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A database and synthesis of northern peatland soil properties and Holocene carbon and nitrogen accumulation

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A database and synthesis of northern peatland soil properties and Holocene carbon and nitrogen accumulation

Running title

Northern peatland database and synthesis

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Abstract

Here we present results from the most comprehensive compilation of Holocene peat soil properties with associated carbon and nitrogen accumulation rates for northern peatlands. Our database consists of 268 peat cores from 215 sites located north of 45°N. It encompasses regions within which peat carbon data have only recently become available, such as the West Siberia Lowlands, the Hudson Bay Lowlands, Kamchatka in Far East Russia, and the Tibetan Plateau. For all northern peatlands, carbon content in organic matter was estimated at 42 ± 3% (S.D.) for *Sphagnum* peat, 51 ± 2% for non-*Sphagnum* peat, and at 49 ± 2% overall. Dry bulk density averaged 0.12 ± 0.07 g cm^{-3}, organic matter bulk density averaged 0.11 ± 0.05 g cm^{-3}, and total carbon content in peat averaged 47 ± 6%. In general, large differences were found between *Sphagnum* and non-*Sphagnum* peat types in terms of peat properties. Time-weighted peat carbon accumulation rates averaged 23 ± 2 (S.E.M.) g C m^{-2} yr^{-1} during the Holocene on the basis of 151 peat cores from 127 sites, with the highest rates of carbon accumulation (25-28 g C m^{-2} yr^{-1}) recorded during the early Holocene when the climate was warmer than the present. Furthermore, we estimate the northern peatland carbon and nitrogen pools at 436 and 10 gigatons, respectively. The database is publicly available at https://peatlands.lehigh.edu.

Keywords

Northern peatlands, Data synthesis, Climate change, Soil carbon and nitrogen, Biogeochemical cycles, Long-term ecosystem dynamics

Introduction

Of all terrestrial ecosystems, peatlands are arguably the most efficient at sequestering carbon (C) over long time scales. Northern peatlands cover approximately 4,000,000 km^2 or 3% of the global land area (Maltby and Immirzi, 1993) and have accumulated about 500 gigatons of C (GtC) mostly during the Holocene, equivalent to ~ 30% of the present-day global soil organic carbon (SOC) pool (Gorham, 1991; Bridgham et al., 2006; Yu et al., 2010). These ecosystems have also played a dynamic role in the Holocene global C cycle as important sinks of carbon dioxide (CO_2) and major sources of methane (CH_4) to the atmosphere (Frolking and Roulet, 2007; Korhola et al., 2010; Yu, 2011). As climate warming positively affects both plant growth and organic matter decomposition, recent and projected climate change could shift the balance between peat production and organic matter decomposition, potentially affecting the peatland C-sink capacity and modifying peat C fluxes to the atmosphere (Frolking et al., 2011; Yu, 2012). This prediction particularly holds true for the northern high-latitude regions, where the intensity of climate change is expected to be greatest (McGuire et al., 2009). The peatland C cycle – climate feedback remains difficult to assess, however, because of (1) limited understanding of peatland responses to climate change (Frolking et al., 2011), (2) data gaps and large uncertainties in regional peatland C stocks (Yu, 2012), and (3) non-linear peatland responses to external forcing (Belyea, 2009).

Very little is known about the nitrogen (N) budget that accompanies C accumulation in northern peatlands (but see Limpens et al., 2006 for a review). Assuming a net C sequestration of ~270 GtC (Yu, 2012) and a C/N ratio of 20-30 for fen peat (Bergner et al., 1990; Rydin and Jeglum, 2013; results therein) during the early Holocene (11-7 ka), about 10-13 GtN would have been required to build such peat deposits. It is therefore possible that northern peatlands have been playing an undocumented, dynamic role in the Holocene global N cycle as important sinks of N, potentially limiting the amount of N available for other ecosystems at the global scale (McLauchlan et al., 2013). Alternatively, if the main N input to peatlands was through N_2 fixation by cyanobacteria, these microorganisms might have been more important in driving the C cycle in peatlands than previously thought. Overall, studying the coupling between N and C cycling in northern peatlands is essential for a better understanding of how key biogeochemical processes interact in these systems and for predicting the future of peat C stocks.

Here we present the most comprehensive compilation of Holocene C and N data for northern peatlands. This synthesis encompasses regions within which peat C and N data have only recently become available, such as the West Siberian Lowlands in Asian Russia, the Hudson Bay Lowlands in Canada, Kamchatka in the Russian Far East, and the Tibetan Plateau. In addition, we present the most comprehensive synthesis of peat soil properties (such as bulk density, organic matter content, C and N content) from the northern hemisphere. Also, this new database and synthesis work represent a major expansion from Yu et al.'s (2009) synthesis on Holocene peat C dynamics, which was based on 33 sites (vs. 127 sites as reported in this paper). Finally, it constitutes a natural continuation of Charman et al.'s (2013) recent study on peat C accumulation in northern peatlands during the last millennium.

In addition to filling regional data and knowledge gaps, the main objectives of this paper are to (1) describe a database of peat soil properties and synthesize this information for different peat types, time intervals, and geographic regions, and (2) produce time series of Holocene peat C and N accumulation rates in 500-yr bins for comparison with climate history. Key differences in Holocene peat properties between different regions and peatland types are also discussed in light of their implications for long-term peat C stocks. Of particular importance and relevance are the differences between *Sphagnum* and non-*Sphagnum* peat types. Finally, we present new estimates for northern peat C and N stocks for northern peatlands on the basis of the expanded database.

Database and analysis

Database

We compiled a dataset of 268 published and unpublished Holocene peat records from 215 sites located in North America and Eurasia (Figure 1, Supplementary Table 1). The difference in the number of peat cores and peatland sites is due to the fact that, in a few instances, multiple cores were collected from a single peatland. As these multiple cores were not designed as true replicates in the original publications, each of these cores was considered as an independent record of peat properties in the present study. However, only the oldest core for each site was used for estimating peat inception age. Finally, when calculating peat C accumulation rates, multiple cores from a single site were each attributed an equal fraction of the weight for that site. For example, for a site with three cores, the peat C accumulation history of each core only accounted for 1/3 of the site's record.

The latitude of most peatland sites ranges from 45 to 69 °N. The cutoff at 45 °N represents the southern limit for defining what is considered to be the area contributing to the C cycle of the Arctic region (McGuire et al., 2009). Four high-elevation sites found in China (the Tibetan Plateau) and Japan were also included, as they developed under similar 'northern' climatic conditions. The name and coordinates of these four sites are as follows: Zoige (33.5 °N, 102.6 °E), Hongyuan (32.8 °N, 102.5 °E), Hani (42.2 °N, 126.5 °E), and Utasai (42.4 °N, 140.2 °E). A total of 155 cores originate from Eurasia, including 112 cores from Russia. The remaining 113 cores come from North America. Approximately 40% of all cores were collected from ombrotrophic bogs (n = 110 cores) and 20% were extracted from minerotrophic fens (n = 50 cores). The remainder (40%)

was collected in peatlands currently affected by permafrost (n = 108 cores). Note that peatland type was identified independently for each site by the original investigators. From an ecosystem functioning perspective, distinguishing bogs from fens and permafrost peatlands is important, as these peatland types are characterized by different hydrological regimes, vegetation communities, and peat-growth trajectories, all of which impact long-term rates of peat C sequestration (Rydin and Jeglum, 2013). Bogs are mineral-poor, rain-fed peatland ecosystems with relatively low plant net primary production (NPP) and slow peat decomposition rates. In contrast, fens are hydrologically connected to surface or ground water, thereby receiving more mineral nutrients. Generally speaking, fens have greater NPP but also faster peat decay rates than bogs (Blodau, 2002). Finally, in the sub-Arctic and Arctic regions, peatland hydrology, structure, and peat C balance are sensitive to the underlying permafrost aggradation and degradation dynamics (Camill, 1999; Turetsky et al., 2007). For the analysis, peat plateaus (87 out of 108 cores), permafrost bogs (18 out of 108 cores), and collapse scars (3 out of 108 cores) were grouped under the peatland type ‘permafrost peatlands’. Original peatland categories can be found in Supplementary Table 1.

The database was built to include as many peat records as possible. Therefore, we included any peat core that was extracted north of 45 °N (or at high elevation) and for which bulk density or organic matter bulk density data were available. Information related to peat-core location, peatland type, peat properties, age, and data source can be found in Supplementary Table 1. Additional information related to the type of coring device used and the year of coring can be found in the original publications. Data used in this synthesis are readily accessible from the Holocene Peatland Carbon Network website (https://peatlands.lehigh.edu). This database will be useful in future studies of ecosystem – C cycle – climate interactions and for modeling long-term peatland dynamics.

In the following sub-sections, we present the criteria for site selection and the protocols used to develop the database. In an effort to only analyze and synthesize *peat* samples, inorganic-rich horizons often found at the base of the peat cores were removed from the database. When available, stratigraphic information was used to distinguish peat vs. non-peat material. For example, gyttja (organic-rich lake sediments) was excluded from the dataset, as well as marshy, clayey, and silty sediments. When stratigraphic information was not available, a bulk density value of 0.5 g cm^{-3} was used as a cut-off between peat and non-peat material. This value was chosen on the basis of stratigraphic information from peatland records where peaty sediments with bulk density values up to 0.5 g cm^{-3} were identified. We acknowledge that this cut-off value is arbitrary, and that our dataset likely contains some non-peat samples. Inorganic horizons (e.g., tephra layers) were also excluded from the database.

<u>*Peat properties*</u>

A total of 232 peat cores (181 sites) were used for characterizing peat properties, though not all cores have all types of peat properties available (Figure 2a). This dataset contains 139 cores from Eurasia (including 109 cores from Russia) and 93 cores from North America (Figure 1). While approximately half of these cores were sampled and analyzed at high resolution (1-5 cm increments), the remainder was sampled at lower resolution, typically at 10 cm increments. Dry bulk density (BD; g cm^{-3}), organic matter content (OM%; gravimetric %), as well as elemental C and N concentration values were compiled and synthesized. On the basis of these raw datasets, C/N mass ratio and organic matter bulk density (OMBD; g OM cm^{-3}) were calculated. These peat geochemical values are examined in light of peat stratigraphy, peat ages, and geographic regions. The following paragraphs briefly describe the protocols used to obtain these values.

Peat stratigraphic information was obtained for 83 peat cores ('peat types' in Figure 2a) for which plant macrofossil analysis or detailed peat description had been performed following standard techniques (e.g., Troels-Smith, 1955; Mauquoy and van Geel, 2007). This peat stratigraphic information was condensed into the following five peat types: *Sphagnum*, herbaceous, woody, brown moss, and humified peat. In a few cases, the investigators only ascribed a general peat type to the samples (e.g., 'bog' vs. 'fen' peat, or '*Sphagnum*' vs. 'herbaceous' peat). In these cases, the uncertainty associated with classifying peat samples mostly relates to the uniformity of naming convention used among the investigators. For example, a peat sample that contains sizable fractions of brown moss and humified peat may be classified by an investigator as 'brown moss peat' and by another one as 'humified peat'. We recognize that, due to their nature, brown moss and humified peat types might be less uniform than *Sphagnum* or herbaceous peat types. We included as much stratigraphic information as possible in the database, though ambiguous or imprecise descriptions were left out to avoid further confusions.

Dry bulk density and organic matter content were determined following standard procedures (Dean, 1974; Chambers et al., 2011). Peat samples of a known fresh volume were either freeze-dried or oven-dried at ca. 100 °C until constant weight was reached and weighed to determine bulk density, then burned at 500-600 °C for one to four hours and weighed again to determine organic matter content. The accuracy of these measurements mostly depends on sample handling (care must be taken to prevent peat compaction in the field and in the laboratory) and the analytical error associated with weighing. The product of bulk density (BD; g cm^{-3}) and organic matter content (OM%) of each peat sample was used to calculate organic matter bulk density (OMBD; g OM cm^{-3}), also referred to as ash-free bulk density (AFBD) or organic bulk density (OBD) in the literature (Yu et al., 2003; Björck and Clemmensen, 2004). We compiled a total of 21,220 bulk density measurements, 18,973 organic matter content values, and computed 18,544 organic matter bulk density values (Figure 2a).

Total peat C and N content were directly measured by combustion and elemental analysis of dry peat samples (Chambers et al., 2011). We compiled 3741 C and 3365 N measurements (Figure 2a). We also computed a total of 3362 C/N mass ratio values.

Finally, the regression between peat C content (C%) and peat organic matter content (OM%) for each peat type is presented as an estimate for C content in organic matter (OC%). A total of 995 samples were used in this analysis. The slope of each one of these regressions is interpreted as the ‘conversion factor’ from OM% to OC%, such that it provides an indirect way for estimating the C% content of ash-free peat for investigators who do not perform elemental C measurements directly.

Peat-core chronology

Peat-core chronologies were almost exclusively based on radiocarbon (^{14}C) dates that were determined mostly by accelerator mass spectrometry (AMS) on terrestrial plant macrofossils or bulk peat (Piotrowska et al., 2011). A few older chronologies were based on conventional ^{14}C dating of bulk samples. Because no systematic offset has been observed in the ^{14}C age of bulk vs. non-woody plant macrofossils (G.M. MacDonald, pers. comm. 2013), the use of bulk dates is justifiable. For the purpose of this study, all ^{14}C dates were calibrated to calendar years before present (cal. BP) using the program CALIB 6.1.0 (Stuiver and Reimer, 1993) with the IntCal09 calibration dataset (Reimer et al., 2009). In this paper, ages are reported in thousands of calibrated years before present (ka).

Age-depth relationships were established for all continuous peat cores for which at least five age determinations were available (n = 151 cores). Except for a few palynostratigraphic and tephrochronologic markers, nearly all records have chronologies exclusively based on ^{14}C ages (Supplementary Table 1). Chronologies were obtained through linear interpolation of calibrated ages between dated horizons. Single-age estimates were taken from the mid-point of each calibrated 2σ probability distribution. This parsimonious approach captures general patterns of temporal changes in peat accumulation and allows for analysis of peat C accumulation trajectories (e.g., Telford et al., 2004). Although more sophisticated approaches are possible (e.g., Charman et al., 2013), we seek to make the fewest or simplest assumptions for this analysis because the temporal resolution target for peat C accumulation rate calculations is relatively low (at 500 years). In the cases where the original investigator identified hiatuses (e.g., peat loss caused by erosion or fire) or depositional anomalies (e.g., thick tephra layers that interrupted peat accumulation) along their peat records, these gaps were taken into consideration when building age-depth relationships (Glaser et al., 2012). Otherwise, peat records were assumed to be continuous.

In an effort to assess the representativeness of our samples in terms of peatland inception timing, peat basal ages were compiled and compared to results from large datasets (MacDonald et al., 2006; Gorham et al., 2007; Korhola et al., 2010). Peat inception ages from 199 sites (Supplementary Table 1) were summed and binned in 500-year intervals.

Long-term rates of carbon and nitrogen accumulation

A total of 151 peat cores from 127 sites were used for estimating rates of peat C accumulation. This dataset contains 96 cores from 78 North American sites and 55 cores from 49 Eurasian sites (Figure 1). Of the 33 sites presented in Yu et al.'s (2009) study, 25 were used in the present study (Supplementary Table 1). The remaining 8 sites did not fulfill our dating quality criterion (presented below). The dating quality of each record was determined by the quotient of the calibrated peat basal age and the number of age determinations. For example, a 10,000-year-old peat core with a chronology constrained by 10 ^{14}C dates was attributed a dating quality of one date per 1000 years. About 58% of our 151 cores were characterized by an acceptable dating quality of one to two ^{14}C dates per 1000 years (Figure 2b). These resolutions are well suited to capture millennial-scale variations in C accumulation. Several peat cores with more than two ^{14}C dates per 1000 years (n = 35 cores) were available from North America and Europe. The lower dating quality cores (<1 date per 1000 years,) were unevenly distributed and comprise 44% of the North American records and 40% of the Eurasian records.

The long-term rate of peat C accumulation was calculated for each core following one of the following five approaches (Supplementary Table 1): (1) whenever possible, peat core chronology was combined with bulk density and C% for each depth increment (n = 47 cores); (2) in the cases where direct C measurements were lacking, peat core chronology was combined with organic matter bulk density measurements and a mean organic C value of 49% in organic matter (n = 57 cores); (3) for cores that lacked organic matter bulk density and direct C%, peat core chronology was combined with bulk density measurements and a mean C content of 47% in total peat (n = 3 cores); (4) whenever neither bulk density nor C% was directly available from the cores, long-term rate of peat C accumulation was calculated for each core by combining time-dependent bulk densities (0.08 g cm^{-3} at 0-0.5 ka; 0.12 g cm^{-3} at 0.5-6 ka; 0.14 g cm^{-3} at 6-12 ka) with a mean C content of 47% in total peat for each dated interval (n = 32 cores), and (5) peat C accumulation rates for the remaining 12 cores were directly obtained from published figures and tables. For all the cores, time-weighted peat C accumulation rates were summed and binned in 500-year intervals. It is important to note that such reconstructions are 'apparent rates' that are different from true rates of C accumulation in peatlands, because decomposition processes have been affecting old peat layers for thousands of years (Turunen et al., 2002). Finally, the long-term rate of peat N accumulation was calculated by combining our binned peat-C accumulation rates with time-dependent C/N values (65 at 0-6 ka, and 40 at 6-10 ka).

Results

Peat Properties

<u>*Descriptive statistics of dataset*</u>

The frequency distribution of each peat property is shown in Figure 3. Mean values and standard deviations for all peat properties are presented by peat type in Table 1, and by region in Table 2.

Bulk density values (n = 21,220) ranges from 0.003 to 0.498 g cm^{-3}, with a mean value of 0.118 ± 0.069 g cm^{-3} (1 standard deviation (S.D.)). A one-way analysis of variance (ANOVA) reveals an effect of peat type on bulk density (F (10709) = 941, $p < 0.0001$), with all peat types significantly different from each other on the basis of post-hoc Tukey's LSD tests ($p < 0.0001$). In increasing order, mean bulk density of the peat types is *Sphagnum* < Woody < Herbaceous < Brown Moss < Humified (Table 1).

Organic matter content (n = 18,973) has a mean value of 90.7 ± 13% (1 S.D.) and a median of 95.7%. The ANOVA reveals an effect of peat type on organic matter content (F (9512) = 349, $p < 0.0001$), with all peat types significantly different from each other

(Tukey's LSD: $p < 0.0001$). In decreasing order, mean organic matter content of the peat types is *Sphagnum* > Woody > Herbaceous > Brown Moss > Humified (Table 1).

Organic matter bulk density (n = 18,544) ranges from 0.003 to 0.452 g OM cm^{-3}, with a mean value of 0.105 ± 0.051 g OM cm^{-3} (1 S.D.). The ANOVA reveals an effect of peat type on organic matter density (F (9081) = 942, $p < 0.0001$), with all peat types significantly different from each other (Tukey's LSD: $p < 0.0001$). In increasing order, mean organic matter density of the peat types is *Sphagnum* < Herbaceous < Woody < Brown Moss < Humified (Table 1).

C content in total peat (n = 3741) ranges from 30 to 60%, with a mean value of 46.8 ± 6.1% (1 S.D.) and a median of 47.8%. While the lowest values (< 35%) are almost exclusively associated with samples from Alaska, western Canada, Fennoscandia, and eastern Russia, the highest values (> 55%) are characteristic of sites located in the western European Islands and Fennoscandia. The ANOVA reveals an effect of peat type on C% (F (2494) = 161, $p < 0.0001$), with *Sphagnum* samples significantly different from other peat types (Tukey's LSD: $p < 0.0001$). Herbaceous and woody peats are distinct from other types, but indistinguishable from one another (Tukey's LSD: $p = 0.238$). Likewise, humified and brown moss peats are distinct from other types, but indistinguishable from each other (Tukey's LSD: $p = 0.448$). In increasing order, mean C% of the peat types is *Sphagnum* < Humified = Brown Moss < Herbaceous = Woody (Table 1). The frequency distribution of C% in peat is also characterized by a second, though minor, mode at 40% (Figure 3d). The latter is mostly associated with *Sphagnum* peat samples, as their average C% is significantly lower than those for other peat types (Table 1). This difference is likely caused by the high content of complex and recalcitrant compounds found in *Sphagnum* tissues such as lipids and waxes, which have lower C% than more labile biopolymers such as cellulose (Cagnon et al., 2009).

On the basis of 995 samples for which both OM% and C% were quantified, we developed conversion factors (slopes of linear regressions) for several peat types to estimate OC% (Figure 4). There is a noticeable difference between the slope of *Sphagnum* peat (0.423 ± 0.030; n = 454) and that of non-*Sphagnum* peat (0.514 ± 0.024; n = 308). The C content in organic matter (OC%) for *Sphagnum* peat is smaller than expected at 42.3 ± 3.0% (e.g., Bauer et al., 2006; Beilman et al., 2009; Table 3). As the majority of our *Sphagnum* samples for this specific analysis are younger than 0.5 ka (304 out of 454 samples) and extracted from raised bogs, it is very likely that our estimated OC% biases towards young and undecomposed *Sphagnum*. This 'young *Sphagnum* peat effect' heavily influenced the slope of the overall relation between C% and OM% (0.467 ± 0.045) due to the overrepresentation of *Sphagnum* samples in the dataset (454 out of 995 samples). To minimize this bias when estimating mean OC% in peat, all 304 young *Sphagnum* samples were removed from the dataset, yielding an overall conversion factor of 0.492 ± 0.024.

N content in peat (n = 3365) ranges from 0.04 to 3.39%, with a mean value of 1.2 ± 0.7% (1 S.D.). The frequency distribution is asymmetric and characterized by a mode at 0.65% (Figure 3e). The latter is largely due to the overrepresentation of *Sphagnum* peat samples (having low N content) in our database. The ANOVA reveals an effect of peat type on N content (*F* (2504) = 666, $p < 0.0001$) with *Sphagnum* and herbaceous peat types significantly different from each other and from all other types (Tukey's LSD: $p < 0.0001$). Humified and brown moss peats are distinct from other types, but indistinguishable from each other (Tukey's LSD: $p = 0.113$). Likewise, woody and brown moss peats are indistinguishable from one another (Tukey's LSD: $p = 0.240$). In increasing order, mean N% of the peat types is *Sphagnum* < Woody = Brown Moss = Humified < Herbaceous (Table 1).

C/N mass ratio (n = 3362) ranges from 12 to 217, with a mean value of 55 ± 33 (1 S.D.). The frequency distribution is asymmetric and characterized by a mode at 25 (Figure 3f). While the distribution mode (25) is associated with non-*Sphagnum* peat types, the distribution mean (55) is skewed towards *Sphagnum* peat samples owing to their overrepresentation in our database (Figures 3f). The ANOVA reveals an effect of peat type on C/N ratio (*F* (2501) = 174, $p < 0.0001$) with *Sphagnum* peat significantly different from all other types (Tukey's LSD: $p <0.0001$). Woody peat is distinguishable from all peat types except for brown moss peat (Tukey's LSD: $p = 0.665$). Herbaceous and humified peat types are indistinguishable from one another (Tukey's LSD: $p = 0.721$). In decreasing order, the mean C/N ratio of peat types is *Sphagnum* > Woody = Brown Moss > Humified = Herbaceous (Table 1).

<u>Temporal changes in peat properties</u>

We find a decreasing trend in bulk density over the Holocene (Figure 5a), with the densest peat characterizing the oldest samples (8-10 ka) and the least-dense peat characterizing the youngest samples (0-2 ka). This trend is most likely attributable to the progressive decomposition and subsequent compaction of peat over time, as well as to higher ash content in early-stage peat (likely from fens). Conversely, a clear increasing trend in organic matter content (OM%) is found over the Holocene (Figure 5b), with the greatest OM% characterizing the youngest samples (0-2 ka) and the least OM% characterizing the oldest samples (8-10 ka). This trend is most likely attributable to higher inorganic material inputs during early-stage peatland development as well as to a greater loss of OM in the deeper portions of peat profiles. Organic matter bulk density (OMBD) remains relatively constant over the Holocene (Figure 5c) because of the opposite trends exhibited by BD and OM% (Figures 5a, 5b). The only exceptions are the low OMBD values characterizing the youngest samples (< 0.5 ka), probably due to the large proportion of young, undecomposed *Sphagnum* peat samples.

C content in peat remains uniform over the Holocene (Figure 5d), except for slightly lower C% during the late Holocene. We find a decreasing trend in N% over the Holocene, such that young peat deposits are associated with low N% (Figure 5e). Peat deposits older than 6 ka are mostly associated with low C/N ratios, whereas peat samples younger than 6 ka are characterized by high C/N values (Figure 5f).

In general, *Sphagnum* peat is characterized by lower BD, OMBD, C%, N%, and C/N ratio than samples composed of non-*Sphagnum* peat (Figure 6). Therefore, peatland development could explain much of the aforementioned temporal trends (Figure 5), as early-stage rich fens are typically characterized by non-*Sphagnum* peat, whereas late-stage poor fens and bogs are *Sphagnum*-dominated (Figure 6h).

Spatial differences in peat properties

Significant differences in bulk density are found at the regional scale (Table 2). The densest peat is observed in Alaska (mean = 0.168 ± 0.087 g cm^{-3}) and western Canada (mean = 0.166 ± 0.076 g cm^{-3}), whereas the least dense peat is found from the western European Islands (mean = 0.055 ± 0.027 g cm^{-3}). Organic matter bulk density values follow a similar pattern across these regions (Table 2). These differences are strongly correlated with peat types and sample ages, with the Alaskan and western Canadian samples largely constituted of herbaceous, humified, and brown moss peat types. OM% does not vary much between regions (> 90% in all regions), with the notable exception of Alaskan and eastern Russian/Asian peatlands that exhibit mean values of 76.6 ± 18.8% and 80.3 ± 16.7%, respectively (Table 2). Aeolian dust and tephra ash inputs to some peatlands in Alaska, Kamchatka, and Japan might partly explain such low OM% values.

Peat inception ages and long-term rates of carbon and nitrogen accumulation

Calibrated ages (mid-point) for peat inception range from 0.6 to 15 ka and the frequency distribution is characterized by a mode at 11-9 ka (Figure 2c). The latter corresponds with peat inception peaks in the West Siberian Lowlands and in Alaska. In general, our samples are in agreement with much larger networks of peat basal ages (Smith et al., 2004; MacDonald et al., 2006; Gorham et al., 2007; Korhola et al., 2010; Ruppel et al., 2013; Yu et al., 2013).

The time-weighted long-term rate of C accumulation averages 22.9 ± 2.0 g C m^{-2} yr^{-1} (standard error of mean (S.E.M.); Figure 7b). Values exhibit an increasing trend that initially peaks during the early Holocene between 10 and 7.5 ka at 27.0 ± 2.6 g C m^{-2} yr^{-1}. This peak is largely caused by rapid peat accumulation in Alaska, the Western Siberia Lowlands, and southeastern Canada. The remainder of the Holocene is characterized by a decreasing trend in C accumulation rates from 24 to 18 g C m^{-2} yr^{-1} and a time-weighted mean at 22.0 ± 1.9 g C m^{-2} yr^{-1} (Figure 7b). There is a notable minimum value between 3 and 1.5 ka at 18-19 g C m^{-2} yr^{-1}. Lack of decomposition probably explains most of the apparent increase in accumulation over the past millennium (24-32 g C m^{-2} yr^{-1}), as young peat appears to be accumulating more quickly than old peat simply because the former has undergone less decomposition than the latter (Clymo, 1984).

The time-weighted long-term rate of N accumulation averages 0.5 ± 0.04 g N m^{-2} yr^{-1} (S.E.M.; Figure 7c). While the mid and late Holocene (6-0 ka) are characterized by the lowest rates of N accumulation at 0.34 g N m^{-2} yr^{-1}, the highest rates (0.61 g N m^{-2} yr^{-1}) occur between 12 and 6 ka (Figure 7c). This trend mirrors that of C accumulation (Figure 7b), as C and N sequestration rates are both mainly influenced by peat density and its accumulation rate. The low rates of N accumulation over the past 6 ka might also relate to the increasing presence and persistence of *Sphagnum* (having high C/N ratio and low N concentration) in northern peatlands (Figures 6 and 7).

Discussion

Representativeness of the database for northern peatlands

The present database contains the most comprehensive compilation of peat properties and C accumulation records for northern peatlands. The previous large-scale synthesis (Yu et al., 2009) only contained 33 sites and lacked records from the Hudson Bay lowlands and the Russian Far East, and had limited sites from West Siberia and the western European Islands. The present database fills gaps from these regions.

However, European Russia, East Siberia, and the Russian Far East clearly remain poorly studied regions in terms of northern peat C stocks and accumulation histories (Figure 1). A wetland map by Stolbovoi and McCallum (2002) suggests that shallow peaty deposits (<50 cm) interspersed with few deeper peat bogs (>50 cm) dominate the Far East Russian landscape. Most of these deeper peatlands are presumably found in Kamchatka and Sakhalin (Stolbovoi, 2002). This broad portrait is, however, based on fewer than 30 soil profiles from across East Siberia and Far East Russia (Stolbovoi et al., 2001), making it difficult to evaluate the importance of this region in the northern peatland C cycle. In general, peat C stocks in Eastern Russia may not be as massive as those from West Siberia or European Russia (Stolbovoi and McCallum, 2002). Therefore, understanding how these shallow peatlands in East Siberia and the Russian Far East have developed during the Holocene would provide useful end-members of climate controls of peat C accumulation, but these peatlands do not seem to represent a large missing C stock.

Northern peatland soil properties: key findings and uncertainties

Peat-carbon stocks

Several studies have quantified the soil C density and total C pool of peatlands using different approaches (e.g., Armentano and Menges, 1986; Gorham, 1991; Yu et al., 2010). These methods have led to total C pool estimates for northern peatlands that vary by at least a factor of two, from 234 to 547 GtC (Lappalainen, 1996; Yu et al., 2010; see Yu, 2012 for a review). Many of these studies have combined mean peat depth, modern peatland area, and a single mean C density value (BD x C% or OMBD x OC%) in their calculations (e.g., Gorham, 1991). Applying Gorham's (1991) mean peat depth and peatland area estimates to the mean BD and C% results from our database yields a C pool estimate of 436 GtC (2.3 m x 3.42 Mkm^2 x 0.118 g cm^{-3} x 47% C). However, it is well documented that most peatlands undergo a shift from herbaceous to *Sphagnum* peat during their developmental history (Hughes, 2000; Figure 6h) and that different BD, C%, and rates of peat accumulation are associated with fen and bog peats (e.g., Vitt et al., 2000; Figure 6). We also know that peat-C accumulation rates have varied asynchronously between regions throughout the Holocene as a result of regional changes in hydroclimatic conditions (e.g., Yu et al., 2009; Charman et al., 2013). Therefore, we argue that reconstructing Holocene changes in peat C accumulation on the basis of *measured* peat C density and reliable peat-core chronologies constitutes a step forward in providing the best possible peat C stock estimates (see Yu et al., 2010 for an example). It also allows for quantifying spatial and temporal differences in rates of peat C accumulation, as well as the temporal trajectories of peat C fluxes to the atmosphere

(MacDonald et al., 2006; Yu et al., 2013). However, better maps of the present peatland area (and its change over time) are still needed to improve current peat C stock estimates.

Carbon content in organic matter

For each peat layer, peat C density can be estimated by the product of either (1) bulk density and C content in total peat (BD x C%), or (2) ash-free bulk density and C content in organic matter (OMBD x OC%). It could be argued that the first option is preferable when estimating peat C stocks, as it produces values that are directly comparable to routine soil C measurements from other terrestrial ecosystems. However, the present database clearly indicates that the majority of peatland scientists routinely analyze organic matter content (OM%; n = 18,973 samples) rather than C% (n = 3741 samples) along peat cores. To provide a way to estimate OC% from OM%, we developed the following conversion factors: 42.3 ± 3.0% for *Sphagnum* peat, 51.4 ± 2.4% for non-*Sphagnum* peat, and 49.2 ± 2.4% overall (Figure 4, Table 1).

While the overall peat and the non-*Sphagnum* peat conversion factors are in line with those from previous studies (e.g., Gorham, 1991; Vitt et al., 2000; Turunen et al., 2002; Beilman et al., 2009), the *Sphagnum* peat factor is lower than other estimates (e.g., Bauer et al., 2006; Beilman et al., 2009; Table 3). Indeed, our mean OC% *Sphagnum* value at 42.3% is close to that of surface *Sphagnum* tissues, suggesting that it constitutes a valid estimate for ash-free and poorly decomposed *Sphagnum* peat. As previously mentioned, this bias towards low OC% is due to a large number of *Sphagnum* samples younger than 0.5 ka (304 out of 454 *Sphagnum* samples).

Although each one of the three conversion factor slopes was significant ($p < 0.0001$), there is a noticeable scatter in the data (Figure 4) that cannot solely be explained by the ~ 1% analytical error associated with the loss-on-ignition procedure (Heiri et al., 2001). The progressive accumulation of recalcitrant C in old samples (lignin ~ 60% C vs. cellulose ~ 42% C), assuming it occurs at a greater rate than the loss of OM in the deeper portions of peat profiles, could explain why C% appears higher than our OC% conversion factors (Cagnon et al., 2009). The presence of inorganic C, particularly for the humified and brown moss peat types, could also explain these results.

Oligotrophication and the fen-to-bog transition in northern peatlands

Sphagnum and non-*Sphagnum* peat types were characterized by very different peat properties, with *Sphagnum* peat having lower BD, OMBD, C%, N%, and C/N ratio than non-*Sphagnum* peat (Figure 6). These differences become important when estimating Holocene peat C fluxes, as the proportion of *Sphagnum*-dominated peat records increases during the late Holocene due to the fen-to-bog transition (Figure 6h). For example, much stronger CH_4 emissions are associated with fens than bogs (e.g., Pelletier et al., 2007). In terms of C sequestration rates, the systematically higher organic C density of non-*Sphagnum* peat suggests that higher accumulation rates are possible in fens than in bogs (Figure 6g), assuming optimal hydroclimatic conditions leading to rapid peat burial. In addition, as non-*Sphagnum* samples contain twice the N mass of *Sphagnum* peat (Figure 6e), early-stage fens have the ability to stock more N than late-stage bogs. Overall, further studies on the timing of the fen-to-bog transition across the northern peatland domain are needed to better our understanding of its impact on C sequestration and CH_4 emissions.

Holocene pattern of carbon accumulation in northern peatlands

The overall trajectory and shape of our Holocene peat C accumulation curve is similar to the synthesis from a much smaller dataset (n = 33; Yu et al., 2009). As such, an early Holocene peak during the Holocene Thermal Maximum (HTM) and an overall slowdown of C accumulation during the mid- and late-Holocene, particularly after 4 ka during the Neoglacial period and associated permafrost development, were found in both syntheses (Figure 7). However, the mean Holocene value of 22.9 ± 2.0 g C m^{-2} yr^{-1} (1 S.E.) presented here is approximately 24% higher than the estimate in Yu et al.'s 2009 study (18.6 g C m^{-2} yr^{-1}). Our larger dataset likely better represents the northern peatland C accumulation rates. These results imply that current peat C stocks might be underestimated.

While the peak value at 27 g C m^{-2} yr^{-1} is about 23% higher than the time-weighted mean peat-C accumulation rate for the remainder of the Holocene at 22 g C m^{-2} yr^{-1}, we only found a 2% difference in organic C density values between young (0.053 ± 0.02 g C cm^{-3}) and old (0.057 ± 0.03 g C cm^{-3}) peat samples. These results clearly show that the peak value during the early Holocene cannot be mainly attributed to presumably dense peat deposits that would be rich in recalcitrant C due to long-term decomposition and compaction. Instead, factors influencing the rate of peat burial such as peat type (*Sphagnum* vs. non-*Sphagnum* peat; Figure 6), growing season length, and other environmental variables, must have been responsible for such high rates of C sequestration during the early Holocene.

The Holocene Thermal Maximum (HTM) is a well-documented period of orbitally-induced warm climate in the northern high-latitude region (Kaufman et al., 2004; Renssen et al., 2012; Marcott et al., 2013) that reaches its maximum around 11 ka (Berger and Loutre, 1991; Figure 7a). The peak in warm climatic conditions shows a transgressional pattern across northern North America that moved eastward with the waning Laurentide Ice Sheet during the early and mid Holocene (Kaufman et al., 2004). This progressive increase in land availability coupled with warming summer conditions have been proposed as the main controls on peatland inception and rapid C accumulation across northern North America (Harden et al., 1992; Gorham et al., 2007, 2012; Yu et al., 2009; Jones and Yu, 2010). In general, our results support the hypothesis that warm summers could promote peat formation and C sequestration (Beilman et al., 2009; Yu et al., 2009; Charman et al., 2013), as the highest rates of C accumulation broadly coincide with the peak in summer insolation from 11 to 7 ka (Figure 7). We acknowledge that sufficient water input was necessary to allow for peatland development. Furthermore, the observed temporal asymmetry in peatland inception age and peaks in C accumulation rates between Alaska, western Canada, and the Hudson Bay Lowlands follows the transgressional pattern of the HTM. For example, peat inception and highest peat C accumulation rates occur at 11-9 ka in Alaska, whereas they are delayed in western Canada with peak values around 9-7 ka. These findings have important implications for projecting the fate of peat-C stocks in a future warmer world.

The Neoglacial period is characterized by generally cooler and wetter conditions than the HTM (Figure 7a; Marcott et al., 2013). Particularly low C accumulation rates coincide with this time period across the northern peatland domain (Figure 7; Vitt et al., 2000; Jones and Yu, 2010). Peat accumulation processes might even have stopped in some regions (e.g., Peteet et al., 1998). The onset of permafrost aggradation in many peatlands also occurred during the Neoglacial period (Zoltai, 1971, 1995; Vitt et al., 2000; Oksanen et al., 2003; Sannel and Kuhry, 2008), reducing the peat C-sink capacity. In addition to shorter and cooler growing seasons, lower C accumulation rates in permafrost sites likely relates to a slower peat burial due to (1) more intense peat decomposition in the acrotelm due to drier surface conditions, and (2) a slower rate of peat formation and associated C inputs to soil because many peat plateaus are not *Sphagnum*-dominated. Overall, our results support the notion that climatic changes such as the HTM and the Neoglacial cooling impact C sequestration rates in peatlands.

Role of northern peatlands in the global nitrogen cycle

As relatively few downcore peat N concentrations have been reported in the literature, it was difficult to compare our mean value of 1.2% to previous estimates. Bragazza et al. (2012) reported N content values of 0.7% for *Sphagnum fuscum* litter and 1.48% for *Eriophorum vaginatum* (herbaceous) litter, in line with our results (Table 1). Similarly, Turunen et al. (2004) documented peat N concentrations ranging from 0.35 to 2.25% (mean value of 0.8%) for the uppermost sections of 23 *Sphagnum* bogs across northeastern Canada. Overall, these values closely match our findings for *Sphagnum* (0.7%) and herbaceous (1.7%) peat types (Table 1).

Using our peat C pool estimate of 436 Gt and assuming a mean C/N ratio of 45 yields a peat N pool of 9.7 Gt, roughly equivalent to 10% of the global soil N pool at 95 Gt (Post et al., 1985). This estimate is within the range proposed by Limpens et al. (2006) at 8-15 GtN. The Holocene time-weighted peat N accumulation rate of 0.5 ± 0.04 g N m^{-2} yr^{-1} (S.E.; Figure 7) is also in line with a previous estimate of 0.19-0.48 g N m^{-2} yr^{-1} (Limpens et al., 2006). While the mid and late Holocene (6-0 ka) are characterized by the lowest rates of peat-N accumulation at 0.34 g N m^{-2} yr^{-1}, the highest rates (0.61 g N m^{-2} yr^{-1}) occurr between 12 and 6 ka (Figure 7c). The low rates of N accumulation over the past 6 ka might also relate to the increasing presence and persistence of *Sphagnum* peat (having high C/N ratio and low N concentration) across the northern peatlands (Figures 6 and 7). Overall, given the bias toward *Sphagnum*-dominated sites in our database, N pools and N accumulation rates are probably underestimated.

Rapid N sequestration in peatlands during the early Holocene might have contributed to the global decline in reactive N availability for terrestrial ecosystems (McLauchlan et al., 2013), pointing to a potentially important and undocumented role of northern peatlands in the global N cycle. These results also raise the important question of N provenance: in the absence of large rates of atmospheric N deposition during the early Holocene, the only process that could account for such a large N pool in peatlands is N fixation, either through symbiotic or asymbiotic processes (Limpens et al., 2006).

The fate of these large peat N stocks remains largely unknown under recent and projected warming. Indeed, the importance of peatlands as sources of nitrous oxide (N_2O) is just emerging (e.g., Repo et al., 2009; Marushchak et al., 2011; Palmer et al., 2012), and studies have suggested that reduced surface moisture or increasing temperatures might significantly promote the production, transformation, and transport of dissolved N, and N_2O emissions to the atmosphere through denitrification (e.g., Kane et al., 2010). On the contrary, some authors have speculated that the potential increase in peatland-N_2O emissions from climate change may not be significant relative to the global N_2O budget (e.g., Martikainen et al., 1993; Frolking et al., 2011). Overall, additional peat N cycling studies are needed to address these remaining questions.

Future directions

Peat core analysis has been extensively used over the past 20 years for estimating rates of peat C accumulation at local, regional, and continental scales (e.g., Mäkilä, 1997; Clymo et al., 1998; Vitt et al., 2000; Turunen et al., 2002; Mäkilä and Saarnisto, 2008; Yu et al., 2010; van Bellen et al., 2011; Gorham et al., 2012). The present study analyzed a new database that comprises 268 peat records from 215 northern peatland sites. This systematic analysis of peat properties and Holocene C accumulation rates is essential for accurately addressing the following general research topics in the future: (1) describing and quantifying spatial and temporal patterns of Holocene peatland C and N accumulation; (2) assessing the sensitivity of C and N accumulation to climate change; (3) estimating peatland soil organic carbon (SOC) and soil organic nitrogen (SON) pools at regional and hemispheric scales, (4) furthering our understanding of peatland C cycle – climate linkages, and (5) providing the scientific community with a large dataset for developing and testing earth system and ecological models.

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Figure and Table Captions

Figure 1. Location of study sites. Map showing the distribution of northern peatlands (green area from Yu et al., 2010) and peatland sites included in this study (n = 215 sites, including 268 peat cores). Long-term rate of peat-carbon accumulation was estimated from 127 sites (151 peat cores; red and blue dots). The yellow dots represent cores for which only peat properties (bulk density, organic matter content, etc.) were available and synthesized. Refer to Supplementary Table 1 for details.

Figure 2. Overview of data availability for North America (black bars) and Eurasia (white bars). (A) Number of cores (total = 238) containing information on carbon/nitrogen ratio (n = 40), nitrogen content (n = 40), carbon content (n = 56), peat

types (n = 83), organic matter bulk density (n = 184), organic matter content (n = 190), and bulk density (n = 214). (B) Number of cores (total = 151) with a dating quality better than two dates per 1000 years (n = 35), one to two dates per 1000 years (n = 52), and less than one date per 1000 years (n = 64). (C) Number of calibrated basal peat ages (median) in 500-year bins from the database (n = 199) compared to all northern hemisphere basal peat ages (median) in 200-year bins (n = 2559, MGK data from MacDonald et al., 2006, Gorham et al., 2007, Korhola et al., 2010).

Figure 3. Distribution histograms of peat properties in northern peatlands. (A) Frequency distribution of bulk density for unidentified peat type samples (white bars) and different peat types (color bars). (B) Frequency distribution of organic matter content for different peat types. (C) Frequency distribution of organic matter bulk density for different peat types. (D) Frequency distribution of carbon content for different peat types. (E) Frequency distribution of nitrogen content for different peat types. (F) Frequency distribution of carbon/nitrogen mass ratio for different peat types.

Figure 4. Relation between carbon content and organic matter content in northern peatlands. The slope of each regression line is used as a conversion factor for estimating carbon content from organic matter content.

Figure 5. Temporal patterns of peat properties (mean, standard deviation, and number of samples). (A) Bulk density. (B) Organic matter content. (C) Organic matter bulk density.

(D) Carbon content. (E) Nitrogen content. (F) Carbon/Nitrogen mass ratio. White bars represent values that were based on a limited number of samples and peat records.

Figure 6. Main differences between *Sphagnum* and non-*Sphagnum* peat samples. (A) Bulk density. (B) Organic matter bulk density. (C) Organic carbon bulk density. (D) Carbon content. (E) Nitrogen content. (F) Carbon/Nitrogen mass ratio. (G) Temporal pattern of organic C bulk density. (H) Proportional change in the number of peat records that are *Sphagnum*-dominated, presented as a percentage of the total number of records.

Figure 7. Long-term apparent rate of carbon and nitrogen accumulation from northern peatlands (n = 127 sites). (A) Summer insolation at 60°N (data from Berger and Loutre, 1991) and temperature anomaly from an 11,300-year reconstruction for the northern extra-polar region from 30 to 90°N (data from Marcott et al., 2013). Temperature anomaly was calculated based on the 1961-1990 temperature averages. (B) Mean peat-carbon accumulation rates (PCAR) and standard error in 500-year bins. The number of sites per 500-year bins is also presented. (C) Mean peat-nitrogen accumulation rates (PNAR) and standard error in 500-year bins. These values were obtained using different C/N values over time, as indicated by the line.

Table 1. Peat properties in northern peatlands. Means and standard deviations are presented, along with the number of samples (n).

Table 2. Northern peatland peat properties by regions. Means and standard deviations are presented, along with the number of samples (n).

Table 3. Comparison of northern peatland peat properties estimates with other published values. Means and standard deviations are presented, along with the number of samples (n) when available.

Supplementary Material

Table S1. Summary information for the study sites included in the database.

A ~~circum-Arctic~~ database and synthesis of northern peatland soil properties and Holocene carbon and nitrogen accumulation

Running title

~~Circum-Arctic~~ Northern peatland database and synthesis

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Abstract

Here we present results from the most comprehensive compilation of Holocene peat soil properties with~~and~~ associated ~~Holocene~~ carbon and nitrogen accumulation rates for northern peatlands. Our database consists of 268 peat cores from 215 sites located north of 45°N. It encompasses regions within which peat carbon data have only recently become available, such as the West Siberia Lowlands~~, and~~ the Hudson Bay Lowlands, Kamchatka in Far East Russia, and the Tibetan Plateau. For all northern peatlands, carbon content in organic matter was estimated at 42~~.3~~ ± 3% (S.D.) for *Sphagnum* peat, 51~~.3~~ ± 2% for non-*Sphagnum* peat, and at 49~~.2~~ ± 2% overall. Dry bulk~~Bulk~~ density averaged 0.12 ± 0.07 g cm^{-3}, organic matter bulk density averaged 0.11 ± 0.05 g cm^{-3}, and total carbon content in peat averaged ~~46.8~~47 ± 6~~.1~~%. ~~-~~In general, large differences were found between *Sphagnum* and non-*Sphagnum* peat types in terms of peat properties. Time-weighted peat ~~-~~carbon accumulation rates averaged 23~~2.9~~ ± 2 (S.E.M.) g C m^{-2} yr^{-1}

during the Holocene on the basis of 151 peat cores from 127 sites, with the highest rates of carbon accumulation (25-28 g C m^{-2} yr^{-1}) recorded during the ~~warmer-than-today~~ early Holocene when the climate was warmer than the present. Furthermore,~~. Finally,~~ we ~~provide the first~~ estimate ~~for~~ the northern peatland carbon and nitrogen pools at 436 and 109~~.7~~ gigatons, respectively~~ equivalent to 10% of the world's soil nitrogen~~. The database is publicly available at https://~~/www.~~peatlands.lehigh.edu.

Keywords

Northern peatlands, Data synthesis, Climate change, Soil carbon and nitrogen, Biogeochemical cycles, Long-term ecosystem dynamics

Introduction

Of all terrestrial ecosystems, peatlands are arguably the most efficient at sequestering carbon (C) over long time scales. Northern peatlands cover approximately 4,000,000 km^2 or 3% of the global land area (Maltby and Immirzi, 1993) and have accumulated about 500 gigatons of C (GtC) mostly during the Holocene, equivalent to ~ 30% of the present-day~~the~~ global soil organic carbon (SOC) pool (Gorham, 1991; Bridgham et al., 2006; Yu et al., 2010). These ecosystems have also ~~been playing~~played a dynamic role in the Holocene global C cycle as important sinks of carbon dioxide (CO_2) and major sources of methane (CH_4) to the atmosphere (Frolking and Roulet, 2007; Korhola et al., 2010; Yu, 2011). As climate warming positively affects both plant growth and organic matter decomposition, r~~R~~ecent and projected climate change could shift the balance between peat production and organic matter decomposition, potentially affecting the peatland C-sink capacity and modifying peat ~~-~~C fluxes to the atmosphere (Frolking et al., 2011; Yu, 2012). This prediction ~~is~~ particularly ~~the case in~~holds true for the northern high-latitude regions, where the intensity of climate change is expected to be greatest (McGuire et al., 2009). The peatland C cycle ~~carbon~~ ~~-~~ – climate feedback remains difficult to assess, however, because of (1) limited understanding of peatland responses to climate change (Frolking et al., 2011), (2) data gaps and large uncertainties in regional peatland C stocks (Yu, 2012), and (3) non-linear peatland responses to external forcing (Belyea, 2009).

Very little is known about the nitrogen (N) budget that accompanies C accumulation in northern peatlands (but see Limpens et al., 2006 for a review). Assuming a net C sequestration of ~270 GtC (Yu, 2012) and a C/N ratio of 20-30 for fen peat (Bergner et al., 1990; Rydin and Jeglum, 2013; results therein) during the early Holocene (11-7 ka), about 10-13 GtN would have been required to build such peat deposits. It is therefore possible that northern peatlands have been playing an undocumented, dynamic role in the Holocene global N cycle as important sinks of N, potentially limiting the amount of N available for other ecosystems at the global scale (McLauchlan et al., 2013). Alternatively, if the main N input to peatlands was through N_2 fixation by cyanobacteria, these microorganisms might have been more important in driving the C cycle in peatlands than previously thought. Overall, studying the coupling between N and C cycling in northern peatlands is essential for a better understanding of how key biogeochemical processes interact in these systems and for predicting the future of peat C stocks.

Here we present the most comprehensive compilation of Holocene C and N data for northern peatlands. ~~Our database consists of 268 peat cores from 215 sites located north of 45 °N or at high elevations (e.g., Tibetan Plateau).~~ This synthesis encompasses regions within which peat ~~-~~C and N data have only recently become available, such as the West Siberian Lowlands in Asian Russia,~~a and~~ the Hudson Bay Lowlands in Canada, Kamchatka in the Russian Far East, and the Tibetan Plateau. In addition, we present the most comprehensive synthesis of peat soil properties (such as bulk density, organic matter content, ~~and carbon~~ C and ~~nitrogen~~ N content) from the northern hemisphere. Also, this new database and synthesis work represent a major expansion from Yu et al.'s (2009) synthesis on Holocene peat C dynamics, which was based on 33 sites (vs. 127 sites as reported in this paper). Finally, it constitutes a natural continuation of Charman et al.'s (2013) recent study on peat C accumulation in northern peatlands during the last millennium.

In addition to filling regional data and knowledge gaps, t~~T~~he main objectives of this paper are to (1) describe a database of peat soil properties and synthesize this information for different peat types, time intervals, and geographic regions, and (2) produce ~~a~~ time series of Holocene peat ~~-~~C and N accumulation rates in 500-yr ~~increments~~ bins for comparison with climate history. Key differences in Holocene peat properties between different regions and peatland types are also discussed in light of their implications for long-term peat C stocks. Of particular importance and relevance are the differences between *Sphagnum* and non-*Sphagnum* peat types. Finally, we present new estimates for northern peat C and N stocks for northern peatlands on the basis of the expanded database.

Database and ~~Database and analytical methods~~analysis

*Data**base**~~base~~*

We compiled a dataset of 268 published and unpublished Holocene peat records from 215 sites located in North America and Eurasia (Figure 1, Supplementary Table 1). The difference in the number of peat cores and peatland sites is due to the fact that, in a few instances, multiple cores were collected from a single peatland. As these multiple cores were not designed as true replicates in the original publications, each of these cores was considered as an independent record of peat properties in the present study. However, only the oldest core for each site was ~~accounted~~ used for ~~when~~ estimating peat inception age. Finally, when calculating peat ~~-~~C~~arbon~~ accumulation rates, ~~estimates,~~ multiple cores from a single site were each attributed an equal fraction of the weight for that site. For example, f~~F~~or a site with three cores, the peat ~~-~~C accumulation history of each core only accounted for 1/3 of ~~a record~~the site's record.

The l~~L~~atitude of most peatland sites range s~~d~~ from 45 to 69 °N. The cutoff at 45 °N represents the southern limit for defining what is considered to be the area contributing to the C cycle of the Arctic region (McGuire et al., 2009). ~~, with the exception of~~ Four high-elevation~~three~~ ~~high-elevation~~ sites found in China (the Tibetan Plateau) and Japan were also included, as they developed under similar 'northern' climatic conditions. ~~.~~The name and coordinates of these four sites are as follows: Zoige (33.5 °N, 102.6 °E), Hongyuan

(32.8 °N, 102.5 °E), Hani (42.2 °N, 126.5 °E), and Utasai (42.4 °N, 140.2 °E). A total of 155 cores originate from Eurasia, ~~comprising~~ including 112 cores from Russia. The remaining 113 cores come from North America~~, including 12 cores from Alaska~~. Approximately 40% of all cores were collected from~~in~~ ombrotrophic bogs (n = 110 cores~~08~~) and 20% were extracted from minerotrophic fens (n = 50 cores). The remainder (40%) was collected in ~~permafrost~~ peatlands currently affected by permafrost (n = 108 cores~~10~~). Note that peatland type was identified independently for each site by the original investigators. From an ecosystem functioning perspective, distinguishing bogs from fens and permafrost peatlands is important, as these peatland types are characterized by different hydrological regimes, vegetation communities, and peat-growth trajectories, all of which impact long-term rates of peat ~~-~~C sequestration (Rydin and Jeglum, 2013~~2006~~). Bogs are ~~nutrient~~mineral-poor, rain-fed peatland ecosystems with relatively low plant net primary production (NPP) and slow peat decomposition rates. In contrast, fens are hydrologically connected to surface or ground water, thereby receiving more ~~nutrients~~ mineral nutrients~~from the groundwater~~. Generally speaking, ~~they~~ fens have greater NPP but also faster peat decay rates than bogs (Blodau, 2002). Finally, in the sub-A~~a~~rctic and A~~a~~rctic regions, peatland hydrology, structure, and peat ~~-~~C balance are sensitive to the underlying permafrost aggradation and degradation dynamics (Camill, 1999; Turetsky et al., 2007). For the analysis, ~~frozen~~ peat plateaus (87~~9~~ out of 108~~10~~ cores), permafrost bogs (18 out of 108~~10~~ cores), and collapse scars (3 out of 108~~10~~ cores) were grouped under the peatland type ‘permafrost peatlands’. Original peatland categories can be found in Supplementary Table 1.

The database was built to include as many peat records as possible. Therefore, we included any peat core that was extracted north of 45 °N (or at high elevation) and for which bulk density or organic matter bulk density data were available. Information related to peat-core location, peatland type, peat properties, age, and data source can be found in Supplementary Table 1. Additional information related to the type of coring device used and the year of coring can be found in the original publications. Data ~~and age-depth relationships~~ used in this synthesis are readily accessible from the Holocene Peatland Carbon Network website (https://~~www.~~peatlands.lehigh.edu). ~~The website includes all published records and will be updated as new records included in this synthesis are eventually published.~~ This database ~~should~~ will be useful in future studies of ecosystem – ~~carbon~~ C cycle – climate interactions and for modeling long-term peatland dynamics.

In the following sub-sections, we present the criteria for site selection and the protocols used to develop the databa~~set~~se. In an effort to only analyze and synthesize *peat* samples, inorganic-rich horizons often found at the base of the peat cores were removed from the database. When available, stratigraphic information was used to distinguish peat vs. non-peat material. For example, gyttja (organic-rich lake sediments) was excluded from the dataset, as well as marshy, clayey, and silty sediments. When stratigraphic information was not available, a bulk density value of 0.5 g cm^{-3} was used as a cut-off between peat and non-peat material. This value was chosen on the basis of stratigraphic information from peatland records where peaty sediments with bulk density values up to 0.5 g cm^{-3} were identified. We ~~do~~ acknowledge that this cut-off value is arbitrary, and that our dataset likely contains some non-peat samples. Inorganic horizons (e.g., tephra layers) were also excluded from the ~~peat records~~database.

Peat properties

A ~~subset~~ total of 232 peat cores (181 sites) were ~~was~~ used for characterizing peat properties, though not all cores have all types of peat properties available (Figure 2a). This dataset contains 139 cores from Eurasia (including 109 cores from Russia) and 93 cores from North America (Figure 1). While approximately half of these cores were~~as~~ sampled and analyzed at high resolution (1-5 cm increments), the ~~remainder w~~remainder was~~as~~ sampled at lower resolution, typically at 10 cm increments. Dry b~~B~~ulk density (BD; g cm^{-3}), organic matter content (OM%; gravimetric %), as well as elemental C and N concentration values were compiled and synthesized. On the basis of these raw datasets, ~~carbon-to-nitrogen ratio (~~C/N mass ratio~~)~~ and organic matter bulk density (OMBD; g OM cm^{-3}) were calculated. These peat geochemical values are examined in light of peat stratigraphy, peat ages, and geographic regions. The following paragraphs briefly describe the protocols used to obtain these values.

Peat stratigraphic information was obtained for 83 peat cores (‘peat types’ in Figure 2a) for which plant macrofossil analysis or detailed peat description had been performed following standard techniques (e.g., Troels-Smith, 1955; Mauquoy and van Geel, 2007). This peat stratigraphic information was condensed into the following five peat types: *Sphagnum*, herbaceous, woody, brown moss, and humified peat. In a few cases, the investigators only ascribed a general peat type to the samples (e.g., ‘bog’ vs. ‘fen’ peat, or

‘*Sphagnum*’ vs. ‘herbaceous’ peat). In these cases, the uncertainty associated with classifying peat samples mostly relates to the uniformity of naming convention used among the investigators. For example, a peat sample that contains sizable fractions of brown moss and humified peat may be classified by an investigator as ‘brown moss peat’ and by another one as ‘humified peat’. We recognize that, due to their nature, brown moss and humified peat types might be less uniform than *Sphagnum* or~~,~~ herbaceous ~~, or woody~~ peat types. We included as much stratigraphic information as possible in the database, though ambiguous or imprecise descriptions were left out to avoid further ~~uncertainties~~confusions.

Dry b~~B~~ulk density and organic matter ~~concentration~~content were determined following standard procedures~~,~~ ~~in all cases where these parameters were measured, were determined following standard procedures~~ (Dean, 1974; Chambers et al., 2011). Peat samples of a known fresh volume were either freeze-dried or oven-dried at ca. 100 °C until constant weight was reached and weighed to determine bulk density, then burned at 500-600 °C for one to four hours and weighed again to determine organic matter content. The accuracy of these measurements mostly depends on sample handling (care must be taken to prevent peat compaction in the field and in the laboratory) and the analytical error associated with weighing. The product of bulk density (BD; g cm^{-3}) and organic matter content (OM%) of each peat sample was used to calculate organic matter bulk density (OMBD; g OM cm^{-3}), also referred to as ash-free bulk density (AFBD) or organic bulk density (OBD) in the literature (Yu et al., 2003; Björck and Clemmensen, 2004). We compiled a total of 21,220 bulk density measurements ~~from 214 cores~~, 18,973 organic matter content values~~ from 190 cores~~, and computed 18,544 organic matter bulk density values ~~from 184 cores ~~(Figure 2a).

Total peat ~~carbon ~~C and ~~nitrogen ~~N content were directly measured by combustion and elemental analysis of dry peat samples (Chambers et al., 2011). We compiled 3741 C and 3365 ~~carbon ~~N measurements ~~from 56 cores and 3365 nitrogen content measurements from 40 cores ~~(Figure 2a). We also computed a total of 3362 ~~carbon-to-nitrogen ratio (~~C/N~~)~~ mass ratio values~~ from 40 cores~~.

Finally, the regression between ~~total ~~peat ~~carbon ~~C content (C%) and peat organic matter content (OM%) for each peat type is presented as an estimate for ~~carbon ~~C content in organic matter (OC%). A total of 995 samples ~~from 19 cores ~~were used in this analysis. The slope of each one of these regressions is interpreted as the 'conversion factor' from OM% to OC%, such that it provides an indirect way for estimating the C% content of ash-free peat for investigators who do not perform elemental C~~%~~ measurements directly.

Peat-core chronology

Peat-core chronologies were almost exclusively based on radiocarbon (^{14}C) dates that were determined mostly by accelerator mass spectrometry (AMS) on terrestrial plant macrofossils or bulk peat (Piotrowska et al., 2011). A few older chronologies were based on conventional ^{14}C dating of bulk samples. Because no systematic offset has been observed in the ^{14}C age of bulk vs. non-woody plant macrofossils ~~The use of bulk dates is justified since the absence of a systematic offset between the ^{14}C dates of bulk peat~~

~~versus those of plant macrofossils it contains~~ (G.M. MacDonald, pers. comm. 2013), the use of bulk dates is justifiable. For the purpose of this study, all ^{14}C ~~ages~~ dates were calibrated to calendar years before present (cal. BP) using the program CALIB 6.1.0 (Stuiver and Reimer, 1993) with the IntCal09 calibration dataset (Reimer et al., 2009). In this paper, ages are reported in thousands of calibrated years before present (ka)~~, such that 1 ka = 1000 cal. B.P~~.

Age-depth relationships were established for all continuous peat cores for which at least five ~~radiocarbon dates (^{14}C)~~age determinations were available (n = 151 cores). Except for a few palynostratigraphic and tephrochronologic markers, nearly all records have chronologies exclusively based on ^{14}C ages (Supplementary Table 1). Chronologies were obtained through linear interpolation of calibrated ages between dated horizons. Single-age estimates were taken from the mid-point of each calibrated 2σ probability distribution. This parsimonious approach captures general patterns of temporal changes in peat accumulation and allows for analysis of peat ~~-~~C accumulation trajectories (e.g., Telford et al., 2004). Although more sophisticated approaches are possible (e.g., Charman et al., 2013), we seek to make the fewest or simplest assumptions for this analysis because the temporal resolution target for peat ~~-~~C accumulation rate calculations is relatively low (at 500 years). In the cases where the original investigator identified hiatuses (e.g., peat loss caused by erosion or fire) or depositional anomalies (e.g., thick tephra layers that interrupted peat accumulation) along their peat records, these gaps were taken into consideration when building age-depth relationships (Glaser et al., 2012). Otherwise, peat records were assumed to be continuous.

In an effort to assess the representativeness of our samples in terms of peatland inception ~~ages~~timing, peat basal ages were compiled and compared to results from large datasets (MacDonald et al., 2006; Gorham et al., 2007; Korhola et al., 2010). ~~When multiple cores were collected from a single peatland, only the oldest core was accounted for when estimating peat inception age.~~ Peat inception ages from 199~~16~~ sites (Supplementary Table 1) were summed and binned in 500-year intervals.

Long-term rates of carbon and nitrogen accumulation

A ~~subset~~ total of 151 peat cores from 127 sites were~~was~~ used for estimating rates of peat ~~-~~C accumulation. This dataset contains 96 cores from 78 North American sites and 55 cores from 49 Eurasian sites (Figure 1). Of the 33 sites presented in Yu et al.'s (2009) study, 25 were used in the present study (Supplementary Table 1). The remaining 8 sites did not fulfill our dating quality criterion (presented below). ~~When multiple cores were collected from a single peatland, each core was attributed a fraction of the weight for that site such that, for a site with three cores, the peat-C accumulation history of each core only accounted for 1/3. For each core, peat chronology was constrained by at least five age determinations.~~ The dating ~~resolution~~ quality of ~~these~~ each record~~s~~ was determined by the quotient of the calibrated peat basal age and the number of age determinations. For example, a 10,000-year-old peat core with a chronology constrained by 10 ^{14}C dates was attributed a dating ~~resolution~~ quality of ~~1000 years per~~one date per 1000 years. About 58% of ~~these~~ our 151 cores we~~a~~re characterized by an acceptable dating ~~resolution between 10 and~~quality of one to two ^{14}C dates per 1000 years (Figure 2b). These

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resolutions are well suited to capture millennial-scale variations in C accumulation. Several p~~P~~eat cores with ~~high resolution (10-500 years~~more than two ^{14}C dates per 1000 years ~~per date,~~ (n = 35 cores) we~~a~~re available from North America and Europe. The ~~coarser~~ lower dating ~~resolution~~ quality cores (<1 date per ~~>~~1000 years~~, per date~~) we~~a~~re unevenly distributed and comprise 44% of the North American records ~~(42 out of 96 cores)~~ and 40% of the Eurasian records ~~(22 out of 55 cores)~~.

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The long-term rate of peat ~~-~~C accumulation was calculated for each core following one of the ~~these~~ following five approaches (Supplementary Table 1):~~.~~ (1) w~~W~~henever possible, peat core chronology was combined with bulk density and C% ~~content values~~ for each depth increment (n = 47 cores);~~.~~ (2) i~~I~~n the cases where direct C measurements were lacking, peat core chronology was combined with ~~ash-free~~organic matter bulk density measurements and a mean organic ~~matter carbon~~ C ~~content~~ value of 49% in organic matter (n = 57 cores~~; see the Results section for details~~);~~.~~ (3) f~~F~~or cores that lacked ~~ash-free~~organic matter bulk density and direct C~~-~~%~~content measurements~~, peat core chronology was combined with bulk density measurements and a mean ~~total carbon~~ C content of 47% in total peat (n = 3 cores~~; see the Results section for details~~);~~.~~ (4) w~~W~~henever neither bulk density nor C% ~~content~~ was directly available from the cores, long-term rate of peat ~~-~~C accumulation was calculated for each core by combining time-dependent bulk densities (0.08 g cm^{-3} at 0-0.5 ka; 0.12 g cm^{-3} at 0.5-6 ka; 0.14 g cm^{-3} at 6-12 ka) with a mean C content of 47% in total peat for each dated interval (n = 32 cores~~; see the Results section for details~~), and~~.~~ (5) p~~P~~eat ~~-~~C accumulation rates for the remaining 12 cores were directly obtained from published figures and tables. For all the cores, time-weighted peat ~~-~~C accumulation rates were summed and binned in 500-year intervals. It is important to note that such reconstructions are ‘apparent rates’ that are different from true rates of C ~~uptake~~ accumulation in peatlands, because decomposition processes have been affecting old peat layers for thousands of years (Turunen et al., 2002). Finally, the long-term rate of peat N accumulation was calculated by combining our binned peat-C accumulation rates with time-dependent C/N values (65 at 0-6 ka, and 40 at 6-10 ka).

Results

Peat Properties

~~, the mean bulk density value for each peat type is reported in Table 1, and regional differences are presented in Table 2.~~*Descriptive statistics of dataset*

The frequency distribution of each peat property is shown in Figure 3. Mean values and standard deviations for all peat properties are presented by peat type in ~~The frequency distribution is presented in Figure 3a~~Table 1, and by region in Table 2.

Bulk density values (n = 21,220) ranges~~d~~ from 0.003 to 0.498 g cm^{-3}, with a mean value of 0.118 ± 0.069 g cm^{-3} (1 standard deviation (S.D.)). A one-way analysis of variance (ANOVA) reveals~~ed~~ an ~~significant~~ effect of peat type on bulk density (F (10709) = 941, $p < 0.0001$), with all peat types significantly different from each other on the basis of post-hoc Tukey’s LSD tests ($p < 0.0001$). In increasing order, mean bulk density of the peat types is *Sphagnum* < Woody < Herbaceous < Brown Moss < Humified (Table 1).

Organic matter content (n = 18,973) has~~d~~ a mean value of 90.7 ± 13% (1 S.D.) and a median of 95.7%. ~~The frequency distribution is presented in Figure 3b, the mean organic matter content for each peat type is reported in Table 1, and regional differences are presented in Table 2.~~ The ANOVA reveals~~ed~~ an ~~significant~~ effect of peat type on organic matter content (F (9512) = 349, $p < 0.0001$), with all peat types significantly different from each other (Tukey's LSD: $p < 0.0001$). In decreasing order, mean organic matter content of the peat types is~~are~~ *Sphagnum* > Woody > Herbaceous > Brown Moss > Humified (Table 1).

Organic matter bulk density ~~or ash-free bulk density~~ (n = 18,544) ranges~~d~~ from 0.003 to 0.452 g OM cm^{-3}, with a mean value of 0.105 ± 0.051 g OM cm^{-3} (1 S.D.). ~~The frequency distribution is presented in Figure 3c, the mean organic matter density for each peat type is reported in Table 1, and regional differences are presented in Table 2.~~ The ANOVA reveals~~ed~~ an ~~significant~~ effect of peat type on organic matter density (F (9081) = 942, $p < 0.0001$), with all peat types significantly different from each other (Tukey's LSD: $p < 0.0001$). In increasing order, mean organic matter density of the peat types is *Sphagnum* < Herbaceous < Woody < Brown Moss < Humified (Table 1).

~~Total peat carbon~~ C content in total peat (n = 3741) ranges~~d~~ from 30 to 60%, with a mean value of 46.8 ± 6.1% (1 S.D.) and a median of 47.8%. While the lowest values (< 35%) are almost exclusively associated with samples from Alaska, western Canada, Fennoscandia, and eastern Russia, the highest values (> 55%) are characteristic of sites located in the western European Islands and Fennoscandia. ~~Mean C% values for all five~~

~~peat types are reported in Table 1, and regional differences are presented in Table 2.~~ The ANOVA reveals~~ed~~ an ~~-significant~~ effect of peat type on C% (*F* (2494) = 161, $p <$ 0.0001), with *Sphagnum* samples significantly different from other peat types (Tukey's LSD: $p < 0.0001$). Herbaceous and woody peats a~~we~~re distinct from other types, but ~~hardly d~~indistinguishable from one another (Tukey's LSD: $p = 0.238$). Likewise, humified and brown moss peats a~~we~~re distinct from other types, but indistinguishable from each other (Tukey's LSD: $p = 0.448$). In increasing order, mean C% of the peat types is *Sphagnum* < Humified = Brown Moss < Herbaceous = Woody (Table 1). The frequency distribution of C% in peat is ~~is~~also characterized by a second, though minor, mode at 40% (Figure 3d). The latter is mostly associated with *Sphagnum* peat samples, as their average ~~C content (~~C%~~)~~ is significantly lower than those for other peat types (Table 1). This difference is likely caused by the high content of complex and recalcitrant compounds found in *Sphagnum* tissues such as lipids and waxes, which have lower C% than more labile biopolymers such as cellulose (Cagnon et al., 2009).

On the basis of 995 samples for which both OM%~~C~~ and C% were quantified, we ~~therefore~~ developed conversion factors (slopes of linear regressions) for several peat types~~, providing ways~~ to estimate OC% ~~for investigators who do not perform C% measurements routinely~~(Figure 4). There i~~wa~~s a noticeable difference between the slope of *Sphagnum* peat (0.423 ± 0.030; n = 454) and that of non-*Sphagnum* peat (0.514 ± 0.024; n = 308). The ~~carbon~~ C content in organic matter (OC%) for *Sphagnum* peat i~~wa~~s smaller than expected ~~(~~at 42.3 ± 3.0% (~~(~~e.g., Bauer et al., 2006; Beilman et al., 2009; Table 3~~)~~). As the majority of our *Sphagnum* samples for this specific analysis a~~we~~re younger than 0.5 ka (304 out of 454 samples) and extracted from raised bogs, it is very likely that our estimated OC% biases towards young and undecomposed *Sphagnum*. This ‘young *Sphagnum* peat effect’ heavily influenced the slope of the overall relation between C% and OM% (0.467 ± 0.045) due to the overrepresentation of *Sphagnum* samples in the dataset (454 out of 995 samples). To minimize this bias when estimating mean OC% in peat, all 304 young *Sphagnum* samples were removed from the dataset, yielding an overall conversion factor of 0.492 ± 0.024.

~~Total peat nitrogen~~ N content in peat (n = 3365) ranges~~d~~ from 0.04 to 3.39%, with a mean value of 1.2 ± 0.7% (1 S.D.). T~~T~~he frequency distribution is~~is~~ asymmetric and characterized by~~, with~~ a mode at 0.65% (Figure 3e). The latter is largely due to the overrepresentation of *Sphagnum* peat samples (having low N content) in our ~~samples~~database. The ANOVA reveals~~ed~~ an~~ significant~~ effect of peat type on N content (F (2504) = 666, $p < 0.0001$) with *Sphagnum* and herbaceous peat types significantly different from each other and from all other types (Tukey’s LSD: $p < 0.0001$). Humified and brown moss peats a~~we~~re distinct from other types, but indistinguishable from each other (Tukey’s LSD: $p = 0.113$). Likewise, woody and brown moss peats a~~we~~re indistinguishable from one another (Tukey’s LSD: $p = 0.240$). In increasing order, mean ~~N content~~N% of the peat types is *Sphagnum* < Woody = Brown Moss = Humified < Herbaceous (Table 1).

C/N mass ratio (n = 3362) ranges~~d~~ from 12 to 217, with a mean value of 55 ± 33 (1 S.D.). The frequency distribution is~~is~~ asymmetric and characterized by~~, with~~ a mode at 25

(Figure 3f). While the distribution mode (25) is~~is~~ associated with non-*Sphagnum* peat types, the distribution mean (55) is skewed towards *Sphagnum* peat samples owing to their overrepresentation in our ~~samples ~~database (Figures 3f). The ANOVA reveals~~ed~~ an ~~significant ~~effect of peat type on C/N ratio (*F* (2501) = 174, $p < 0.0001$) with *Sphagnum* peat significantly different from all other types (Tukey's LSD: p <0.0001). Woody peat i~~wa~~s distinguishable from all peat types except for brown moss peat (Tukey's LSD: p = 0.665). Herbaceous and humified peat types a~~we~~re indistinguishable from one another (Tukey's LSD: p = 0.721). In decreasing order, the mean C/N ratio of peat types is *Sphagnum* > Woody = Brown Moss > Humified = Herbaceous (Table 1).

Temporal changes in peat properties

~~The frequency distribution is presented in Figure 3a~~

We find a decreasing trend in bulk density over the Holocene (Figure 5a), with the densest peat characterizing the oldest samples (8-10 ka) and the least-dense peat characterizing the youngest samples (0-2 ka). This trend is most likely attributable to the progressive decomposition and subsequent compaction of peat over time, as well as to higher ash content in early-stage peat (likely from fens). Conversely, a~~A~~ clear increasing trend in organic matter content (OM%) is found over the Holocene (Figure 5b), with the greatest OM% characterizing the youngest samples (0-2 ka) and the least OM% characterizing the oldest samples (8-10 ka). This trend is most likely attributable to higher inorganic material inputs during early-stage peatland development as well as to a greater loss of OM in the deeper portions of peat profiles~~.~~ O~~O~~rganic matter bulk density

(OMBD) remains relatively constant over the Holocene (Figure 5c) because of the opposite trends exhibited by BD and OM% (Figures 5a, 5b). The only exceptions ~~except~~ ~~for~~are the low OMBD values characterizing the youngest samples (< 0.5 ka), probably due to the large proportion of young, undecomposed *Sphagnum* peat samples.

~~While OMBD values closely tracked changes in bulk density during the mid and late Holocene (0-8 ka), their trajectory diverged between 8 and 10 ka (Figure 4a and 4c) because of decreasing organic matter content in early Holocene peat samples (Figure 4b).~~ C content in peat remains uniform over the Holocene (Figure 5d), except for slightly lower C% during the late Holocene. ~~However, as C values for early Holocene samples are based on a very limited number of samples and peat records (white bars in Fig. 4d), we caution against analysis or interpretation of the documented trend in our data.~~ We ~~also~~ find a decreasing trend in N%~~ content~~ over the Holocene, such that young peat deposits are associated with low N%~~ content~~ (Figure 5e). ~~This trend could be explained by a progressive retention of N downcore as a result of long-term peat decomposition processes and associated C loss (e.g., Kuhry and Vitt, 1996).~~ Peat deposits older than 6 ka are mostly associated with low~~er~~ C/N ratios, whereas peat samples younger than 6 ka are characterized by high C/N values (Figure 5f).

In general, *Sphagnum* peat is characterized by lower BD, OMBD, C%, N%, and C/N ratio than samples composed of non-*Sphagnum* peat (Figure 6). Therefore, peatland development could explain much of the aforementioned temporal trends (Figure 5), as e~~dense peat (herbaceous, brown moss, and humified types) typically charact~~arly-stage rich fens are typically characterized by non-*Sphagnum* peat, whereas~~and~~ late-stage poor fens and bogs are *Sphagnum*-dominated (Figure 6h). ~~ AlternativelThis effect may be partly explained by peat type differences between young and old samples, with young samples mostly composed of *Sphagnum* peat (having low N content) and old samples composed of non-*Sphagnum* peat (having high N content). peat type differences between young and old samples, with young samples mostly composed of *Sphagnum* peat (having low N content) and old samples composed of non-*Sphagnum* peat (having high N content). This 'peat type effect' may also be combined with~~

Spatial differences in peat properties

Significant differences in bulk density are found at the regional scale (Table 2). The densest peat is observed in Alaska (mean = 0.168 ± 0.087 g cm^{-3}) and western Canada (mean = 0.166 ± 0.076 g cm^{-3}), whereas the least dense peat is found from the western European Islands (mean = 0.055 ± 0.027 g cm^{-3}). Organic matter bulk density values follow a similar pattern across these regions (Table 2). These differences are strongly correlated with peat types and sample ages, with the Alaskan and western Canadian samples largely constituted of herbaceous, humified, and brown moss peat types. ~~These regional differences were strongly correlated with peat types and sample ages, with the United Kingdom samples mostly composed of young *Sphagnum* peat and the Alaskan samples largely constituted of old herbaceous, humified, and brown moss peat types.~~

~~Significant differences in bulk density were found at the regional scale (Table 2 and Figure 6a). The densest peat was found at permafrost sites (), whereas the least dense peat was reported from non-permafrost peatlands (). There was also a marked difference between Alaskan (mean = 0.168 ± 0.087 g cm^{-3}) and western Canadian sites (mean = 0.166 ± 0.076 g cm^{-3}) versus the Western European Island sites (mean = 0.055 ± 0.027 g cm^{-3}). These regional differences were strongly correlated with peat types and sample ages, with the United Kingdom samples mostly composed of young *Sphagnum* peat and the Alaskan samples largely constituted of old herbaceous, humified, and brown moss peat types.~~

OM% does not vary much between regions (> 90% in all regions), with the notable exception of Alaskan and eastern Russian/Asian peatlands that exhibit~~ a~~ mean values of 76.6 ± 18.8% and 80.3 ± 16.7%, respectively (Table 2). Aeolian dust and tephra ash inputs to some peatlands in Alaska, Kamchatka, and Japan might partly explain such low OM% values.

Peat inception ages and long-term rates of carbon and nitrogen accumulation

Calibrated ages (mid-point) for peat inception range~~d~~ from 0~~1~~.6 to 15 ka and the frequency distribution ~~followed a bimodal distribution with~~is characterized by a mode~~s~~ at 11-9 ka ~~and at 8-6 ka~~ (Figure 2c). The ~~early-Holocene mode~~latter corresponds with peat inception peaks in the West Siberian Lowlands and~~,~~ in Alaska~~, and Fennoscandia~~. ~~The mid-Holocene peak is linked with peatland inception across western Canada and the~~

~~Hudson Bay Lowlands. While the majority of sites older than 11 ka are found in Alaska and Siberia, most sites younger than 6 ka are located in northeastern Canada. Generally speaking~~In general, our samples are in agreement with much larger networks of peat basal ages (Smith et al., 2004; MacDonald et al., 2006; Gorham et al., 2007; Korhola et al., 2010; Ruppel et al., 2013; Yu et al., 2013)~~, except for our underrepresentation of peatlands with inception ages between 10 and 8 ka (Figure 2b). This discrepancy may be attributable to an underrepresentation of Siberian sites in our dataset (Smith et al., 2004)~~.

The time-weighted long-term rate of C accumulation average~~sd~~s 22.9 ± 2.0 g C m^{-2} yr^{-1} (standard error of mean (S.E.M.); Figure 7b~~6~~). Values exhibit an increasing trend that initially peaks during the early Holocene between 10 and 7.5 ka at ~~25-28~~27.0 ± 2.6 g C m^{-2} yr^{-1}. This peak is largely caused by rapid peat accumulation in Alaska, the Western Siberia Lowlands, and s~~s~~outheastern Canada. The remainder of the Holocene is characterized by a decreasing trend in C accumulation rates from 24 to 18 g C m^{-2} yr^{-1} and a time-weighted mean at 22.0 ± 1.9 g C m^{-2} yr^{-1}~~, and millennial-scale variations~~ (Figure 7b~~6~~). There is a notable minimum value between 3 and 1.5 ka at 18-19 g C m^{-2} yr^{-1}. Lack of decomposition probably explains most of the apparent increase in accumulation over the past millennium (24-32 g C m^{-2} yr^{-1}), as young peat appears to be accumulating more quickly than old peat simply because the former has undergone less decomposition than the latter (Clymo, 1984).

The time-weighted long-term rate of N accumulation averages 0.5 ± 0.04 g N m^{-2} yr^{-1} (S.E.M.; Figure 7c). While the mid and late Holocene (6-0 ka) are characterized by the lowest rates of N accumulation at 0.34 g N m^{-2} yr^{-1}, the highest rates (0.61 g N m^{-2} yr^{-1}) occur between 12 and 6 ka (Figure 7c). This trend mirrors that of C accumulation (Figure 7b), as C and N sequestration rates are both mainly influenced by peat density and its accumulation rate. The low rates of N accumulation over the past 6 ka might also relate to the increasing presence and persistence of *Sphagnum* (having high C/N ratio and low N concentration) in northern peatlands (Figures 6 and 7).

Discussion

R~~Data r~~epresentativeness of the database for northern peatlands

The present database contains the most comprehensive compilation of peat properties and C accumulation records for northern peatlands. The previous large-scale synthesis (Yu et al., 2009) only contained 33 sites and lacked records from the Hudson Bay lowlands and the Russian Far East, and had limited sites from West Siberia and the western European Islands. The present database fills gaps from these regions.

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However, European Russia, ~~The database comprises 268 peat cores from 215 sites located between 45 and 69 °N, throughout the circum-Arctic peatland domain. These sites were found across broad gradients of continentality, temperature, growing season length, and precipitation (Yu et al., 2009). The majority of our study sites were found in large peatland complexes such as the Hudson Bay Lowlands or in peatland-rich regions such as the northwestern European Islands and Fennoscandia. Conversely, smaller peatland systems such as kettle bogs and other isolated features were sparsely represented. As the main objective of our dataset was to estimate the northern peatland C~~

~~stock, the high proportion of sites from large peatland complexes seems justified. On another note, further studies of small depressional peatlands could potentially lead to a better understanding of peat C accumulation processes and peatland sensitivity to climate change (e.g., Buffam et al., 2010; Ireland et al., 2013).~~ East Siberia, and the Russian Far East clearly remain poorly studied regions in terms of northern peat C stocks and accumulation histories (Figure 1). A wetland map by Stolbovoi and McCallum (2002) suggests that shallow peaty deposits (<50 cm) interspersed with few deeper peat bogs (>50 cm) dominate the Far East Russian landscape. Most of these deeper peatlands are presumably found in Kamchatka and Sakhalin (Stolbovoi, 2002). This broad portrait is, however, based on fewer than 30 soil profiles from across East Siberia and Far East Russia (Stolbovoi et al., 2001), making it difficult to evaluate the importance of this region in the northern peatland C cycle. In general, peat C stocks in Eastern Russia may not be as massive as those from West Siberia or European Russia (Stolbovoi and McCallum, 2002). Therefore, understanding how these shallow peatlands in East Siberia and the Russian Far East have developed during the Holocene would provide useful end-members of climate controls of peat C accumulation, but these peatlands do not seem to represent a large missing C stock.

Northern peatland soil properties: key findings and uncertainties

Peat-carbon stocks ~~and density~~

Several studies have quantified the soil C density and total C pool of peatlands using different approaches (e.g., Armentano and Menges, 1986; Gorham, 1991; Yu et al., 2010). These ~~different~~ methods have led to total C pool estimates for northern peatlands that vary by at least a factor of two, from 234 to 547 GtC (Lappalainen, 1996; Yu et al., 2010; see Yu, 2012 for a review). Many of these studies have combined mean peat depth, modern peatland area, and a single mean ~~peat~~ C ~~bulk~~ density value (BD x C% or OMBD x OC%) in their calculations (e.g., Gorham, 1991). Applying Gorham's (1991) mean peat depth and peatland area estimates to the mean BD and C% results ~~presented in this~~from our database yields a ~~peat~~ C pool estimate of 436 GtC (2.3 m x 3.42 Mkm^2 x 0.118 g cm^{-3} x 47% C). However, it is well documented that most peatlands undergo a shift from herbaceous ~~fen~~ to *Sphagnum* peat~~bog~~ during their developmental history (Hughes, 2000; Figure 6h) and that different BD, C%, and rates of peat accumulation are associated with fen and bog peats (e.g., Vitt et al., 2000; Figure 6). We also know that peat-C accumulation rates have varied asynchronously between regions throughout the Holocene as a result of regional changes in hydroclimatic conditions (e.g., Yu et al., 2009; Charman et al., 2013). Therefore, we argue that reconstructing Holocene changes in peat ~~-~~C accumulation on the basis of *measured* peat C density ~~peat-C bulk density values~~ and reliable peat-core chronologies constitutes a step forward in providing the best possible peat ~~-~~C stock estimates (see Yu et al., 2010~~09~~ for an example). It also allows for quantifying spatial and temporal differences in rates of peat ~~-~~C accumulation, as well as the temporal trajectories of peat ~~-~~C fluxes to the atmosphere (MacDonald et al., 2006; Yu et al., 2013). However, better maps of the present peatland area (and its change over time) are still needed to improve current peat C stock estimates. ~~Therefore, our database should be of great use for updating current peat-C stock estimates, as it contains the most extensive set of peat-C bulk density measurements.~~

Carbon content in organic matter

For each peat layer, peat ~~-~~C~~carbon bulk~~ density can be estimated by the product of either (1) bulk density and ~~total peat~~C~~ carbon~~ content in total peat (BD x C%), or (2) ash-free bulk density and ~~carbon ~~C content in organic matter (OMBD x OC%). ~~It is important to mention that peat-C stocks estimated using BD x C% or OMBD x OC% yield the same value. Whenever BD and C% measurements were available along peat cores, we used the former formula. However, when only OMBD was available, the second formula was used. ~~It could be argued that the first option is preferable when estimating peat ~~-~~C stocks, as it produces values that are directly comparable to routine soil ~~-~~C measurements from other terrestrial ecosystems. However, the present database clearly indicates that the majority of peatland scientists routinely analyze organic matter content (OM%; n = 18,973 samples) rather than C% (n = 3741 samples) along peat cores. To provide a way to estimate OC% from OM%, we developed the following conversion factors: 42.3 ± 3.0% for *Sphagnum* peat, 51.4 ± 2.4% for non-*Sphagnum* peat, and 49.2 ± 2.4% overall (Figure 4, Table 1).

While the overall peat and the non-*Sphagnum* peat conversion factors are in line with those from previous studies (e.g., Gorham, 1991; Vitt et al., 2000; Turunen et al., 2002; Beilman et al., 2009), the *Sphagnum* peat factor is lower than other estimates (e.g., Bauer et al., 2006; Beilman et al., 2009; Table 3). Indeed, our mean OC% *Sphagnum* value at 42.3% is close to that of surface *Sphagnum* tissues, suggesting that it constitutes a valid estimate for ash-free and poorly decomposed *Sphagnum* peat. As previously mentioned, this bias towards low OC% is due to a large number of *Sphagnum* samples younger than 0.5 ka (304 out of 454 *Sphagnum* samples).

Although each one of the three conversion factor slopes was significant ($p < 0.0001$), there is a noticeable scatter in the data (Figure 4) that cannot solely be explained by the ~ 1% analytical error associated with the loss-on-ignition procedure (Heiri et al., 2001). The progressive accumulation of recalcitrant C in old samples (lignin ~ 60% C vs. cellulose ~ 42% C), assuming it occurs at a greater rate than the loss of OM in the deeper portions of peat profiles, could explain why C% appears higher than our OC% conversion factors (Cagnon et al., 2009). The presence of inorganic C, particularly for the humified and brown moss peat types, could also explain these results. ~~While the overall peat and the non-*Sphagnum* peat conversion factors are in line with those from previous studies (e.g., Gorham, 1991; Vitt et al., 2000; Turunen et al., 2002; Beilman et al., 2009), the *Sphagnum* peat factor is lower than other estimates. Indeed, our mean OC% *Sphagnum* value at 42% is close to that of surface *Sphagnum* tissues, suggesting that it constitutes a valid estimate for ash-free and poorly decomposed *Sphagnum* peat. As previously mentioned, this bias toward low OC% is due to a large number of *Sphagnum* samples younger than 0.5 ka (304 samples out of 454).~~

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Oligotrophication and the fen-to-bog transition in northern peatlands~~*Carbon content in organic matter*~~

~~The relation between total peat carbon content (C%) and peat organic matter content (OM%) is presented in Figure 4 (n = 995).~~

~~Our averaged bulk density (0.12 ± 0.07 g cm^{-3}) and organic matter bulk density (0.11 ± 0.05 g OM cm^{-3}) values are within the range of most widely used estimates (e.g., Clymo, 1984; Yu et al., 2010; Table 3).~~

Sphagnum and non-*Sphagnum* peat types were characterized by very different peat properties, with *Sphagnum* peat having lower BD, OMBD, C%, N%, and C/N ratio than non-*Sphagnum* peat (Figure 6). These differences become important when estimating Holocene peat C fluxes, as the proportion of *Sphagnum*-dominated peat records increases during the late Holocene due to the fen-to-bog transition (Figure 6h). For example, much stronger CH_4 emissions are associated with fens than bogs (e.g., Pelletier et al., 2007). In terms of C sequestration rates, the systematically higher organic C density of non-*Sphagnum* peat suggests that higher accumulation rates are possible in fens than in bogs (Figure 6g), assuming optimal hydroclimatic conditions leading to rapid peat burial. In addition, as non-*Sphagnum* samples contain twice the N mass of *Sphagnum* peat (Figure 6e), early-stage fens have the ability to stock more N than late-stage bogs. Overall, further studies on the timing of the fen-to-bog transition across the northern peatland domain are needed to better our understanding of its impact on C sequestration and CH_4 emissions.

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Holocene pattern of ~~circum-Arctic peatland~~ carbon accumulation in northern peatlands

The overall trajectory and shape of our Holocene peat ~~-~~C accumulation curve is similar to the synthesis from~~of~~ a much smaller ~~-~~dataset (n = 33; Yu et al., 2009). As such, an ~~that shows an~~ early Holocene peak during the Holocene Thermal Maximum (HTM) ~~as well as~~and an overall slowdown of ~~carbon~~ C accumulation during the mid- and late-Holocene, particularly after 4 ka during the Neoglacial period and associated permafrost development, were found in both syntheses (~~Vitt et al., 2000;~~ Figure 7~~6~~). However, the mean Holocene value of 22.9 ± 2.0 g C m^{-2} yr^{-1} (1 S.E.) presented here is approximately 24% higher than the estimate in Yu et al.'s 2009 study (18.6 g C m^{-2} yr^{-1}). Our larger dataset likely better represents the northern peatland ~~-~~C accumulation rates~~stock~~. These results imply that current peat ~~-~~C stocks might be underestimated.

While the peak value at 27 g C m^{-2} yr^{-1} is about 23% higher than the time-weighted mean peat-C accumulation rate for the remainder of the Holocene at 22 g C m^{-2} yr^{-1}, we only found a 2% difference in organic C density values between young (0.053 ± 0.02 g C cm^{-3}) and old (0.057 ± 0.03 g C cm^{-3}) peat samples. These results clearly show that the peak value during the early Holocene cannot be mainly attributed to presumably dense peat deposits that would be rich in recalcitrant C due to long-term decomposition and compaction. Instead, factors influencing the rate of peat burial such as peat type (*Sphagnum* vs. non-*Sphagnum* peat; Figure 6), growing season length, and other environmental variables, must have been responsible for such high rates of C sequestration during the early Holocene.

The Holocene Thermal Maximum (HTM) is a well-documented period of orbitally-induced warm climate in the northern high-latitude region (Kaufman et al., 2004; Renssen et al., 2012; Marcott et al., 2013) that reaches its maximum around 11 ka (Berger and Loutre, 1991; Figure 7a). The peak in warm climatic conditions shows a transgressional pattern across northern North America that moved eastward with the waning Laurentide Ice Sheet during the early and mid Holocene (Kaufman et al., 2004). This progressive increase in land availability coupled with warming summer conditions have been proposed as the main controls on peatland inception and rapid C accumulation across northern North America (Harden et al., 1992; Gorham et al., 2007, 2012; Yu et al., 2009; Jones and Yu, 2010). ~~As such, the highest rates of C accumulation have been recorded between 11 and 8.5 ka in Alaska, but only around 7 ka in western Canada (Figure 6; Vitt et al., 2000; Yu et al., 2009; Jones and Yu, 2010).~~ In general, our results ~~confirm this trend and~~ support the hypothesis that warm summers could promote peat formation and C sequestration (Beilman et al., 2009; Yu et al., 2009; Charman et al., 2013), as the highest rates of C accumulation broadly coincide with the peak in summer insolation from 11 to 7 ka (Figure 7). We acknowledge that water input was necessary to allow for peatland development. Furthermore, the observed temporal asymmetry in peatland inception age and peaks in C accumulation rates between Alaska, western Canada, and the Hudson Bay Lowlands follows the transgressional pattern of the HTM. For example, peat inception and highest peat C accumulation rates occur at 11-9 ka in Alaska, whereas they are delayed in western Canada with peak values around 9-7 ka.

These findings have important implications for projecting the fate of peat-C stocks in a future warmer world.

The Neoglacial period is characterized by generally cooler and wetter conditions than the HTM (Figure 7a; Marcott et al., 2013). Particularly low C accumulation rates coincide with this time period across the northern peatland domain (Figure 7; Vitt et al., 2000; Jones and Yu, 2010). Peat accumulation processes might even have stopped in some regions (e.g., Peteet et al., 1998). The onset of permafrost aggradation in many peatlands also occurred during the Neoglacial period (Zoltai, 1971, 1995; Vitt et al., 2000; Oksanen et al., 2003; Sannel and Kuhry, 2008), reducing the peat C-sink capacity. In addition to shorter and cooler growing seasons, lower C accumulation rates in permafrost sites likely relates to a slower peat burial due to (1) more intense peat decomposition in the acrotelm due to drier surface conditions, and (2) a slower rate of peat formation and associated C inputs to soil because many peat plateaus are not *Sphagnum*-dominated. Overall, our results support the notion that climatic changes such as the HTM and the Neoglacial cooling impact C sequestration rates in peatlands.

Role of northern peatlands in the global nitrogen cycle

As relatively few downcore peat N concentrations have been reported in the literature, it was difficult to compare our mean value of 1.2% to previous estimates. ~~Percent N in new foliage of vascular species growing in subarctic peatlands average 1.8% (Schuur et al., 2007), similar to our mean value for non-*Sphagnum* peat types (1.5%).~~ Bragazza et al. (2012) reported N content values of 0.7% for *Sphagnum fuscum* litter and 1.48% for

Eriophorum vaginatum (herbaceous) litter, ~~also~~ in line with our results (Table 1). Similarly, Turunen et al. (2004) documented peat N concentrations ranging from 0.35 to 2.25% (mean value of 0.8%) for the uppermost sections of 23 *Sphagnum* bogs across northeastern Canada. Overall, these values closely match our findings for *Sphagnum* (0.7%) and herbaceous (1.7%) peat types (Table 1).

Using our peat C pool estimate of 436 Gt and assuming a mean C/N ratio of 45 yields a peat-N pool of 9.7 Gt, roughly equivalent to 10% of the global soil N pool at 95 Gt (Post et al., 1985). This estimate is within the range proposed by Limpens et al. (2006) at 8-15 GtN. ~~We also calculated 500-year bin N accumulation rates for the past 10,000 years by combining our binned peat-C accumulation rates with time-dependent C/N values.~~ ~~Results indicate a~~The Holocene time-weighted peat-N accumulation rate of~~of~~ 0.5 ± 0.04 g N m^{-2} yr^{-1} (S.E.; Figure 7~~6~~) is also in line with a previous estimate of 0.19-0.48 g N m^{-2} yr^{-1} (Limpens et al., 2006). While the mid and late Holocene (6-0~~0-6~~ ka) a~~we~~re characterized by the lowest rates of peat-N accumulation at 0.34 g N m^{-2} yr^{-1}, the highest rates (0.61 g N m^{-2} yr^{-1}) occurr~~ed~~ between 12~~6~~ and 6~~12~~ ka (Figure 7c~~6~~). ~~This trend mirrors that of C accumulation (Figure 6), as C and N sequestration rates are both influenced by bulk density and peat accumulation rates.~~ The low rates of N accumulation over the past 6 ka might also relate to the increasing presence and persistence of *Sphagnum* peat (having high C/N ratio and low N concentration) across the northern peatlands ~~as a result of the fen-to-bog transition~~ (Figures 6 and 7~~6~~). Overall, given the bias toward *Sphagnum*-dominated sites in our database, N pools and N accumulation rates are probably underestimated.

Rapid N sequestration in peatlands during the early Holocene might have contributed to the global decline in reactive N availability for terrestrial ecosystems (McLauc~~g~~hlan et al., 2013), pointing to a potentially important and undocumented role of northern peatlands in the global N cycle. These results also raise the important question of N provenance: in the absence of large rates of atmospheric N deposition during the early Holocene, the only process that could account for such a large N pool in peatlands is N fixation, either through symbiotic or asymbiotic processes (Limpens et al., 2006).

The fate of these large peat ~~-~~N stocks remains largely unknown under recent and projected warming. Indeed, the importance of peatlands as sources of nitrous oxide (N_2O) is just emerging (e.g., Repo et al., 2009; Marushchak et al., 2011; Palmer et al., 2012), and studies have suggested that reduced surface moisture or increasing temperatures might significantly promote the production, transformation, and transport of dissolved N, and N_2O emissions to the atmosphere through denitrification (e.g., Kane et al., 2010). On the contrary, some authors have speculated that the potential increase in peatland-N_2O emissions from climate change may not be significant relative to the global N_2O budget (e.g., Martikainen et al., 1993; Frolking et al., 2011). Overall, additional peat N cycling studies are needed to address these remaining questions.

F~~Conclusions and f~~uture directions

Peat core analysis has been extensively used over the past 20 years for estimating rates of peat ~~-~~C~~carbon~~ accumulation at local, regional, and continental scales (e.g., Mäkilä, 1997;

Clymo et al., 1998; Vitt et al., 2000; Turunen et al., 2002; Mäkilä and Saarnisto, 2008; Yu et al., 2010; van Bellen et al., 2011; Gorham et al., 2012). The present study analyzed a new database that comprises 268 peat records from 215 northern peatland sites~~ located throughout the circum-Arctic peatlands~~. This systematic analysis of peat properties and Holocene C accumulation rates is essential for accurately addressing the following general research topics in the future: (1) describing and quantifying spatial and temporal patterns of Holocene peatland C and N accumulation; (2) assessing the sensitivity of C and N accumulation to climate ~~forcing~~change; (3) estimating peatland ~~soil organic matter (SOM), ~~soil organic carbon (SOC)~~,~~ and soil organic nitrogen (SON) pools at regional and hemispheric scales, (4) furthering our understanding of peatland C cycle~~ carbon~~ – ~~-~~climate linkages, and (5) providing the scientific community with a large dataset for developing and testing earth system and ecological models.

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Figure and Table Captions

Figure 1. Location of study sites. Map showing the distribution of northern peatlands

(green area from Yu et al., 2010) and peatland sites included in this study (n = 215 sites, including 268 peat cores). Long-term rate of peat-carbon accumulation was estimated from 127 sites (151 peat cores; red and blue dots). The yellow dots represent cores for which only peat properties (bulk density, organic matter content, etc.) were available and synthesized. Refer to Supplementary Table 1 for details.

Figure 2. Overview of data availability for North America (black bars) and Eurasia (white bars). (A) Number of cores (total = 238) containing information on carbon/nitrogen ratio (n = 40), nitrogen content (n = 40), carbon content (n = 56), peat types (n = 83), organic matter bulk density (n = 184), organic matter content (n = 190), and bulk density (n = 214). (B) Number of cores (total = 151) with a ~~temporal~~ dating ~~resolution~~ quality better than ~~500 years~~two dates per 1000 years (n = 35), ~~500-1000~~one to two dates per 1000 years (n = 52), and less than one date per~~>~~ 1000 years (n = 64). (C) Number of calibrated basal peat ages (median) in 500-year bins from the database (~~black bars,~~ n = 199) compared to all northern hemisphere basal peat ages (median) in 200-year bins (~~grey bars,~~ n = 2559, MGK data from MacDonald et al., 2006, Gorham et al., 2007, Korhola et al., 2010).

Figure 3. Distribution histograms of peat properties in northern peatlands. (A) Frequency distribution of bulk density for unidentified peat type samples (white bars) and different peat types (color bars). (B) Frequency distribution of organic matter content for different peat types. (C) Frequency distribution of organic matter bulk density for different peat types. (D) Frequency distribution of carbon content for different peat types. (E)

Frequency distribution of nitrogen content for different peat types. (F) Frequency distribution of carbon/nitrogen mass ratio for different peat types.

Figure 4. Relation between carbon content and organic matter content in northern peatlands. The slope of each regression line is used as a conversion factor for estimating carbon content from organic matter content.

Figure 5. Temporal patterns of peat properties (mean, standard deviation, and number of samples). (A) Bulk density. (B) Organic matter content. (C) Organic matter bulk density. (D) Carbon content. (E) Nitrogen content. (F) Carbon/Nitrogen mass ratio. White bars represent values that were based on a limited number of samples and peat records.

Figure 6. Main differences between *Sphagnum* and non-*Sphagnum* peat samples. (A) Bulk density. (B) Organic matter bulk density. (C) Organic carbon bulk density. (D) Carbon content. (E) Nitrogen content. (F) Carbon/Nitrogen mass ratio. (G) Temporal pattern of organic C bulk density. (H) Proportional change in the number of peat records that are *Sphagnum*-dominated, presented as a percentage of the total number of records.

Figure 7. Long-term apparent rate of carbon and nitrogen accumulation from northern peatlands (n = 127 sites). (A) Summer insolation at 60°N (data from Berger and Loutre, 1991) and temperature anomaly from an 11,300-year reconstruction for the northern extra-polar region from 30 to 90°N (data from Marcott et al., 2013). Temperature anomaly was calculated based on the 1961-1990 temperature averages. (B) Mean peat-

carbon accumulation rates (PCAR) and standard error in 500-year bins. The number of sites per 500-year bins is also presented. (C) Mean peat-nitrogen accumulation rates (PNAR) and standard error in 500-year bins. These values were obtained using different C/N values over time, as indicated by the line. ~~PCAR: peat-carbon accumulation rate; PNAR: peat-N accumulation rate.~~

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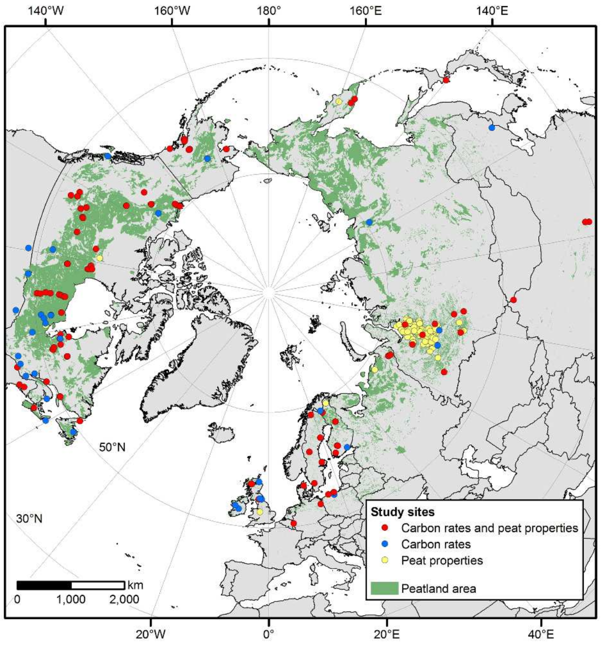
Table 2. Northern peatland peat properties by regions. Means and standard deviations are presented, along with the number of samples (n).

Table 3. Comparison of northern peatland peat properties estimates with other published values. Means and standard deviations are presented, along with the number of samples (n) when available.

Supplementary Material

Table S1. Summary information for the study sites included in the database.



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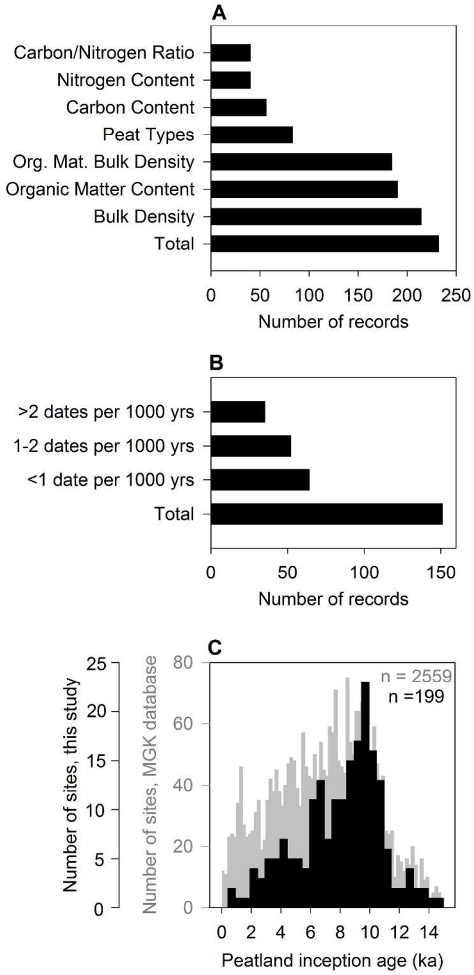

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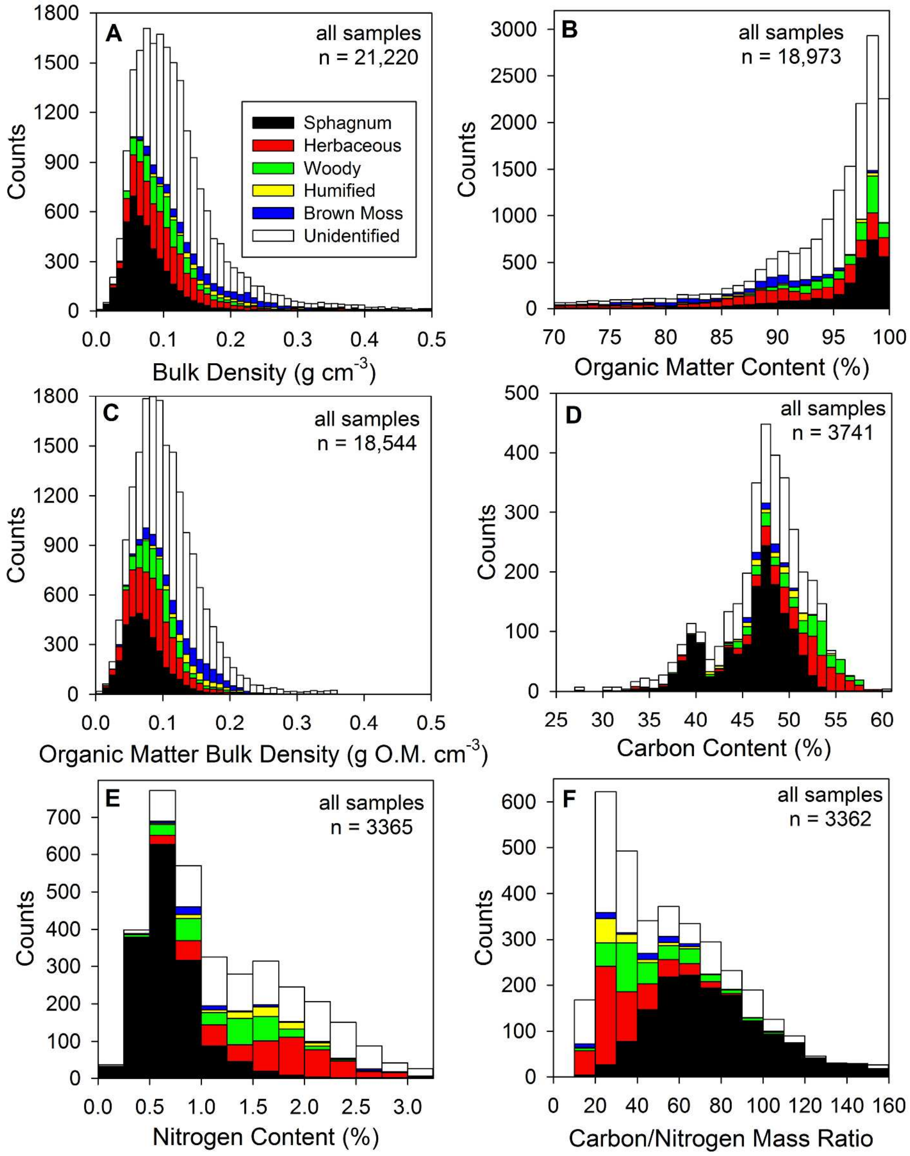

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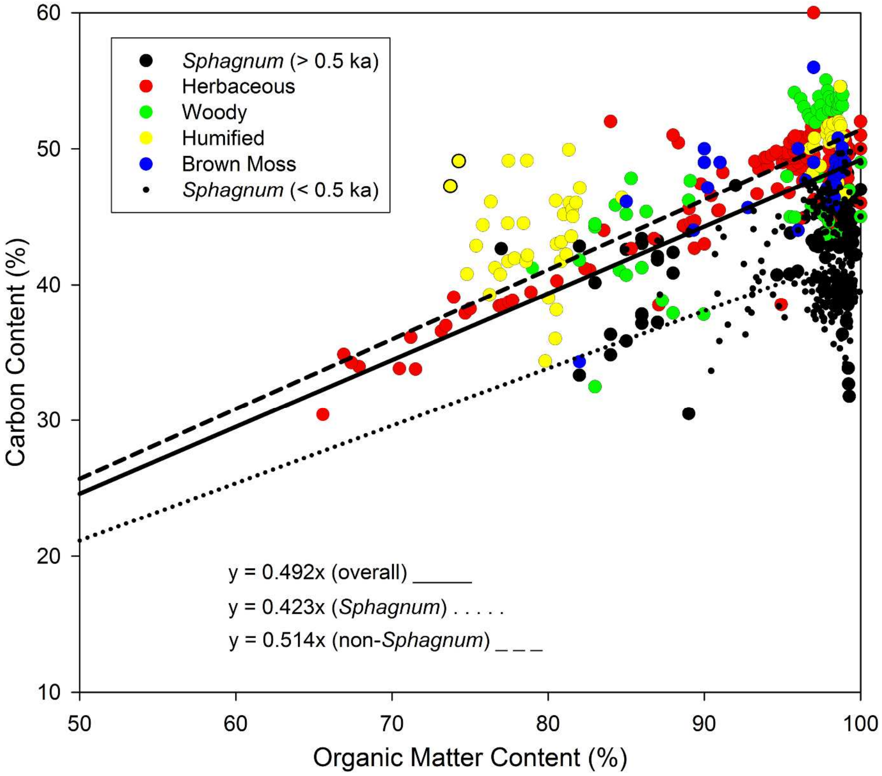

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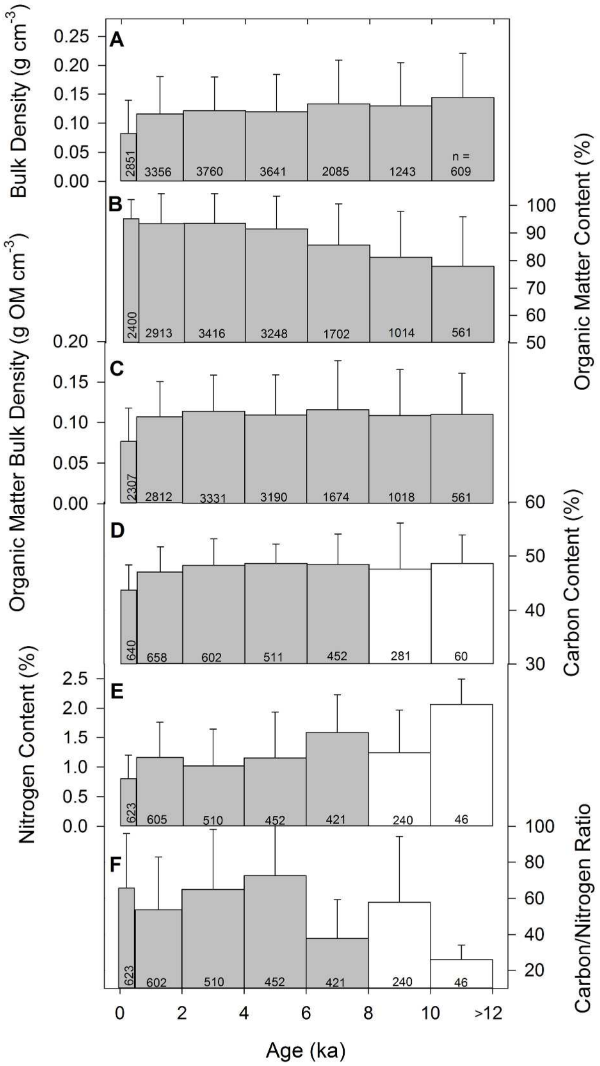

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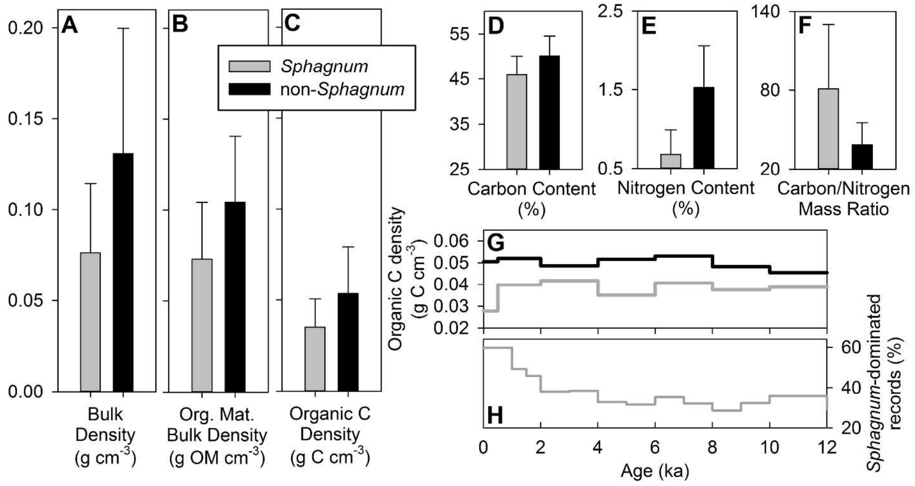

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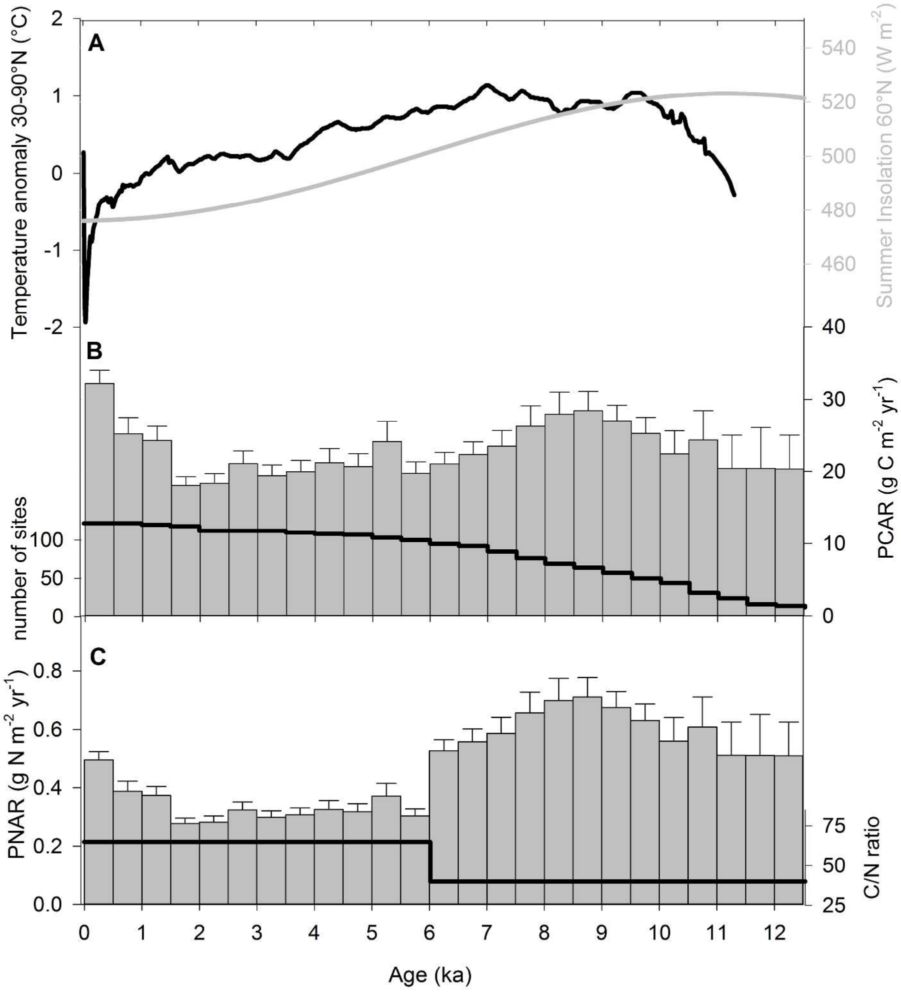

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Table 1. **Peat properties in northern peatlands.** Means and standard deviations are presented, along with the number of samples (*n*).

	Sphagnum	**Herbaceous**	**Woody**	**Humified**	**Brown Moss**	**Overall*****
Bulk density (g cm^{-3})	0.076 ± 0.038 (*n* = 4372)	0.118 ± 0.075 (3188)	0.108 ± 0.047 (1584)	0.192 ± 0.082 (452)	0.177 ± 0.076 (1114)	0.118 ± 0.069 (21,220)
Organic matter content (%)	94.3 ± 9.3 (3297)	85.6 ± 15.4 (3121)	92.0 ± 13.5 (1587)	78.4 ± 17.8 (418)	81.4 ± 15.5 (1090)	90.7 ± 13.0 (18,973)
Organic matter bulk density (g OM cm^{-3})	0.073 ± 0.031 (3332)	0.089 ± 0.036 (2854)	0.098 ± 0.032 (1388)	0.144 ± 0.036 (418)	0.136 ± 0.043 (1090)	0.105 ± 0.051 (18,544)
Carbon content in total peat (%)	46.0 ± 4.1 (1520)	50.5 ± 4.9 (519)	50.9 ± 4.0 (308)	47.4 ± 4.1 (96)	47.9 ± 2.8 (72)	46.8 ± 6.1 (3741)
Carbon content in organic matter (%)	42.3 ± 3.0* (454)	51.1 ± 1.7* (147)	51.4 ± 3.4* (59)	53.2 ± 2.6* (58)	50.0 ± 2.0* (44)	49.2 ± 2.4** (458)
Nitrogen content in peat (%)	0.7 ± 0.3 (1523)	1.7 ± 0.6 (518)	1.3 ± 0.5 (308)	1.5 ± 0.4 (96)	1.4 ± 0.7 (60)	1.2 ± 0.7 (3365)
Carbon/Nitrogen mass ratio	81.0 ± 49.2 (1520)	34.4 ± 15.0 (518)	45.3 ± 19.1 (308)	36.0 ± 17.6 (96)	42.9 ± 18.8 (60)	55 ± 33 (3362)

*Obtained from regression between carbon content and organic matter content (see the Database and analysis section).
**Includes all herbaceous, woody, humified and brown moss samples, as well as *Sphagnum* samples older than 0.5 ka (see Results section).
***Includes samples for which peat type was not ascribed.

Table 2. **Northern peatland peat properties by regions.** Means and standard deviations are presented, along with the number of samples in parentheses (n).

	Alaska	**Western Canada**	**Hudson & James Bays**	**Eastern Canada/USA**	**Western European Islands**	**Continental Europe**	**Fennoscandia**	**Western Russia**	**Eastern Russia & Asia**
Bulk density ($g\ cm^{-3}$)	0.168 ± 0.087 (*n* = 1659)	0.166 ± 0.076 (3635)	0.097 ± 0.038 (6002)	0.100 ± 0.039 (2834)	0.055 ± 0.027 (656)	0.120 ± 0.139 (410)	0.075 ± 0.043 (562)	0.118 ± 0.070 (2701)	0.116 ± 0.063 (2761)
Organic matter content (%)	76.6 ± 18.8 (1659)	91.6 ± 8.1 (3442)	94.8 ± 8.2 (5129)	97.8 ± 6.5 (1835)	97.5 ± 1.8 (227)	97.4 ± 5.43 (305)	95.6 ± 8.7 (789)	94.6 ± 10.3 (2666)	80.3 ± 16.7 (2700)
Organic matter bulk density ($g\ OM\ cm^{-3}$)	0.119 ± 0.049 (1659)	0.151 ± 0.062 (3441)	0.088 ± 0.029 (5129)	0.107 ± 0.028 (1750)	0.055 ± 0.035 (227)	0.056 ± 0.028 (222)	0.073 ± 0.034 (422)	0.106 ± 0.058 (2773)	0.088 ± 0.034 (2700)
Carbon content in total peat (%)	42.4 ± 3.7 (64)	45.0 ± 4.3 (382)	47.9 ± 4.5 (1026)	48.9 ± 3.7 (1084)	54.0 ± 2.5 (242)	38.9 ± 1.3 (60)	44.4 ± 5.7 (580)	49.2 ± 3.2 (74)	36.0 ± 9.2 (229)
Nitrogen content in peat (%)	1.3 ± 0.6 (64)	1.1 ± 0.8 (265)	1.6 ± 0.7 (910)	0.9 ± 0.5 (1084)	1.6 ± 0.4 (242)	0.7 ± 0.1 (60)	1.0 ± 0.5 (565)	1.6 ± 0.9 (44)	1.4 ± 0.6 (131)
Carbon/Nitrogen mass ratio	43.9 ± 32.8 (64)	62.4 ± 37.5 (265)	39.5 ± 23.7 (910)	77.2 ± 56.1 (1084)	35.7 ± 10.8 (242)	54.2 ± 7.6 (60)	57.9 ± 31.4 (562)	40.8 ± 21.7 (44)	34.2 ± 21.9 (131)

Table 3. **Northern peatland peat properties estimates from published studies.** Means and standard deviations are presented, along with the number of samples in parentheses (*n*) when available.

Bulk density (g cm^{-3})	**Organic matter content (%)**	**Organic matter bulk density (g OM cm^{-3})**	**Carbon content in organic matter (%)**	**Carbon/Nitrogen mass ratio**	**Region**	**Reference**
-	-	0.094 open fens & bogs 0.105 wooded & shrubby fens	51.8 ± 4.7 (*n* = 253)	-	Western Canada	Vitt et al., 2000
0.073 ± 0.029 *Sphagnum* 0.091 ± 0.025 brown moss 0.110 ± 0.037 sedge-moss 0.211 ± 0.061 humified 0.138 ± 0.036 wood	95.5 ± 2.6 *Sphagnum* 90.3 ± 6.6 brown moss 91.4 ± 4.4 sedge-moss 73.6 ± 13.0 humified 87.8 ± 6.3 wood	0.069 ± 0.028 *Sphagnum* 0.082 ± 0.023 brown moss 0.100 ± 0.032 sedge-moss 0.149 ± 0.023 humified 0.120 ± 0.029 wood	50.7 ± 5.0 *Sphagnum* 51.9 ± 3.4 brown moss 53.4 ± 2.9 sedge-moss 54.0 ± 3.8 humified 52.1 ± 3.5 wood	-	Western Canada	Bauer et al., 2006
-	-	0.0784 bogs	52.8 (*n* = 276)	-	Eastern Canada and USA	Gorham, 1990
-	-	0.112	51.7	-	Eastern Canada and USA	Gorham, 1991
0.128 ± 0.065	96.26 ± 3.16	0.123*	52	-	West Siberia Lowlands	Sheng et al., 2004
-	-	-	51 ± 5 *Sphagnum*** 55 ± 3 non-*Sphagnum*** 52 ± 3 overall**	-	West Siberia Lowlands	Beilman et al., 2009
-	-	0.074 bogs 0.081 fens	50	-	Finland	Turunen et al., 2002
0.118 ± 0.069 (*n* = 21,220)	90.7 ± 13.0 (*n* = 18,973)	0.105 ± 0.051 (*n* = 18,544)	49.2 ± 2.4 (*n* = 458)	55 ± 33 (*n* = 3362)	circum-Arctic	This study

*This value was obtained by multiplying bulk density (0.128 g cm^{-3}) by organic matter content (96.26%).

**Standard errors

Supplementary Material: Table S1. **Summary information for the study sites included in the circum-Arctic peatland database.**

Abbreviated reference*	Core name and ID	Peatland type	Country	Latitude	Longitude	Number of ^{14}C dates	Oldest age (cal BP)	Basal age (cal BP)	Other dates	Carbon rate site	Peat properties site
NORTH AMERICA											
Beaulieu-Audy, 2009	La Grande 3	Bog	Canada	53.57	-76.13	7	6816	Y	N	Y[3]	Y
Beaulieu-Audy, 2009	La Grande 2	Bog	Canada	53.65	-77.73	6	6543	Y	N	Y[3]	Y
Beaulieu-Audy, 2009	La Grande 1	Intermediate fen	Canada	53.9	-78.77	8	1612	Y	N	Y[3]	Y
Belyea, 1996	Rainy River Bog	Bog	Canada	48.78	-94.55	9	5310	N	N	Y[5]	N
Bender, 1969	Porcupine	Bog	Canada	52.52	-101.25	7	7624	Y	N	Y[5]	N
Bender, 1969	Colville Lake	Bog	Canada	67.1	-125.78	7	7650	Y	N	Y[5]	N
Booth, 2004	South Rhody	Kettle bog	USA	46.55	-86.07	9	10,562	Y	N	Y[5]	N
Bunbury, 2012	VC04-06	Shrub bog	Canada	52.71	-84.18	6	6599	Y	N	Y[2]	Y
Camill, 2009	Joey Lake 5	Permafrost bog	Canada	55.46	-98.16	8	8100	Y[1]	N	Y[2]	Y
Camill, 2009	Joey Lake 7	Permafrost bog	Canada	55.46	-98.16	10	8256	Y	N	Y[2]	Y
Camill, 2009	Joey Lake 2	Permafrost bog	Canada	55.47	-98.16	11	7980	Y[1]	N	Y[2]	Y
Camill, 2009	Joey Lake 12	Permafrost bog	Canada	55.47	-98.15	8	6564	Y[1]	N	Y[2]	Y
Camill, 2009	Joey Lake 15	Permafrost bog	Canada	55.47	-98.15	10	7882	Y[1]	N	Y[2]	Y
Camill, 2009	Joey Lake 17	Permafrost bog	Canada	55.47	-98.16	7	7632	Y[1]	N	Y[2]	Y
P. Camill, unpubl	Lake 785 core 4	Permafrost bog	Canada	59.11	-97.4	9	6833	Y	N	Y[2]	Y
P. Camill, unpubl	Unit Lake core 4	Permafrost bog	Canada	59.42	-97.48	9	7053	Y	N	Y[2]	Y
P. Camill, unpubl	Lake 396 core 3	Permafrost bog	Canada	59.58	-98.57	6	6077	Y	N	Y[2]	Y
P. Camill, unpubl	Shuttle Lake core 2	Permafrost bog	Canada	59.86	-97.64	6	6242	Y	N	Y[2]	Y
Charman, 1995	Wally Creek Area	Bog	Canada	49.07	-80.6	10	6672	Y	N	Y[5]	N
D. Charman, unpubl	Burnt Village	Raised bog	Canada	51.13	-55.93	26	8526	Y	N	Y[2]	Y
D. Charman, unpubl	Petite Bog	Raised bog	Canada	45.14	-63.94	32	13,474	Y	N	Y[2]	Y
D. Charman, unpubl	Sidney Bog	Raised bog	USA	44.39	-69.79	31	9311	Y	N	Y[2]	Y
Elliott, 2011	Mer Bleue	Bog	Canada	45.68	-75.8	11	8463	Y	N	Y[5]	N

Abbreviated reference[*]	Site name	Peatland type	Country	Latitude	Longitude	^{14}C dates (number)	Oldest age (cal BP)	Basal age (cal BP)	Other dates	Carbon rate site	Peat properties site
M. Garneau, unpubl	Ours 1	Fen	Canada	54.05	-72.45	6	5491	N	N	Y[3]	Y
M. Garneau, unpubl	Ours 3	Fen	Canada	54.05	-72.46	5	3899	N	N	Y[3]	Y
M. Garneau, unpubl	Ours 4	Fen	Canada	54.05	-72.46	6	4774	N	N	Y[3]	Y
M. Garneau, unpubl	Aero 1	Fen	Canada	54.1	-72.52	6	5485	N	N	Y[3]	Y
M. Garneau, unpubl	Aero 5	Fen	Canada	54.1	-72.52	6	4252	N	N	Y[3]	Y
Glaser, 2004	Oldman Bog	Bog	Canada	51.02	-84.57	13	6728	Y	N	Y[5]	N
Glaser, 2004	Albany River Bog	Bog	Canada	51.43	-83.62	6	5492	Y	N	Y[5]	N
Glaser, 2004	Belec Lake Bog	Bog	Canada	51.62	-82.28	7	4480	Y	N	Y[5]	N
Gorham, 2003[a]	Miscou	Bog	Canada	47.93	-64.5	7	9000	Y	N	Y[6]	N
Gorham, 2003 [a]	Fourchou	Bog	Canada	45.93	-60.27	8	11,200	Y	N	Y[6]	N
Gorham, 2003	Denbigh	Fen	USA	48.22	-100.5	8	12,500	Y	N	Y[6]	N
J. Holmquist, unpubl	JBL8	Sphagnum bog	Canada	50.47	-89.93	11	4481	Y	N	Y[3]	Y
J. Holmquist, unpubl	JBL1	Sphagnum bog	Canada	51.07	-89.8	11	6034	Y	N	Y[3]	Y
J. Holmquist, unpubl	JBL2	Sphagnum bog	Canada	52.02	-90.13	13	6742	Y	N	Y[3]	Y
J. Holmquist, unpubl	JBL3	Sphagnum bog	Canada	52.87	-89.93	10	7708	Y	N	Y[3]	Y
J. Holmquist, unpubl	JBL7	Sphagnum bog	Canada	54.4	-89.52	12	7607	Y	N	Y[3]	Y
J. Holmquist, unpubl	JBL6	Permafrost bog	Canada	54.77	-89.32	8	3248	Y	N	Y[3]	Y
J. Holmquist, unpubl	JBL4	Sphagnum bog	Canada	55.27	-88.93	11	6051	Y	N	Y[3]	Y
J. Holmquist, unpubl	JBL5	Peat plateau	Canada	55.42	-88.95	12	5826	Y	N	Y[3]	Y
Hu, 1994	Caribou Bog RC-2	Bog	USA	45	-69	6	9707	Y	pollen (1)	Y[5]	Y
Hughes, 2006	Nordan's Pond Bog	Bog	Canada	53.6	-49.17	10	8827	N	N	Y[5]	N
Hunt, 2013	Nuikluk 10-1	Peat plateau	USA (Alaska)	64.83	-163.45	5	6392	Y[1]	N	Y[3]	Y
Hunt, 2013	Nuikluk 10-2	Collapse Scar	USA (Alaska)	64.83	-163.45	9	13,545	Y	N	Y[3]	Y
Jones, 2010 [a]	Horse Trail Fen	Poor fen	USA (Alaska)	60.42	-150.9	11	12,695	Y	N	Y[3]	Y
Jones, 2010 [a]	Kenai Gasfield 07-2	Poor Fen	USA (Alaska)	60.45	-151.25	17	11,448	Y	N	Y[3]	Y
Jones, 2010 [a]	No Name Creek 07-1	Poor Fen	USA (Alaska)	60.63	-151.08	10	10,993	Y	N	Y[3]	Y

Abbreviated reference[*]	Site name	Peatland type	Country	Latitude	Longitude	^{14}C dates (number)	Oldest age (cal BP)	Basal age (cal BP)	Other dates	Carbon rate site	Peat properties site
Jones, 2010[a]	Swanson Fen	Poor fen	USA (Alaska)	60.79	-150.83	10	14,065	Y	N	Y^{3}	Y
Klein, 2013	Kahiltna Valley Mor.	Bog	USA (Alaska)	62.37	-151.09	5	1949	N	N	Y^{3}	Y
E. Klein, unpubl	HERC 09-3	Bog	USA (Alaska)	62.37	-151.07	8	11,768	Y	N	Y^{3}	Y
Kuhry, 1996[a]	Slave Lake Bog	Bog	Canada	55.01	-114.09	6	10,516	Y	N	Y^{2}	Y
Lamarre, 2012	KUJU-PD2	Permafrost bog	Canada	55.23	-77.7	8	5084	Y	N	Y^{3}	Y
Lavoie, 2000	Lac Malbaie MAL-2	Bog	Canada	47.6	-70.97	5	10,654	Y	N	Y^{5}	N
Lavoie, 2000	Frontenac FRON-2	Bog	Canada	45.97	-71.13	7	12,851	Y	N	Y^{5}	N
Lavoie, 2013	Covey Hill	Bog	Canada	45.00	-73.49	12	12,720	Y	N	Y^{3}	Y
Loisel, 2010	Lac Le Caron RiP2	Bog	Canada	52.28	-75.83	6	2731	N	N	Y^{2}	Y
Loisel, 2013	Petersville 08-S	Bog	USA (Alaska)	62.42	-150.68	6	2825	N	tephra (1)	Y^{2}	Y
J. Loisel, unpubl	Petersville 09-MC	Bog	USA (Alaska)	62.42	-150.68	12	13,881	Y	tephra (4)	Y^{3}	Y
MacDonald, 1983	Natla River Bog	Bog	Canada	63.02	-128.8	6	9747	Y	tephra (1)	Y^{5}	Y
Magnan, 2012	Radisson	Semi-forested bog	Canada	53.73	-77.7	6	6154	Y	N	Y^{5}	N
G. Magnan, unpubl	Lebel	Raised bog	Canada	49.1	-68.25	12	5831	Y	N	Y^{3}	Y
G. Magnan, unpubl	Baie	Raised bog	Canada	49.1	-68.22	9	4221	Y	N	Y^{3}	Y
G. Magnan, unpubl	Morts	Peat plateau	Canada	50.26	-63.67	10	3246	Y	N	Y^{3}	Y
G. Magnan, unpubl	Plaine	Peat plateau	Canada	50.27	-63.54	12	7451	Y	N	Y^{3}	Y
Muller, 2003[a]	Mirabel bog (7 cores)	Bog	Canada	45.68	-74.03	2 to 7	10,000	Y	N	Y^{6}	N
J. Nichols, unpubl	Bear Bog	Bog	USA (Alaska)	60.53	-145.45	13	10357	Y	N	Y^{3}	Y
O'Donnell, 2012	Koyukuk Flats PP2	Peat plateau	USA (Alaska)	65.19	-155.36	7	12,329	Y	N	Y^{5}	N
O'Reilly, 2011	Victor Fen	Fen	Canada	52.71	-84.17	6	6405	Y	N	Y^{5}	N
M. Packalen, unpubl	HL-02	Patterned bog	Canada	54.61	-84.61	5	4494	Y	N	Y^{2}	Y
Robinson, 2006[a]	Martin River	Bog	Canada	61.8	-121.4	6	7552	Y	N	Y^{4}	Y
Sannel, 2009[a]	Selwyn Lake 1	Peat plateau	Canada	59.88	-104.2	14	6573	Y	N	Y^{2}	Y
C. Tarnocai, 2010	T5	Polygon bog	Canada	68.57	-133.50	6	8805	Y	N	Y^{2}	Y
C. Tarnocai, 2010	IN-BG-1	Polyg. peat plateau	Canada	68.32	-133.42	9	9121	Y	N	Y^{2}	Y

Abbreviated reference*	Site name	Peatland type	Country	Latitude	Longitude	^{14}C dates (number)	Oldest age (cal BP)	Basal age (cal BP)	Other dates	Carbon rate site	Peat properties site
C. Tarnocai, 2010	IN-BG-3	Polyg. peat plateau	Canada	68.32	-133.43	6	6293	Y	N	Y[2]	Y
C. Tarnocai, 2010	NW-BG-8	Polyg. peat plateau	Canada	65.21	-127.01	5	10,818	Y	N	Y[2]	Y
C. Tarnocai, 2010	NW-BG-10	Polyg. peat plateau	Canada	65.21	-127.00	5	10,480	Y	N	Y[2]	Y
C. Tarnocai, unpubl	T1	Polygon bog	Canada	68.32	-133.42	7	8623	Y	N	Y[2]	Y
C. Tarnocai, unpubl	T6	Polygon bog	Canada	69.12	-134.18	5	3014	Y	N	Y[2]	Y
C. Tarnocai, unpubl	IN-BG-2B	Polyg. peat plateau	Canada	68.32	-133.43	6	5828	Y	N	Y[2]	Y
C. Tarnocai, unpubl	NW-BG-2	Polyg. peat plateau	Canada	65.21	-127.01	5	10,932	Y	N	Y[2]	Y
C. Tarnocai, unpubl	NW-BG-3	Polyg. peat plateau	Canada	65.21	-127.01	6	11,010	Y	N	Y[2]	Y
Turunen, 2003[a]	Diana Lake bog	Slope bog	Canada	54.15	-130.25	5	8500	Y	N	Y[6]	N
van Bellen, 2011	Mosaik	Bog	Canada	51.98	-75.4	10	7120	Y	N	Y[3]	Y
van Bellen, 2011	Sterne	Bog	Canada	52.05	-75.17	11	7134	Y	N	Y[3]	Y
van Bellen, 2011	Lac Le Caron	Bog	Canada	52.28	-75.83	12	7510	Y	N	Y[3]	Y
Yu, 2003[a]	Upper Pinto Fen	Rich fen	Canada	53.58	-118.02	20	7599	Y	N	Y[3]	Y
Yu, 2006[a]	Goldeye Lake Fen	Rich fen	Canada	52.45	-116.2	6	9207	Y	tephra (2)	Y[3]	Y
Z. Yu, unpubl	Sundance Fen 03-2	Rich fen	Canada	53.58	-116.75	5	6719	Y[1]	N	Y[3]	Y
Z. Yu, unpubl	Sundance Fen 03-3	Rich fen	Canada	53.58	-116.75	13	10,973	Y	N	Y[3]	Y
Z. Yu, unpubl	Utikuma	Poor Fen	Canada	55.84	-115.09	18	5079	Y	N	Y[3]	Y
Z. Yu, unpubl	Mariana Lake 03-1	Poor Fen	Canada	55.9	-112.09	14	7222	Y	N	Y[3]	Y
Z. Yu, unpubl	Mariana Lake 03-2	Poor Fen	Canada	55.9	-112.09	11	6105	Y[1]	N	Y[3]	Y
Z. Yu, unpubl	Mariana Lake 03-3	Poor Fen	Canada	56.02	-111.93	18	5872	Y[1]	N	Y[3]	Y
Z. Yu, unpubl[a]	Patuanak	Internal lawn	Canada	55.85	-107.68	11	9017	Y	N	Y[3]	Y
M. Garneau, unpubl	Ours 5	Fen	Canada	54.05	-72.46	3	5958	N	N	N	Y
M. Garneau, unpubl	Ours 2	Fen	Canada	54.05	-72.46	2	3496	N	N	N	Y
M. Garneau, unpubl	Aero 3	Fen	Canada	54.1	-72.52	2	3387	N	N	N	Y
Hu, 1994	Caribou Bog RC-1	Bog	USA	45	-69	2	9547	Y[1]	pollen (3)	N	Y
Lamarre, 2012	KUJU-BF2	Permafrost bog	Canada	55.23	-77.7	4	3914	Y	N	N	Y

Abbreviated reference[*]	Site name	Peatland type	Country	Latitude	Longitude	^{14}C dates (number)	Oldest age (cal BP)	Basal age (cal BP)	Other dates	Carbon rate site	Peat properties site
Loisel, 2010	Mosaik RiP2	Bog	Canada	51.97	-75.4	4	2433	N	N	N	Y
M. Paackalen, unpubl	KJ2-3	Poor fen	Canada	51.59	-81.76	4	4677	Y	N	N	Y
Robinson, 2000	Peat Plateau LC	Peat Plateau	Canada	61.8	-121.4	0		N	tephra (1)	N	Y
Robinson, 2000	Peat Plateau 13	Peat Plateau	Canada	61.8	-121.4	0		N	tephra (1)	N	Y
Robinson, 2000	Poor Fen 11	Poor Fen	Canada	61.8	-121.4	0		N	tephra (1)	N	Y
Robinson, 2000	Rich Fen 12	Rich fen	Canada	61.8	-121.4	0		N	tephra (1)	N	Y
Robinson, 2000	Unfrozen Bog 10	Permafrost bog	Canada	61.8	-121.4	0		N	tephra (1)	N	Y
Robinson, 2000	Collapse Scar Fen 06	Collapse Scar	Canada	61.8	-121.4	0		N	tephra (1)	N	Y
Sannel, 2009	Ennadai Lake 1	Peat plateau	Canada	60.83	-101.55	4	5792	Y	N	N	Y
C. Tarnocai, unpubl	NW-BG-4	Polyg. peat plateau	Canada	65.21	-127.01	3	9916	Y	N	N	Y
C. Tarnocai, unpubl	NW-BG-9	Polyg. peat plateau	Canada	65.23	-127.00	3	9575	Y	N	N	Y
Z. Yu, unpubl	Hondo	Rich fen	Canada	55.08	-114.14	4	10,012	Y	N	N	Y
EURASIA											
Anderson, 1998[a]	Glen Torridon	Olig. topogen. bog	UK	57.56	-5.37	7	9568	Y	N	Y[2]	Y
Anderson, 1998[a]	Glen Carron	Olig. topogen. bog	UK	57.53	-5.15	6	10,431	Y	N	Y[2]	Y
Andersson, 2010	Lilla Backsjömyren 1	Mixed mire	Sweden	62.41	14.32	5	8527	Y	tephra (2)	Y[5]	Y
Andersson, 2010	Lilla Backsjömyren 2	Mixed mire	Sweden	62.41	14.32	13	3804	Y[1]	tephra (2)	Y[5]	Y
Barber, 2003	Bolton Fell Moss J,L	Bog	UK	55	-2	28	10,476	Y	N	Y[5]	N
Barber, 2003	Mongan Bog	Bog	Ireland	53	-8	13	4607	N	N	Y[5]	N
Barber, 2003	Abbeyknockmoy Bog	Bog	Ireland	53.5	-9	10	6707	N	N	Y[5]	N
C. Bocchicchio, unpubl.	KAM12-C4	Bog	Russia (Far-E)	54.01	156.08	10	12,891	Y	N	Y[3]	Y
Borren, 2004[a]	Vasyugan (V21)	Bog	Russia (Siberia)	56.83	78.42	11	9709	Y	N	Y[3]	Y
Borren, 2004[a]	86-Kvartal (Zh0)	Fen	Russia (Siberia)	56.83	84.58	9	8711	Y	N	Y[3]	Y
Charman, 1994	East Southerland	Fen	UK	58	-3	6	10,084	Y	N	Y[5]	N
De Vleeschouwer, 2009	Słowińskie Błota	Raised bog	Poland	54.36	16.49	8	1165	N	N	Y[2]	Y
De Vleeschouwer, 2012	Misten	Raised bog	Belgium	50.56	6.16	15	1434	N	N	Y[2]	Y

Abbreviated reference*	Site name	Peatland type	Country	Latitude	Longitude	^{14}C dates (number)	Oldest age (cal BP)	Basal age (cal BP)	Other dates	Carbon rate site	Peat properties site
Gałka, 2013a	Stażki-B	Bog	Poland	54.43	18.09	9	7352	Y	N	Y[5]	Y
Gałka, 2013b	Kusowo	Raised bog	Poland	54	18	8	578	N	N	Y[5]	N
Glebov, 2002	Ob-Vasygan	Bog	Russia (Siberia)	60.52	77.68	17	10,817	Y	N	Y[5]	N
Hendon, 2001	Butternburn Flow 1	Intermed. ombrotr	UK	55.08	-2.5	7	9,213	Y	N	Y[5]	N
Hughes, 2013	Utasai Bog	Oligotrophic bog	Japan	42.38	140.18	7	2954	N	tephra (4)	Y[2]	Y
Kokfelt, 2010	Stordalen	Permafrost bog	Sweden	68.35	19.05	11	4717	Y	N	Y[2]	Y
Lamentowicz, 2013	Stażki-F	Rich fen	Poland	54.43	18.09	8	1225	Y[1]	N	Y[5]	Y
Large, 2009	Hongyuan HYLK1	Bog	China	32.77	102.52	14	10,827	Y	N	Y[2]	Y
J. Loisel, unpubl.	KAM12-C1	Bog	Russia (Far-E)	54.9	156.6	13	11,914	Y	N	Y[3]	Y
G. MacDonald, unpubl	N-1	Peat plateau	Russia (W Sib)	63.16	74.82	8	10,072	Y	N	Y[3]	Y
G. MacDonald, unpubl	V-34	Open raised bog	Russia (W Sib)	61.47	79.46	8	8824	Y	N	Y[3]	Y
G. MacDonald, unpubl	E-110	Peat plateau	Russia (W Sib)	66.47	76.99	6	9496	Y	N	Y[3]	Y
G. MacDonald, unpubl	D-127	Peat plateau	Russia (W Sib)	64.31	70.29	6	10,034	Y	N	Y[3]	Y
G. MacDonald, unpubl	SIB06	Pine-domin. bog	Russia (W Sib)	58.44	83.43	17	8680	Y	N	Y[3]	Y
Mäkilä, 2007[a]	Hanhijänkä	Palsa	Finland	68.4	23.55	7	9800	Y	N	Y[6]	N
Mäkilä, 2007[a]	Luovuoma (3 cores)	Fen	Finland	68.4	23.55	6	9800	Y	N	Y[6]	N
Mäkilä, 2001[a]	Ruosuo (P8)	Aapa	Finland	65.65	27.32	7	9500	Y	N	Y[2]	Y
Mäkilä, 2001[a]	Ruosuo (P20)	Aapa	Finland	65.65	27.32	9	9500	Y[1]	N	Y[2]	Y
Mäkilä, 2001[a]	Saarisuo (B800)	Fen	Finland	65.65	27.32	11	9600	Y	N	Y[2]	Y
Mäkilä, 1997[a]	Haukkasuo (3 cores)	Bog	Finland	60.82	26.95	13	9500	Y	N	Y[6]	N
P. Mathijssen, unpubl	Lompolojänkkä	Fen	Finland	68	24.22	10	9969	Y	N	Y[3]	Y
P. Mathijssen, unpubl	Siikaneva	Bog	Finland	61.84	24.17	6	9622	Y	N	Y[4]	Y
Mauquoy, 2002	Walton Moss 21	Raised bog	UK	54.98	-2.77	21	1120	N	N	Y[2]	Y
Mauquoy, 2002	Walton Moss 20	Raised bog	UK	54.98	-2.77	23	1048	N	N	Y[2]	Y
Mauquoy, 2002	Walton Moss 19	Raised bog	UK	54.98	-2.77	30	925	N	N	Y[2]	Y
Mauquoy, 2002	Lille Vildmose	Raised bog	Denmark	56.83	10.25	19	609	N	N	Y[2]	Y

Abbreviated reference[*]	Site name	Peatland type	Country	Latitude	Longitude	^{14}C dates (number)	Oldest age (cal BP)	Basal age (cal BP)	Other dates	Carbon rate site	Peat properties site
Oksanen, 2001	Rogovaya River 2	Peat plateau	Russia (E Eur.)	67.27	62.14	5	10,413	Y[1]	N	Y[2]	Y
Oksanen, 2001	Rogovaya River 3	Peat plateau	Russia (E Eur.)	67.25	62.07	6	10,641	Y	N	Y[3]	Y
Oksanen, 2003	Usinsk Mire 1	Peat plateau	Russia (E. Eur.)	57.42	65.67	6	13,236	Y	N	Y[2]	Y
Ronkainen, unpubl	Seida	Peat plateau	Russia (E. Eur.)	67.05	62.92	6	8469	Y	N	Y[4]	Y
Ruhland, 2000	Lena River Valley	Wet fen	Russia (E Sib)	69.38	125.13	6	8022	Y	N	Y[5]	N
Tuittila, 2007	Lakkasuo (hummock)	Bog	Finland	61.78	24.3	12	6567	Y[1]	N	Y[5]	Y
Tuittila, 2007	Lakkasuo (lawn)	Bog	Finland	61.78	24.3	7	6803	Y	N	Y[5]	Y
Turunen, 2001[a]	Salym-Gyugan Mire 3	Bog	Russia (W Sib)	60.17	72.83	6	10,500	Y	N	Y[6]	N
Väliranta, 2007	Kontolanrahka	Bog	Finland	60.78	22.78	40	4937	Y	^{137}Cs	Y[2]	Y
van der Linden, 2006	Saxnäs Mosse	Raised bog	Sweden	56.86	13.46	36	1068	N	N	Y[2]	Y
van der Linden, 2007	Barschpfuhl	Kettle hole	Germany	53.05	13.83	32	134	N	N	Y[2]	Y
van der Linden, 2008	Lappmyran	String & flark mire	Sweden	64.16	19.58	40	1712	N	N	Y[2]	Y
van der Linden, 2008	Åkerlänna Römosse	Raised bog	Sweden	60.02	17.36	36	392	N	N	Y[2]	Y
Y. Zhao, unpubl.	Altay	Sedge-dom rich fen	China	48.12	88.35	18	11,308	Y	N	Y[3]	Y
Zhao, 2011	Zoige	Sedge-dom rich fen	China	33.45	102.63	7	9996	Y	N	Y[3]	Y
Zhou, 2010	Hani Peat Bog	Bog	China	42.22	126.52	6	15,014	Y	N	Y[5]	N
Anderson, 1998	Eilean Subhainn	Olig. topogen. bog	UK	57.69	-5.48	4	8700	Y	N	N	Y
D. Beilman, unpubl.	KAM12-C10	Fen	Russia (Far-E)	55.5	159.87	1	7500	Y	N	N	Y
Juutinen, 2013	Kiposuo III	Fen	Finland	69.18	27.28	3	9510	Y	pollen (1)	N	Y
Juutinen, 2013	Kiposuo IV	Fen	Finland	69.18	27.28	2	8574	Y[1]	N	N	Y
J. McCarroll, unpubl	Mossdale Moor 2	Blanket bog	UK	49.85	-7.46	3	1429	N	N	N	Y
Smith, 2004, 2012	N-2	Peat plateau	Russia (W Sib)	63.88	75.02	1	3600	Y	N	N	Y
Smith, 2004, 2012	S-4	Non-permafrost	Russia (W Sib)	61.55	72.71	1	6285	Y	N	N	Y
Smith, 2004, 2012	S-5	Non-permafrost	Russia (W Sib)	61.98	72.18	1	3885	Y	N	N	Y
Smith, 2004, 2012	S-6	Non-permafrost	Russia (W Sib)	61.62	73.98	1	11,120	Y	N	N	Y
Smith, 2004, 2012	S-7	Non-permafrost	Russia (W Sib)	61.49	74.32	1	8675	Y	N	N	Y

Abbreviated reference*	Site name	Peatland type	Country	Latitude	Longitude	^{14}C dates (number)	Oldest age (cal BP)	Basal age (cal BP)	Other dates	Carbon rate site	Peat properties site
Smith, 2004, 2012	S-8	Pine-domin. bog	Russia (W Sib)	61.75	73.39	1	9860	Y	N	N	Y
Smith, 2004, 2012	S-9	Non-permafrost	Russia (W Sib)	62.12	73.84	2	8725	Y	N	N	Y
Smith, 2004, 2012	N-10	Peat plateau	Russia (W Sib)	63.14	76.54	1	4720	Y	N	N	Y
Smith, 2004, 2012	N-11	Non-permafrost	Russia (W Sib)	62.66	76.77	1	5090	Y	N	N	Y
Smith, 2004, 2012	N-12	Peat plateau	Russia (W Sib)	63.50	76.82	1	10,080	Y	N	N	Y
Smith, 2004, 2012	N-13	Peat plateau	Russia (W Sib)	63.77	76.64	1	9465	Y	N	N	Y
Smith, 2004, 2012	N-14	Peat plateau	Russia (W Sib)	63.77	75.51	1	9035	Y	N	N	Y
Smith, 2004, 2012	N-15	Peat plateau	Russia (W Sib)	63.65	74.27	2	9630	Y	N	N	Y
Smith, 2004, 2012	N-16	Peat plateau	Russia (W Sib)	64.50	75.53	1	3540	Y	N	N	Y
Smith, 2004, 2012	N-17	Peat plateau	Russia (W Sib)	64.07	74.99	1	11,330	Y	N	N	Y
Smith, 2004, 2012	N-18	Peat plateau	Russia (W Sib)	62.85	75.22	1	1005	Y	N	N	Y
Smith, 2004, 2012	N-19	Peat plateau	Russia (W Sib)	62.96	74.26	1	8290	Y[1]	N	N	Y
Smith, 2004, 2012	N-19-1	Peat plateau	Russia (W Sib)	62.96	74.26	1	8675	Y	N	N	Y
Smith, 2004, 2012	S-20	Pine-domin. bog	Russia (W Sib)	62.55	71.72	1	3395	Y	N	N	Y
Smith, 2004, 2012	S-21	Pine-domin. bog	Russia (W Sib)	62.40	72.87	1	9905	Y	N	N	Y
Smith, 2004, 2012	S-22	Pine-domin. bog	Russia (W Sib)	60.84	71.26	2	7125	Y	N	N	Y
Smith, 2004, 2012	S-23	Pine-domin. bog	Russia (W Sib)	60.65	73.08	1	6665	Y	N	N	Y
Smith, 2004, 2012	S-24	Open raised bog	Russia (W Sib)	61.32	73.24	1	2305	Y	N	N	Y
Smith, 2004, 2012	S-25	Pine-domin. bog	Russia (W Sib)	62.25	74.78	1	9910	Y	N	N	Y
Smith, 2004, 2012	V-26	Open raised bog	Russia (W Sib)	61.03	76.47	2	9700	Y	N	N	Y
Smith, 2004, 2012	V-27	Open raised bog	Russia (W Sib)	61.32	76.73	1	4540	Y	N	N	Y
Smith, 2004, 2012	V-28	Open raised bog	Russia (W Sib)	61.81	77.50	1	7750	Y	N	N	Y
Smith, 2004, 2012	V-29	Open raised bog	Russia (W Sib)	61.23	75.31	1	9750	Y	N	N	Y
Smith, 2004, 2012	V-30	Open raised bog	Russia (W Sib)	61.74	75.20	1	5455	Y	N	N	Y
Smith, 2004, 2012	V-31	Open raised bog	Russia (W Sib)	62.37	75.79	1	5600	Y	N	N	Y
Smith, 2004, 2012	V-32	Open raised bog	Russia (W Sib)	62.36	77.48	1	2140	Y	N	N	Y

Abbreviated reference*	Site name	Peatland type	Country	Latitude	Longitude	^{14}C dates (number)	Oldest age (cal BP)	Basal age (cal BP)	Other dates	Carbon rate site	Peat properties site
Smith, 2004, 2012	V-33	Open raised bog	Russia (W Sib)	62.00	76.71	1	10,975	Y	N	N	Y
Smith, 2004, 2012	V-35	Open raised bog	Russia (W Sib)	60.80	77.62	1	10,350	Y	N	N	Y
Smith, 2004, 2012	V-36	Open raised bog	Russia (W Sib)	60.81	78.58	1	4400	Y	N	N	Y
Smith, 2004, 2012	V-37	Betula & Salix fen	Russia (W Sib)	61.25	74.73	1	2425	Y	N	N	Y
Smith, 2004, 2012	V-38	Open raised bog	Russia (W Sib)	60.80	74.54	2	7525	Y	N	N	Y
Smith, 2004, 2012	V-39	Open raised bog	Russia (W Sib)	61.09	79.38	2	10,925	Y	N	N	Y
Smith, 2004, 2012	V-40	Open raised bog	Russia (W Sib)	61.20	77.84	1	7850	Y	N	N	Y
Smith, 2004, 2012	E-101	Peat plateau	Russia (W Sib)	66.46	76.68	1	10,970	Y	N	N	Y
Smith, 2004, 2012	E-102	Peat plateau	Russia (W Sib)	66.04	76.59	1	8065	Y	N	N	Y
Smith, 2004, 2012	E-103	Peat plateau	Russia (W Sib)	66.74	76.48	1	10,395	Y	N	N	Y
Smith, 2004, 2012	E-104	Peat plateau	Russia (W Sib)	65.97	77.99	1	4240	Y	N	N	Y
Smith, 2004, 2012	E-105	Peat plateau	Russia (W Sib)	65.98	77.61	1	735	Y	N	N	Y
Smith, 2004, 2012	E-106	Peat plateau	Russia (W Sib)	66.00	77.35	1	9175	Y	N	N	Y
Smith, 2004, 2012	E-107	Peat plateau	Russia (W Sib)	66.01	75.86	1	6650	Y	N	N	Y
Smith, 2004, 2012	E-108	Peat plateau	Russia (W Sib)	65.86	75.29	1	10,685	Y	N	N	Y
Smith, 2004, 2012	E-111	Peat plateau	Russia (W Sib)	66.20	79.14	1	8630	Y	N	N	Y
Smith, 2004, 2012	E-112	Peat plateau	Russia (W Sib)	66.20	79.14	1	8765	Y	N	N	Y
Smith, 2004, 2012	E-113	Peat plateau	Russia (W Sib)	66.45	79.32	4	8305	Y	N	N	Y
Smith, 2004, 2012	E-114	Peat plateau	Russia (W Sib)	66.44	76.32	1	605	Y	N	N	Y
Smith, 2004, 2012	E-115	Peat plateau	Russia (W Sib)	67.81	75.43	2	9120	Y	N	N	Y
Smith, 2004, 2012	E-116	Peat plateau	Russia (W Sib)	67.46	76.42	1	3050	Y	N	N	Y
Smith, 2004, 2012	E-118	Peat plateau	Russia (W Sib)	66.60	77.41	1	2540	Y	N	N	Y
Smith, 2004, 2012	E-118M	Peat plateau	Russia (W Sib)	66.60	77.41	0		N	N	N	Y
Smith, 2004, 2012	E-119	Peat plateau	Russia (W Sib)	65.50	75.50	2	9750	Y	N	N	Y
Smith, 2004, 2012	E-120	Peat plateau	Russia (W Sib)	65.61	77.96	1	2585	Y	N	N	Y
Smith, 2004, 2012	E-120M	Peat plateau	Russia (W Sib)	65.61	77.96	0		N	N	N	Y

Abbreviated reference*	Site name	Peatland type	Country	Latitude	Longitude	^{14}C dates (number)	Oldest age (cal BP)	Basal age (cal BP)	Other dates	Carbon rate site	Peat properties site
Smith, 2004, 2012	E-121	Peat plateau	Russia (W Sib)	65.87	78.81	1	2190	Y	N	N	Y
Smith, 2004, 2012	E-121M	Peat plateau	Russia (W Sib)	65.87	78.81	0		N	N	N	Y
Smith, 2004, 2012	D-122	Peat plateau	Russia (W Sib)	65.58	73.01	2	8495	Y	N	N	Y
Smith, 2004, 2012	D-123	Peat plateau	Russia (W Sib)	64.42	71.03	1	10,080	Y	N	N	Y
Smith, 2004, 2012	D-123M	Peat plateau	Russia (W Sib)	64.42	71.03	0		N	N	N	Y
Smith, 2004, 2012	D-124	Peat plateau	Russia (W Sib)	65.08	72.97	1	6475	Y	N	N	Y
Smith, 2004, 2012	D-124M	Peat plateau	Russia (W Sib)	65.08	72.97	0		N	N	N	Y
Smith, 2004, 2012	D-125	Peat plateau	Russia (W Sib)	64.52	72.16	1	9600	Y	N	N	Y
Smith, 2004, 2012	D-125M	Peat plateau	Russia (W Sib)	64.52	72.16	1	9735	Y	N	N	Y
Smith, 2004, 2012	D-126	Peat plateau	Russia (W Sib)	64.33	71.20	1	9140	Y	N	N	Y
Smith, 2004, 2012	D-126M	Peat plateau	Russia (W Sib)	64.33	71.20	0		N	N	N	Y
Smith, 2004, 2012	D-127M	Peat plateau	Russia (W Sib)	64.31	70.29	1	10,420	Y	N	N	Y
Smith, 2004, 2012	D-128	Peat plateau	Russia (W Sib)	65.55	72.46	1	9180	Y	N	N	Y
Smith, 2004, 2012	P-129	Peat plateau	Russia (W Sib)	66.61	73.75	1	9635	Y	N	N	Y
Smith, 2004, 2012	P-130	Peat plateau	Russia (W Sib)	66.87	74.53	1	8815	Y	N	N	Y
Smith, 2004, 2012	P-131	Peat plateau	Russia (W Sib)	66.17	73.99	2	9940	Y	N	N	Y
Smith, 2004, 2012	P-132	Peat plateau	Russia (W Sib)	66.50	73.95	1	10,065	Y	N	N	Y
Smith, 2004, 2012	P-133	Peat plateau	Russia (W Sib)	65.79	74.35	1	6515	Y	N	N	Y
Smith, 2004, 2012	G-134	Peat plateau	Russia (W Sib)	64.43	77.18	1	8285	Y	N	N	Y
Smith, 2004, 2012	G-135	Peat plateau	Russia (W Sib)	64.83	77.67	1	9450	Y	N	N	Y
Smith, 2004, 2012	G-136	Peat plateau	Russia (W Sib)	64.15	75.36	2	7820	Y	N	N	Y
Smith, 2004, 2012	G-136M	Peat plateau	Russia (W Sib)	64.15	75.36	1	6385	Y	N	N	Y
Smith, 2004, 2012	G-137	Peat plateau	Russia (W Sib)	63.75	75.77	4	9360	Y	N	N	Y
Smith, 2004, 2012	G-138	Peat plateau	Russia (W Sib)	64.52	76.67	1	9915	Y	N	N	Y
Smith, 2004, 2012	G-139	Peat plateau	Russia (W Sib)	64.89	76.73	1	6240	Y	N	N	Y
Smith, 2004, 2012	G-139M	Peat plateau	Russia (W Sib)	64.89	76.73	0		N	N	N	Y

Abbreviated reference*	Site name	Peatland type	Country	Latitude	Longitude	^{14}C dates (number)	Oldest age (cal BP)	Basal age (cal BP)	Other dates	Carbon rate site	Peat properties site
Smith, 2004, 2012	G-140	Peat plateau	Russia (W Sib)	64.27	79.55	1	10,365	Y	N	N	Y
Smith, 2004, 2012	G-140M	Peat plateau	Russia (W Sib)	64.27	79.55	0		N	N	N	Y
Smith, 2004, 2012	G-141	Peat plateau	Russia (W Sib)	64.69	75.40	1	10,410	Y	N	N	Y
Smith, 2004, 2012	G-142	Peat plateau	Russia (W Sib)	64.09	78.60	0		N	N	N	Y
Smith, 2004, 2012	G-142M	Peat plateau	Russia (W Sib)	64.09	78.60	1	8675	Y	N	N	Y
Smith, 2004, 2012	SIB01	Pine-domin. bog	Russia (W Sib)	59.36	68.98	3	6970	Y	N	N	Y
Smith, 2004, 2012	SIB02	Pine-domin. bog	Russia (W Sib)	61.06	70.06	2	8500	Y	N	N	Y
Smith, 2004, 2012	SIB03	Pine-domin. bog	Russia (W Sib)	56.36	79.07	3	2770	Y	N	N	Y
Smith, 2004, 2012	SIB04	Pine-domin. bog	Russia (W Sib)	56.80	78.74	3	3770	Y	N	N	Y
Smith, 2004, 2012	SIB05	Pine-domin. bog	Russia (W Sib)	57.35	81.16	3	4240	Y	N	N	Y
Väliranta, 2003	Ortino 1	Peat plateau	Russia (E. Eur.)	68	54	4	10,374	Y	N	N	Y
Väliranta, 2003	Ortino 2	Peat plateau	Russia (E. Eur.)	68	54	3	8786	Y[1]	N	N	Y

[*] A list of detailed references is presented below the table.

[a] Site used in Yu et al.'s (2009) synthesis.

[1] Basal age not considered in the peatland inception age database because older cores were collected from the same site.

[2] Measured bulk density was multiplied by measured C content (elemental analyzer) for each layer to estimate C bulk density (g C cm^{-3}).

[3] Measured ash-free bulk density was multiplied by inferred C content (ash-free bulk density x 49%) for each layer to estimate C bulk density.

[4] Measured bulk density was multiplied by assumed C content (47%) for each layer to estimate C bulk density.

[5] Assumed time-dependent bulk density was multiplied by assumed C content (47%) for each dated interval to estimate peat-C density.

[6] Peat-C accumulation rates directly obtained from published figures and tables.

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