CO_2 flux studies. In a synthesis of eddy covariance flux studies from 12 peatland and wet tundra sites from temperate to Arctic climates, Lund

et al. (2010) found that the length of growing seasons is the most important variable explaining the spatial variation in summertime gross primary production and ecosystem respiration, both together determining the net ecosystem exchange (that is, CO_2 flux component of NECB). Also, Lund et al. (2010) concluded from their synthesis results that gross primary production would increase more with a prolonged growing season as compared with ecosystem respiration. This suggests that a warm climate would stimulate more carbon uptake. Therefore, if there is no major difference in CH_4 and DOC fluxes among these sites, it is possible that these high contemporary sites only capture NECB from the most productive peatlands under warm climates, which do not necessarily represent other northern peatlands.

Spatial scales have been considered as an important factor affecting carbon dynamics in peatlands (Waddington and Roulet, 2000; Belyea and Baird, 2006; Limpens et al., 2008; Baird et al., 2009). However, less attention has been paid to the discussion of temporal scales in the literature. Peatland carbon dynamics may have been controlled by different factors at different temporal and spatial scales. For example, both hydrology and temperature may play major roles in determining the carbon balance at interannual scales at individual sites (Fig. 4a), but some data show that summer temperature might have played a major role in carbon accumulation at millennial scales in the early Holocene over the entire northern peatlands (Yu et al., 2009, 2010) and at the regional scale in Alaska (Jones and Yu, 2010). Also, temperature and precipitation may have different impacts on different components of the carbon balance (CO_2, CH_4 and DOC) (see above discussion; Lund et al., 2010). Therefore, it is conceivable that different factors may control carbon dynamics and balance at decadal and centennial time scales, the most relevant time scales for climate impact and feedback assessments (Yu et al., 2011). However, at the present there are major data and knowledge gaps at this intermediate timescale (Fig. 4).

5   Concluding remarks

The following outstanding issues and relevant future research directions are discussed for improving peatland carbon stock estimates and for understanding peatland carbon dynamics.

5.1   Filling data gaps and increasing data representation

We have very limited data and information from several large peatland regions in the world, including the Hudson Bay Lowlands (see some paleo studies in Glaser et al., 2004, and general overview of these peatlands in Riley, 2011), East Siberia and the Far East of Russia (Yu et al., 2009). Filling these data gaps is essential for robust estimates of peatland carbon stocks and Holocene carbon dynamics. Also, it would be preferable and ideal to generate separate carbon stock estimates for different regions, as done for Continental Western Canada (Vitt et al., 2000), Finland (Turunen et al., 2002), West Siberia (Sheng et al., 2004), and the Mackenzie River Basin (Vitt et al., 2005; Beilman et al., 2008), before we sum all these together to derive estimates for the entire northern peatlands. This means that we need to develop region-specific values of mean peat depth and bulk density values using the peat volume approach (or carbon density approach). Similarly, regional patterns of peat carbon accumulation could be developed if more accumulation records were available from different regions. So eventually not only a more representative database will be developed for the entire northern peatlands, but also we have the information to discuss regional differences in peatland carbon sequestration and their controls by regional climate. One possible way to expand the carbon accumulation records is to use the still underutilized basal peat age database (> 2500 compiled dates available; MacDonald et al., 2006; Gorham et al., 2007; Kohorla et al., 2010) for calculating LORCA as described in Tolonen and Turunen (1996). However, a new approach needs to be developed to decompose the observed LORCA data into net carbon balance (NCB) or its equivalent. Also, it would be

useful to compare results of carbon stock estimates of the same region using different (e.g., peat volume vs. time history) approaches.

5.2 Establishing empirical relationship and process understanding

Before we reach our goals of sampling all major peatland complexes, we inevitably need to extrapolate knowledge learned from subsets of peatland regions to the entire northern peatlands. Understanding peatland processes and establishing empirical relationships between important peatland properties (area, depth, and ages) in well-studied regions are essential to make immediate progress in generating more robust carbon stock estimates. For example, Zoltai (1991) and Vitt et al. (2000) developed relationships between peat ages and depth (cumulative mass) from their large regional data sets or individual sites from West-Central Canada. Thus, it would be highly valuable to establish relationships of the essential parameters of depth, ages and bulk density for different types of peatlands in regions that have detailed information (Finland: Clymo et al., 1998; Turunen et al., 2002; Continental Western Canada and the Mackenzie River Basin: Vitt et al., 2000, 2005; West Siberia: Sheng et al., 2004). Then, these relationships can be used to estimate essential parameters and carbon stocks in other remote or understudied regions. A promising approach would be to stratify other peat carbon properties (such as bulk density, carbon density) by peatland types and stratigraphic depths as suggested by Beilman et al. (2008). Riley (2011) also emphasized the importance of establishing the relationship between peatland types and peat depth in calculating peat volume and carbon, as in remote parts of the Hudson Bay Lowlands. Also, the established relationships may contribute to the development of new approaches for using basal ages and the derived LORCA for modeling net carbon balance.

5.3 Focusing on peatland lateral expansion data and process

Peatland lateral expansion is an important process that is likely controlled by local topography and regional climate. Peatland expansion dynamics during the Holocene directly affects the estimates of change in peatland area over time. There are limited data available at individual sites, as the data collections and analysis are often expensive and labor intensive (see Korhola, 1994; Bauer et al., 2003; van Bellen et al., 2011; Loisel et al., 2012). As a result, peatland expansion processes are not well understood. The novel method of analyzing the multidate data sets as presented in Korhola et al. (2010) would be needed to derive a robust peatland expansion history during the Holocene. Also, more studies at peatland site scale are needed, especially using the combination of ground penetration radar (GPR) for large-scale survey and peat-core analysis for detailed depth and age determinations. This approach has been successfully used in some recent studies (van Bellen et al., 2011; Loisel et al., 2012). In the future combining GPR, LIDAR and other remote sensing tools with peat-core analysis will allow us to generate not only surface morphology information but also subsurface stratigraphy to understand peatland expansion process on landscape at the present and in the past. Also, a general model of peatland lateral expansion that incorporates climate (e.g., precipitation, or recharge rate) and topography (e.g., slope), potentially modified and integrated from existing models (e.g., Ingram, 1982; Couwenberg, 2005; Morris et al., 2011), would help derive necessary parameters for estimating peatland expansion rates during the Holocene.

5.4 Understanding carbon dynamics across timescales

There are major data and knowledge gaps at the timesscales of decades and centuries (Fig. 4), which prevent understanding peatland carbon dynamics at this intermediate, but most relevant, timescale. ^{210}Pb and post-bomb AMS ^{14}C dating and carbon analysis of recent peat cores are needed to fill this important data gap (e.g., Wieder, 2001; Turetsky et al., 2004; Malmer and Wallén, 2004). Data sets used in a recent

data synthesis of the last millennium peat carbon dynamics (Charman et al., 2012) can be further explored for deriving net carbon balance at 100-yr intervals for the last 1000 yr. Also, as pointed out by Roulet et al. (2007) we "need more replications across a diverse set of ecoclimatic regions and other peatland types" for contemporary NECB measurements, and I argue that measurements from sites in colder boreal and sub-arctic climates would fill an important data and knowledge gap (Fig. 3). In addition to large-scale synthesis effort, further analyzing contemporary flux and paleo data from the same site (e.g., Roulet et al., 2007) by decomposing peat-core data to NECB equivalent at site scale (Yu, 2011) may provide insights into carbon dynamics across different timescales. Robust comparisons between long-term and contemporary carbon balance would also require a systematic error analysis, but this goal is still elusive due to under-representation of both types of data. Meanwhile, a data-model assimilation procedure may be useful to decompose peat-core data into short-term NECB or to integrate annual NECB measurements into long-term averages of peatland carbon balance. Also, process modeling (e.g., Frolking et al., 2010) will be essential in understanding the roles of different environmental parameters (temperature, precipitation, and hydrology) in determining carbon accumulation at various (interannual, decadal, centennial, and millennial) timescales.

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Northern peatland carbon stocks and dynamics: a review

Z. Yu

Table 1. General equations of different approaches for estimating peatland carbon stocks.

Approach	Equation	Examples	Note
Peat volume approach	$C_{peat} = \sum_i (A_i \times \overline{D_i} \times \overline{BD_i} \times \overline{CC_i})$	Vitt et al., 2000; Turunen et al., 2002; and Sheng et al., 2004 for regional C stock estimates	Sjör (1980) and Gorham (1990, 1991) used one set of values for all northern peatlands (that is, a special case when $i = 1$)
Carbon density approach	$C_{peat} = \sum_i (A_i \times \overline{CD_i})$	Armentano and Menges, 1986 (for different peatland regions)	Schlesinger (1977) and Lappalainen (1996) for all peatlands when $i = 1$
Time history approach	$C_{peat} = \sum_j (A_j \times \overline{CR_j})$	Yu et al., 2010	Yu et al. (2010) used 1000-yr bins for calculating C rates (CR) and C stocks

Notes: C_{peat}: peat carbon stocks; i: peatland region, or peatland type; j: time period; A_i or A_j: peatland area in region i, for peatland type i, or during time period j; $\overline{D_i}$: mean peat depth for peatland region or type i; $\overline{BD_i}$: mean peat bulk density for peatland region or type i; $\overline{CC_i}$: mean carbon content for peatland region or type i; $\overline{CD_i}$: carbon density for peatland region or type i; $\overline{CR_j}$: mean carbon (accumulation) rates during the time period j.

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Table 2. Estimates of northern peatland carbon stocks by different authors.

#	Authors	Year	Area used ($\times 10^6$ km^2)	Depth (m)	Bulk density (g cm^{-3})	Carbon proportion	Carbon density (kg C m^{-2})	Basal ages (cal years BP)	Carbon accumulation rates (g C m^{-2} yr^{-1})	Carbon stock (Gt C) (range)	Note
	Peat volume approach										
1	Sjörs	1980	4	> 1	> 0.1	0.5				300	The estimate is not different from Sjörs 1981
2	Gorham	1990	3.84	1.13–1.74	0.0784	0.528				180–227	
3	Gorham	1991	3.42	2.3	0.112	0.517				455	Based on data from USSR, Canada, USA and Fennoscandia
4	Turunen et al.	2002	3.46	1.1	0.081–0.091	0.5		4200	18.5	270–370	Estimates for northern peatlands were extrapolated from Finnish data shown here
	Carbon density approach										
5	Schlesinger	1977	2				68.8			137	Top 1 m peat
6	Post et al.	1982	2.8				72.3			202	Top 1 m peat; data were from Schlesinger, 1984
7	Armentano and Menges	1986	3.49	1	0.147 (0.12–0.29)	0.5	73.4			256	Top 1 m peat; area-weighted bulk density, C density and total C pools are calculated from their Table 1; carbon proportion is assumed
8	Oechel	1989	1.1				113.6			125	Only for boreal peatlands
9	Lappalainen	1996	3.985				58.7–63			234–252	Global peatlands for C stocks, but area for northern peatlands
10	Adams and Faure	1998	2.43				2 for biomass			466	Assuming 46 Gt C increase per kyr in the Holocene
	Time history approach										
11	Yu et al.	2010	4					7300	18.6	473–621	Age was for the mean basal age (as in Yu, 2011), not necessarily the mean age of peat deposits

Table 3. Contemporary net ecosystem carbon balance (NECB) from northern peatlands.

| #	Site	Latitude	Longitude	Altitude (m a.s.l.)	MAT (C)	MAP (mm)	Peatland type	Measurement period	NECB ($\mathrm{gC\,m^{-2}\,yr^{-1}}$) $\pm 1\,\mathrm{SD}$	Reference
1	Mer Bleue (Canada)	45.41	−75.48	69	6	943	Ombotrophic bog	1998–2004	21.5 ± 39.0	Roulet et al. (2007)
2	Degerö Stormyr (Sweden)	64.18	19.55	270	1.2	523	Minerogenic fen	2004–2005	24 ± 4.9	Nilsson et al. (2008)
3	Auchencorth Moss (Scotland)	55.79	−3.24	265	4.4	1165	Ombrotrophic bog	2007–2008	69.6 ± 44.4	Dinsmore et al. (2010)
4	Glencar (Ireland)	51.92	−9.92	150	10	2674	Blanket bog	2003–2008	29.7 ± 30.6	Koehler et al. (2011)
5	Stordalen (Sweden)	68.37	19.05	351	0	336	Permafrost palsa mire	2008–2009	44.5 ± 16.3	Olefeldt et al. (2012)
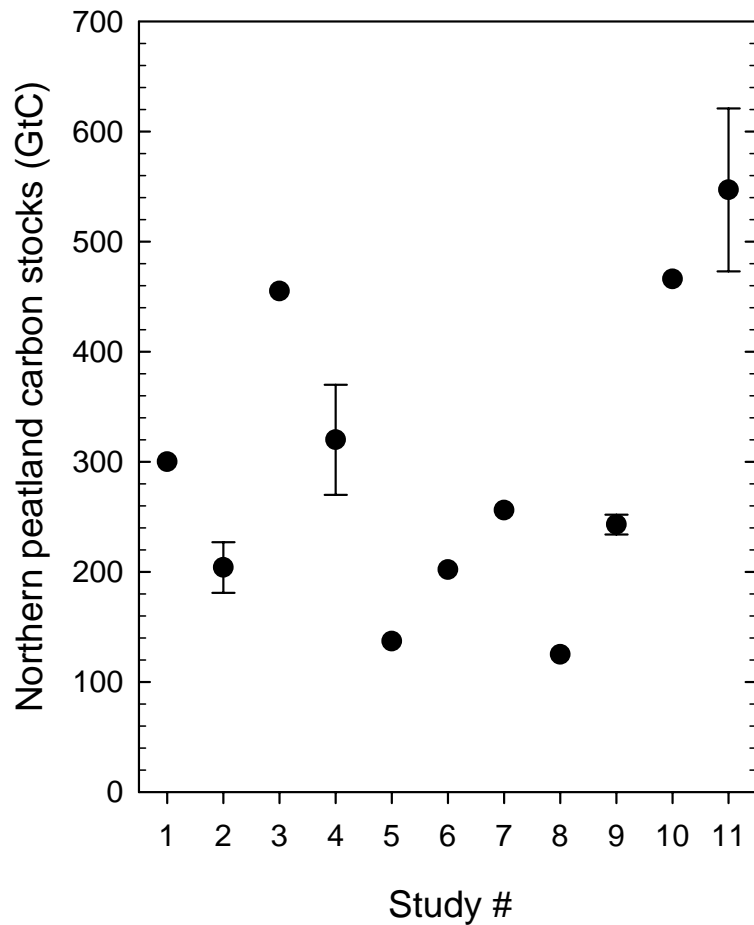
Fig. 1. Peatland carbon stocks estimated by different authors using different approaches (see Table 2 for study # and more details about carbon stock values as well as data used).
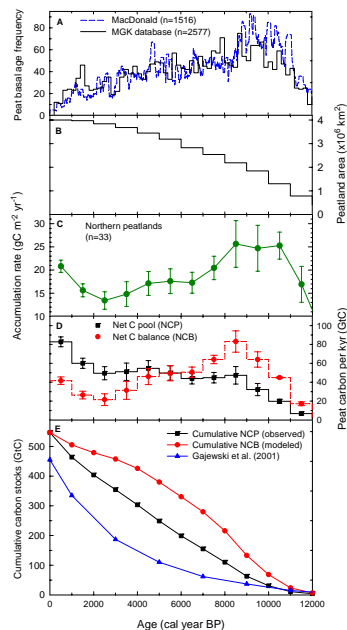
Fig. 2. Peatland change over time during the Holocene. **(A)** Basal ages and peatland initiation histories (dashed line (*n* = 1516): MacDonald et al., 2006; solid line (2577): combined data sets from MacDonald et al., 2006; Gorham et al., 2007; and Korhola et al., 2010 as in Yu et al., 2012); **(B)** peatland area change at 1000-yr intervals over time estimated from cumulative basal age histogram as in A (MacDonald et al., 2006) and the present peatland area of 4×10^6 km^2 (Yu, 2011); **(C)** carbon accumulation rates based on 33 sites across northern peatlands with error bars from standard errors of the means (Yu et al., 2009); **(D)** observed net carbon pool (NCP) and modeled net carbon balance (NCB) for northern peatlands at 1000-yr intervals, with standard errors as error bars (Yu et al., 2010; Yu, 2011); **(E)** cumulative peatland carbon stocks from NCP (black squares; Yu et al., 2010), NCB (red circles), and from scaling the carbon stocks of Gorham (1991) using *Sphagnum*-spore data (blue triangles; Gajewski et al., 2001).

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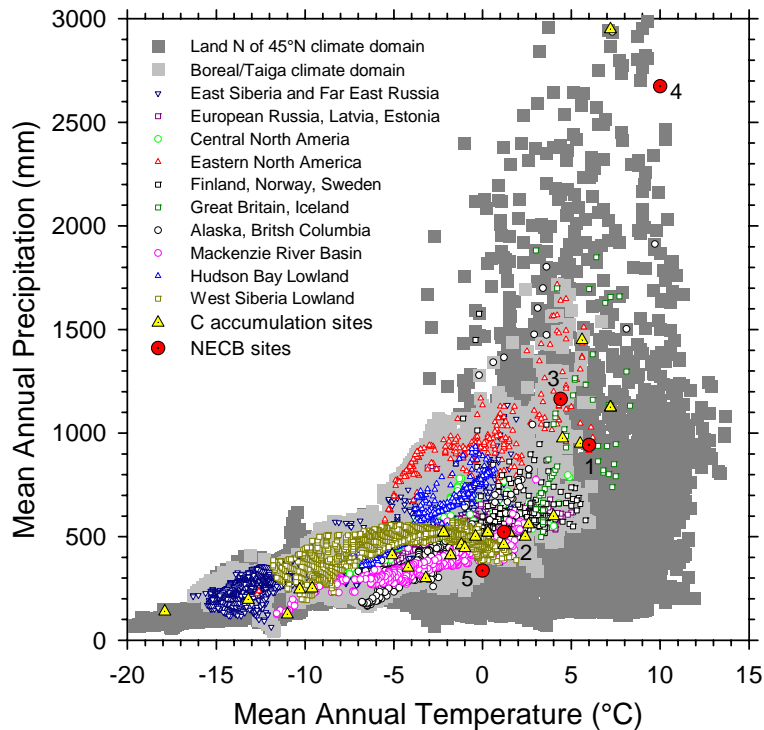
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Fig. 3. Distribution of contemporary NECB sites in the climate space of mean annual temperature and precipitation of the northern peatland domain. The locations of NECB (net ecosystem carbon balance) (red circles; $n = 5$) and Holocene carbon accumulation sites (yellow triangles; $n = 33$) are shown. NECB site numbers are the same as in Table 3: site 1: Mer Bleue; 2: Degeröö; 3: Auchencorth; 4: Glencer; and 5: Stordalen. The 33 carbon accumulation sites were used to derive the synthesis carbon accumulation curve in Fig. 2c (see Yu et al., 2009 for detail and site information). Modified from Yu et al. (2009).
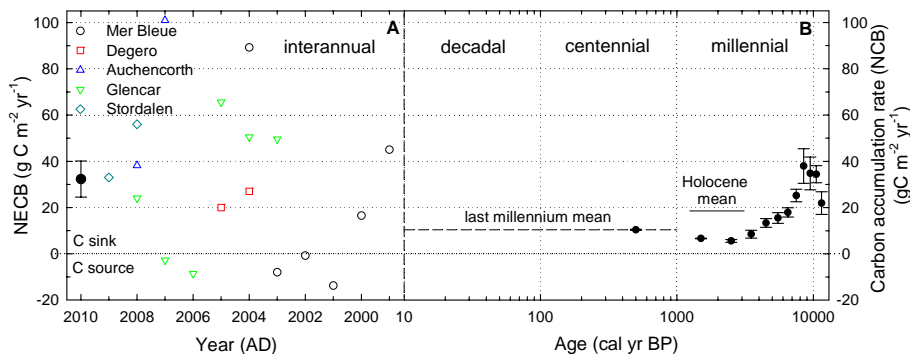
Fig. 4. Net ecosystem carbon balance across time scales in northern peatlands. **(A)** Net ecosystem carbon balance (NECB) from 5 peatland sites with a total of 18 yr of measurements over the last decade (see Table 3 for details; Mer Bleue: Roulet et al., 2007; Degerö: Nilsson et al., 2008; Auchencorth: Dinsmore et al., 2010; Glencar: Koehler et al., 2011; Stordalen: Olefeldt et al., 2012), and solid circle for the overall mean with standard error as error bar; **(B)** peat-core derived net carbon balance (NCB) during the Holocene (Yu et al., 2011) plotted on log scale to emphasize the different time scales (millennial, centennial and decadal), on the basis of 33 accumulation records (Fig. 2c; Yu et al., 2009) and 1516 basal ages (Fig. 2a; MacDonald et al., 2006).