No support for carbon storage of >1000 GtC in northern peatlands

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Northern peatlands store large amounts of carbon (C) and have played an important role in the global carbon cycle since the Last Glacial Maximum. Most northern peatlands have established since the end of the deglaciation and accumulated C over the Holocene, leading to a total present-day stock of 500 ± 100 GtC. This is a consolidated estimate, emerging from a diversity of methods[1-5]. Recently, Nichols and Peteet (hereafter N&P)[6] presented an estimate of the northern peat C stock of 1055 GtC—exceeding previous estimates by a factor of two. Here, we argue that this is an overestimate, caused by systematic bias introduced by their inclusion of data that is not representative for the major peatland regions and of records that lack direct measurements of C density. Furthermore, we argue that their estimate cannot be reconciled within the constraints offered by ice-core and marine records of stable C isotopes and estimated contributions from other processes that affected the terrestrial C storage during the Holocene.

Suitability of data and methodology used

As in previous studies[2], N&P used the *time-history approach* to estimate peatland C stocks and their evolution in time, using the time-varying peatland area and net C accumulation rates. We notice that area-specific net C accumulation rates used by N&P (j_c) as shown in their Fig. 2c have a Holocene mean value of 33.4–37.6 gC m^{-2} yr^{-1} (median across three methods), and are thus 80-102% higher than reported in previous studies of 18.6 gC m^{-2} yr^{-1} (ref. 2) and 46-64% higher than values of 22.9 gC m^{-2} yr^{-1} (ref. 3) (Table 1). Why this difference?

Table 1. Summary of estimates of Holocene peat C accumulation rates and total C storage in northern peatlands

Number of sites	**Number of cores**	**Accumulation rates (gC m^{-2} yr^{-1})**	**Carbon storage (GtC)**	**Reference**
Unknown	Unknown	33.4-37.6*	1055	Ref. 6 (N&P)
NA**	NA**	NA**	455	Ref. 1
33	33	18.6	546	Ref. 2
127	151	22.9	436	Ref. 3

*Calculated from the spreadsheets provided in the N&P's Supplementary Information.
**NA: not applicable, as Ref. 1 used peat volume approach based on total peat area, mean peat depth, and C density.

N&P calculated C accumulation rates from sedimentation rates (cm yr^{-1}) and C density (gC cm^{-3}). We argue here that both of these parameters were overestimated by N&P. An important factor that may introduce a high bias in estimates of regional sedimentation rates is the inclusion of additional data from the Neotoma Paleoecology Database (NPD). The vast majority of these new data used by N&P originate from locations that are not representative for the areas where the vast majority of northern peatland areas are located (their Fig. 1a and Fig. S1). Their use may be motivated as a complement to the relatively limited set of available peat cores with sufficient information to reconstruct accumulation rates. However, these additional data are almost exclusively originating from lower latitudes than the data underlying previous estimates[2,3,7], and thus represent peatlands or wetlands located in different climates. Yet, the total peatland area in these regions is small, if not negligible, compared to the peatland area north of 50° N (ref. 8). A more reasonable approach would have been to treat additional data from outside the boreal and subarctic regions separately and scale their accumulation rates with the relatively modest peatland area of these respective regions.

N&P claim that they calculated C accumulation rates for each of eight peat regions to account for spatial bias. However, as discussed above, their regional delineation matters. Furthermore, using a single average value for C density (gC cm^{-3}) for all sites that are located within these regions and that lack direct measurements is prone to introducing bias. N&P use a median of peat C density measurements from measurements of C content (%) or organic matter content (%) and dry bulk density (g cm^{-3})[3,7]. However, N&P fail to account for the variability in C density among regions and among different types of peatlands[3]. For example, there is a more than two-fold difference in C density between *Sphagnum* peat (0.037 gC cm^{-3}; *n*=3332) and humidified peat (0.072 gC cm^{-3}; *n*= 418) and between western European islands/continental Europe (0.028 gC cm^{-3}; *n*=449) and western Canada (0.076 gC cm^{-3}; *n*= 3441)[3]. Also, peat likely experiences different degrees of decomposition and compaction with ages, resulting in highly variable C density often observed along a single peat profile. The propagation estimates of uncertainties of C density in N&P would not resolve the issue about the representativeness of that single median C density value. Previous large-scale syntheses[2,3] used ^{14}C-dated individual peat profiles to reconstruct their C accumulation history and excluded sites that did not have direct C density measurements. Those studies thus avoided these biases.

Furthermore, N&P estimated an average sedimentation rate for each region “by dividing the depth of the deepest sample by the most likely calibrated age of the oldest sample in the region". We argue that the use of only the deepest and oldest peat sample risks skewing the estimate towards sites with unusually high sedimentation rates. A more appropriate approach would be to use mean rates based on multiple observations. In addition, sites with the highest sedimentation rates are likely affected by more mineral particle input, which inflate mass accumulation rates but is not representative of C accumulation rates. In fact, some records from Neotoma appear to show that portions of sedimentary sequence may represent lake deposits before peat accumulation (see Supplementary Information). All these effects were not considered and corrected for by N&P.

Unfortunately, we were not able to quantitatively assess the effects of the inclusion of these non-representative data and the use of mean C density values for filling data gaps. Required information was not accessible through the paper by N&P, nor its Supplementary Information.

Lack of support from global carbon budget constraints

The exceptionally large peat C storage of >1000 GtC in N&P is also not supported by top-down constraints from the global C budget reconstructions. To illustrate the effect such large perturbations would have on the global carbon cycle we carried out a sensitivity analysis using a simple carbon-cycle box model[9]. The model considers the C exchange among the atmosphere, land biosphere, oceans and marine sediments. We used the ranges (median ± 1 s.d.) from all three scenarios (literature, combined, grid-box) in N&P as model inputs. All scenarios essentially yielded the same solutions. Therefore, we only show the results from the "combined" approach here. We also ran a separate sensitivity experiment by turning off the simple "carbonate compensation" mechanism using just the median scenario. The results show that an increase in peat C storage of >1000 GtC during the Holocene would induce a decrease in atmospheric CO_2 to below 220 ppm, an increase in atmospheric $\delta^{13}C$ to a value more than 0.8‰ higher than the observed, and a steady rise in deep ocean $\delta^{13}C$ -DIC throughout the Holocene (Fig. 1).

Firstly, our box-model calculations demonstrate that the simplified conversion of peat C uptake into an atmospheric signal of >600 ppm, as shown in their Fig. 2f of N&P, was erroneous due to the neglection of the compensating effect by the ocean that acts to reduce any atmospheric perturbation by up to 80% on the millennial time scale relevant here[10]. We assume that N&P instead converted their estimated terrestrial C stock increase by a division factor of 2.12 GtC per ppm to arrive at a peat C uptake-related decrease in atmospheric CO_2 of more than 300 ppm over the Holocene. Translating the same peat C uptake into an atmospheric CO_2 signal with our box-model yielded a decrease of about 60 ppm (Fig. 1b)—perfectly consistent with our presumption that the ~80% reduction by ocean uptake was neglected in N&P.

Secondly, the experiments suggest that, at face value, exceptionally large peat C storage is difficult to reconcile with the atmospheric and oceanic C budgets. Previously, the observed changes in atmospheric CO_2 concentration and in $\delta^{13}C$ from ice cores have been used to partition the contributions from the land biosphere and ocean, providing a global constraint on land C budget during the Holocene. The measured increase in CO_2

concentration from 265 ppm at 11 ka to 278 ppm in 1750 CE and the small change in δ^{13}C (Fig. 1b, c) were used to reconstruct the preindustrial terrestrial net C uptake over the Holocene to be about 250 GtC (ref. 11). This total Holocene land C balance reflects a strong uptake in the early Holocene through the growth of boreal forests and early peat buildup—which is consistent with the observed early-Holocene increase in atmospheric and oceanic δ^{13}C values[12]—and a C release of 50 GtC during the late Holocene[11]. The small decrease in land C storage in the last 5 kyr contrasts with the large estimated increase in peat C storage of ~400 GtC during the same time period as suggested by N&P (their Fig. 2e). A compensating C source of 400-500 GtC with a biogenic δ^{13}C signature would have to be invoked to close the budget. A detailed analysis of this budget concluded that CO_2 emissions from land-use change by early agriculturalists were not sufficient to close the gap between peat C uptake and the atmospheric constraint before about 3 ka (ref. 13). The two-fold higher estimates of peat C storage by N&P, compared to the record used[13], make it even harder to reconcile the budget. This conflict is not discussed in N&P.

N&P speculate that C release from terrestrial cold steppe permafrost that accumulated during the glacial time could have compensated the large peat C uptake and thereby satisfy the isotopic δ^{13}C mass balance constraint. However, this release occurred mostly during the deglacial warming, not during the Holocene, when most of the present extratropical peat C storage grows. Rather than balancing the C budget with terrestrial C sources in the Holocene, N&P suggest that "most important mechanisms for balancing the peatland sink" is a continued C release from the deep ocean by the wind-driven upwelling during the Holocene. This mechanism requires an even greater loss of C from the deep ocean than implied by the peatland C sink alone and is not supported by observation and simulation of marine $\delta^{13}C$ and carbonate ion changes. For example, an increase in Southern Ocean upwelling would further increase $\delta^{13}C$-DIC in the deep ocean[14] than the already untenable increase $\delta^{13}C$-DIC from peatland regrowth (Fig. 1d), yet $\delta^{13}C$ values remained constant after 7 ka, as observed from a stack of benthic $\delta^{13}C$ data from 33 deep-ocean (>3000 m) cores around the world oceans[12] (Fig. 1d). Furthermore, the CO_2 release from the deep ocean would lead to an increase in the carbonate ion concentration and enhanced preservation of carbonates in the deep ocean, but deep ocean cores show the opposite—a reduction in the carbonate ion and an increase in carbonate dissolution during the Holocene[15]. If any oceanic C source contributed to the Holocene CO_2 rise, it would likely be due to carbonate compensation after deglaciation[12] and surface ocean processes, including shallow water carbonate accumulation such as coral reefs on newly exposed continental shelves[16]. Both processes would cause no significant change in the $\delta^{13}C$ value of released CO_2, and therefore would not mask the imprint of peat C uptake in the atmospheric $\delta^{13}C$ record, but, as demonstrated in our box model experiments, are insufficient to compensate for such a large peat sink.

N&P also relate peat initiation and growth to the atmospheric methane record as archived in polar ice cores. In particular, they relate the strong and rapid increase in CH_4 at the onset of the Holocene[17] with their peak in peat initiation (Fig. 2b in N&P). While this coincidence is remarkable, we consider that it is problematic to relate peat initiation to the large magnitude and abrupt increase in CH_4 emissions at that time, as the latter should be related to total area of existing CH_4 emitting wetlands/peatlands and climate-dependent rates of

CH_4 emissions, not the rates of initiation and peat area increase[18]. It is important to note that the strong increase of CH_4 at that time occurred likely much too quickly to allow for substantial peat area expansion. Therefore the abrupt CH_4 increase is more likely caused by increases in plant productivity, availability of labile C, and suitable CH_4 producing environments in a warm and wet climate[19] at the onset of the Holocene.

In summary, N&P have made an extraordinary claim of doubled C storage in northern peatlands, compared to the estimates available in the literature (500 ±100 GtC). But "Extraordinary claims require extraordinary evidence" (per Carl Sagan), and we conclude that the evidence presented by N&P is not sufficient to support their extraordinary claim.

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Author contributions

Z.Y. and F.J. designed the research, T.K.B. carried out the box-model simulation and created the figure, and all authors were involved in writing and revising the manuscript.

Competing interests

The authors declare no competing interests.

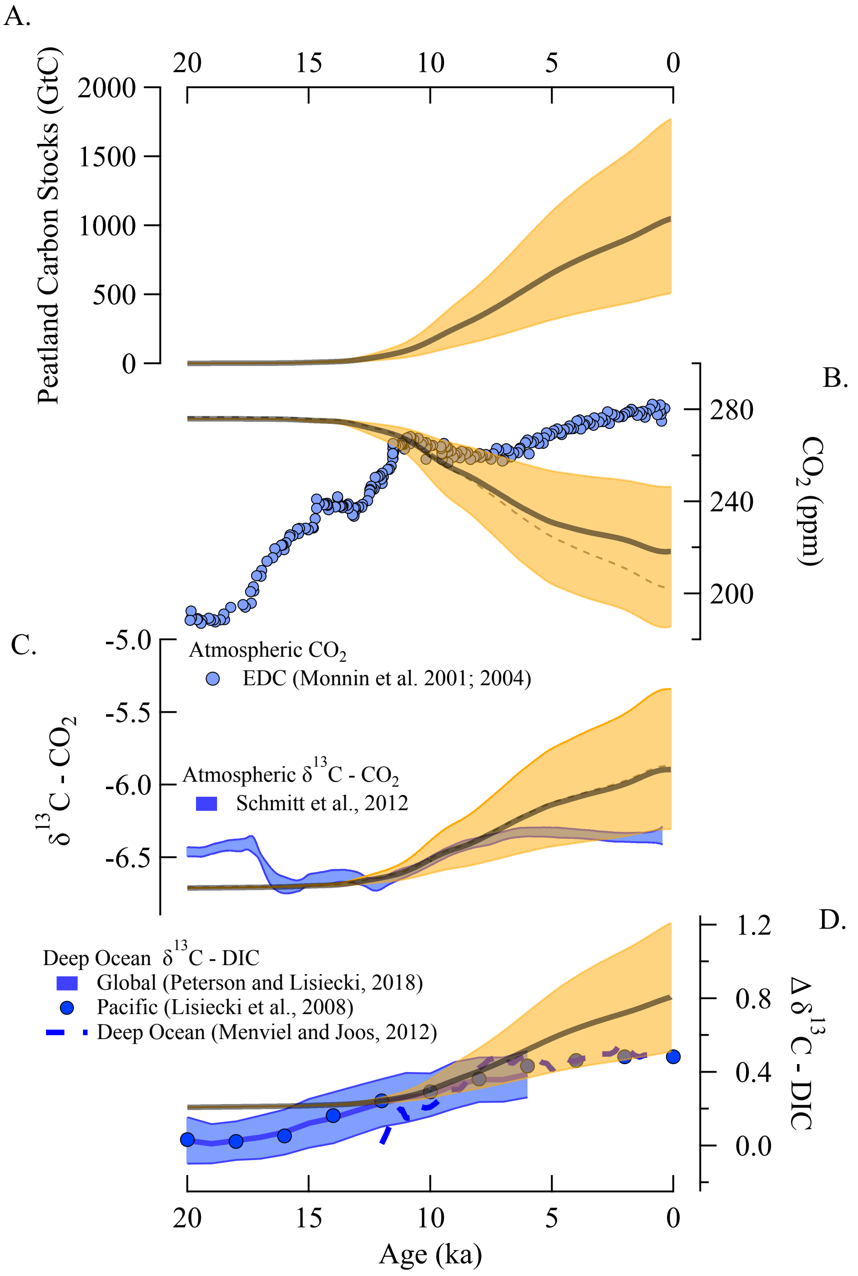

Fig. 1. Unrealistic consequences of large peat carbon storage. **A.** Peat C storage change (line) over time with uncertainties (orange band) as reported in N&P[6]. **B.** Observed atmospheric CO_2 concentration from ice core (dots)[20,21] and box-model calculated CO_2 concentration. **C.** Observed atmospheric $\delta^{13}CO_2$ from ice core (blue shading)[22] and model-calculated value. **D**. Observed deep ocean δ^{13}C -DIC from the global ocean (blue shading)[23], from deep Pacific (dashed blue line)[24] and from a stack of 33 deep-ocean cores[12] and

model-calculated values. The $\delta^{13}C$ values are plotted as anomalies relative to model results to highlight divergence in the mid- and late Holocene. In **B**, **C** and **D** solid line and orange band show the median values and uncertainties corresponding to peat C storage in **A**. Dashed line in **B** represents the outcome without "carbonate compensation" mechanism in the model. The box-model calculations show that peat C storage of >1000 GtC would result unrealistic atmosphere CO_2 and $\delta^{13}CO_2$ values and deep ocean $\delta^{13}C$ value, significantly diverged from the observations.