This is a non-peer reviewed preprint of a revised manuscript that is now under review at *Nature Geoscience.*

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

Comment on the paper by Nichols & Peteet (2019) in *Nature Geoscience* (**12**: 917-921)

[2nd Revised version of Manuscript Ref. NGS-2019-11-02825A]

Zicheng Yu[1, 2,*], Fortunat Joos[3], Thomas K. Bauska[4], Benjamin D. Stocker[5,6], Hubertus Fischer[3], Julie Loisel[7], Victor Brovkin[8], Gustaf Hugelius[9], Christoph Nehrbass-Ahles[10], Thomas Kleinen[8] and Jochen Schmitt[3]

[1]Institute for Peat and Mire Research, School of Geographical Sciences, Northeast Normal University, 130024 Changchun, China (PeatHunter@gmail.com)

[2]Department of Earth and Environmental Sciences, Lehigh University, Bethlehem, PA 18015, USA

[3]Climate and Environmental Physics, Physics Institute, & Oeschger Centre for Climate Change Research, University of Bern, Sidlerstrasse 5, CH-3012 Bern, Switzerland (joos@climate.unibe.ch; hubertus.fischer@climate.unibe.ch; schmitt@climate.unibe.ch)

[4]British Antarctic Survey, High Cross, Madingley Road, Cambridge, CB3 0ET, UK (thausk@bas.ac.uk)

[5]Department of Environmental Systems Science, ETH Zürich, Switzerland (bestocke@ethz.ch)

[6]Swiss Federal Institute for Forest, Snow and Landscape Research WSL, Birmensdorf, Switzerland

[7]Department of Geography, Texas A&M University, 3147 TAMU, College Station, TX 77843, USA (julieloisel@tamu.edu)

[8]Max-Planck Institute for Meteorology, Hamburg, Germany (victor.brovkin@mpimet.mpg.de; thomas.kleinen@mpimet.mpg.de)

[9]Department of Physical Geography, Stockholm University, 106 91 Stockholm, Sweden (gustaf.hugelius@natgeo.su.se)

[10]Department of Earth Sciences, University of Cambridge, Downing Street, Cambridge, CB2 3EQ, UK (cn425@cam.ac.uk)

*Correspondence author:
Emails: PeatHunter@gmail.com; Phone: +1-484-904-8404

Northern peatlands store large amounts of carbon (C): 500 ± 100 GtC according to a consolidated estimate from a diversity of methods[1-6]. However, Nichols and Peteet (hereafter N&P)[7] presented an estimate of 1055 GtC—exceeding previous estimates of carbon stock in global peatlands[2] and in northern peatlands by a factor of two. Here we argue that this is an overestimate, caused by systematic bias introduced by their inclusion of ^{14}C dates from mineral deposits and other unsuitable sites, the use of records that lack direct measurements of carbon density, and the methodology issues. Furthermore, their estimate is difficult to reconcile within the top-down constraints imposed by ice-core and marine records, and estimated contributions from other processes that affected the terrestrial carbon storage during the Holocene.

Unsuitable datasets and methodology issues

N&P[7] used the *time-history approach*[2] to estimate peatland carbon stocks and their evolution over time. Their area-specific net carbon accumulation rates (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), which is 46-102% higher than previous estimates of 18.6 to 22.9 gC m^{-2} yr^{-1} (refs. 2,3). Why this difference? N&P calculated j_c from sedimentation rates (cm yr^{-1}) and carbon density (gC cm^{-3}). We argue that both of these parameters were overestimated by N&P.

Sedimentation rates are biased by the inclusion of ^{14}C dates derived from mineral-rich non-peat deposits. N&P claimed to include “all the sites in Neotoma [Paleoecology Database]…labeled as peatlands or synonyms”, such as bogs or fens. However, many of these records, despite being called “bogs”, are deposits that developed from initial lake stages. For example, Chatsworth Bog in Illinois (Neotoma ID 364) contains >12 m sediments but was a lake for most of its 14,000-year history. Mineral lacustrine sediment had almost completely filled the basin about 3000 years ago, when it changed from a lake to a marl fen that accumulated peat. The large difference in j_C—up to 30 gC m^{-2} yr^{-1} during the early Holocene—between N&P[7] and ref.3 (using the same data compilation) was partly due to N&P’s inclusion of rapidly accumulating mineral deposits. In addition, many sites from N&P originate from low-latitude locations that are not representative of the areas where the vast majority of northern peatland areas are located (their Figs. 1a and S1); this also compromises their estimates.

As stated by N&P, “rather than individual measurements of carbon density, a median carbon density (g cm^{-3}) was used to calculate the jC from sedimentation rate (cm yr^{-1}).” Thus, N&P fail to account for the variability in carbon density in different regions and among different types of peatlands[3,8]. For example, there is a more than two-fold difference in C density 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 undergoes different degrees of decomposition and compaction with age, resulting in highly variable C density often observed along a single peat profile. Furthermore, using one median carbon density value to all sites that lack direct measurements is prone to introducing bias and greatly inflates j_C calculations, especially for mineral-rich deposits. The propagation analysis of carbon density uncertainties by N&P[7] does not resolve this problem.

Furthermore, we find an inherent problem in N&P's algorithm that inflates the sedimentation rates and total carbon storage. Their probabilistic method was initially developed in a case study from an Alaskan peatland[9]. Using their data[9] and algorithm, we find that a composite stratigraphy of 197 cm in length (in their Table 2) would change to a 246 cm long core. We arrived at this 24.5% increase in core length by summing the product of the sedimentation rate (as annotated on their Fig. 3D) and time duration (shown in their Fig. 3E) of their 10 core intervals. By the same argument, the observed peat carbon storage of 126.3 kgC m^{-2} (as calculated from their Table 2) would change to 155.8 kgC m^{-2}, an increase of 23.4%. This case study demonstrates that the assumptions behind their probabilistic method artificially create new carbon mass. The same problem exists in N&P[7], but unfortunately N&P did not provide us their specific and complete data in order to reproduce their results and quantify the effects of this carbon mass inflation as well as of the inclusion of the erroneous data and the use of median carbon density values for filling data gaps.

Lack of support from global carbon budget constraints

The exceptionally large peat C storage[7] is not supported by top-down constraints from the global C budget reconstructions. Our model simulation results show that an increase in peat carbon storage of >1000 GtC during the Holocene would induce a decrease in atmospheric CO_2 to below 220 ppm, an increase in atmospheric $\delta^{13}CO_2$ to a value more than 0.8‰ higher than the observed, and a steady rise in deep ocean δ^{13}C-DIC throughout the Holocene (Fig. 1).

Firstly, our box-model calculations demonstrate that the simplified conversion of peat carbon uptake into an atmospheric signal of >600 ppm, as shown in their Fig. 2f, 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 carbon stock increase by a division factor of 2.12 GtC per ppm to arrive at the claimed peat carbon uptake-related decrease in atmospheric CO_2 of >300 ppm during the Holocene. Translating the same peat carbon uptake into an atmospheric CO_2 signal with our model yielded a decrease of about 60 ppm (Fig. 1b).

Secondly, our simulations suggest that exceptionally large peat carbon storage is difficult to reconcile with the atmospheric and oceanic carbon 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 carbon 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 $\delta^{13}C$ (Fig. 1b, c) were used to reconstruct the preindustrial terrestrial net carbon uptake over the Holocene to be about 250 GtC[11]. This total Holocene land carbon 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 $\delta^{13}C$ values[12]—and a carbon release of 50 GtC during the late Holocene[11]. The small decrease in land carbon storage in the last 5 kyr contrasts with the large estimated increase in peat carbon storage of ~400 GtC during the same time period as in their Fig. 2e.

A compensating carbon source of 400-500 GtC with a biogenic $\delta^{13}C$ 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[13]. The two-fold higher estimates of peat carbon storage by N&P[7]—compared to the one used[13]—make it even harder to reconcile the budget. This conflict is not discussed in N&P[7].

Rather than balancing the carbon budget with terrestrial carbon sources, N&P suggest that "most important mechanisms for balancing the peatland sink" is a continued carbon release from the deep ocean by the wind-driven upwelling during the Holocene. This mechanism requires an even greater loss of carbon from the deep ocean than implied by the peatland carbon 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 in $\delta^{13}C$-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].

In summary, we conclude that the evidence presented by N&P[7] is not sufficient to support their claim of doubled carbon storage in northern peatlands compared to earlier estimates.

References

1. Gorham, E. Northern peatlands: Role in the carbon cycle and probable responses to climatic warming. *Ecol. Appl.* **1**, 182–195 (1991).

2. Yu, Z., Loisel, J., Brosseau, D. P., Beilman, D. W. & Hunt, S. J. Global peatland dynamics since the Last Glacial Maximum. *Geophys. Res. Lett.* **37**, L13402 (2010).

3. Loisel, J. et al. A database and synthesis of northern peatland soil properties and Holocene carbon and nitrogen accumulation. *Holocene* **24**, 1028–1042 (2014).

4. Jackson, R.B. et al. The ecology of soil carbon: Pools, vulnerabilities, and biotic and abiotic controls*. Annu. Rev. Ecol. Evol. Syst.* **48**, 419–45 (2017).

5. Lindgren, A., Hugelius, G. & Kuhry, P. Extensive loss of past permafrost carbon but a net accumulation into present day soils. *Nature* **560**, 219-222 (2019).

6. Hugelius, G. et al. Large stocks of peatland carbon and nitrogen are vulnerable to permafrost thaw. *Proc. Natl. Acad. Sci. USA* **117**, 20438-20446 (2020).

7. Nichols, J.E. & Peteet, D.M. Rapid expansion of northern peatlands and doubled estimate of carbon storage. *Nature Geoscience* **12**, 917-921 (2019).

8. Treat, C.C. et al. Effects of permafrost aggradation on peat properties as determined from a pan-Arctic synthesis of plant macrofossils. *J. Geophys. Res. Biogeosci.* **121**, 78–94 (2016).

9. Nichols, J. E. et al. A probabilistic method of assessing carbon accumulation rate at Imnavait Creek Peatland, Arctic Long Term Ecological Research Station, Alaska. *J. Quat. Sci.* **32**, 579–586 (2017).

10. Joos, D., et al. Carbon dioxide and climate impulse response functions for the computation of greenhouse gas metrics: a multi-model analysis. *Atmos. Chem. Phys.* **13**, 2793–2825 (2013).

11. Elsig, J. et al. Stable isotope constraints on Holocene carbon cycle changes from an Antarctic ice core. *Nature* **461**, 507-510 (2009).

12. Menviel, L. & Joos, F. Toward explaining the Holocene carbon dioxide and carbon isotope records: Results from transient ocean carbon cycle-climate simulations. *Paleoceanography* **27**, PA1207, doi:10.1029/2011PA002224 (2012).

13. Stocker, B.D., Yu, Z., Massa, C. & Joos, F. Holocene peatland and ice-core data constraints on the timing and magnitude of CO_2 emissions from past land use. *Proc. Natl. Acad. Sci. USA* **114**, 1492-1497 (2017).

14. Tschumi, T., Joos, F., Gehlen, M., and Heinze, C. Deep ocean ventilation, carbon isotopes, marine sedimentation and the deglacial CO_2 rise. *Clim. Past* **7**, 771–800 (2011).

15. Yu, J., Anderson, R.F. & Rohling, E.J. Deep ocean carbonate chemistry and glacial-interglacial atmospheric CO_2 changes. *Oceanography* **27**, 16–25 (2014).

Methods

To illustrate the effect of such large peat carbon perturbations on the global carbon cycle we carried out a sensitivity analysis using a simple carbon-cycle box model[16]. The model considers the carbon 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[7] 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.

References

16. Bauska, T.K. et al. Carbon isotopes characterize rapid changes in atmospheric carbon dioxide during the last deglaciation. *Proc. Natl. Acad. Sci. USA* **113**, 3465-3470 (2016).

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.

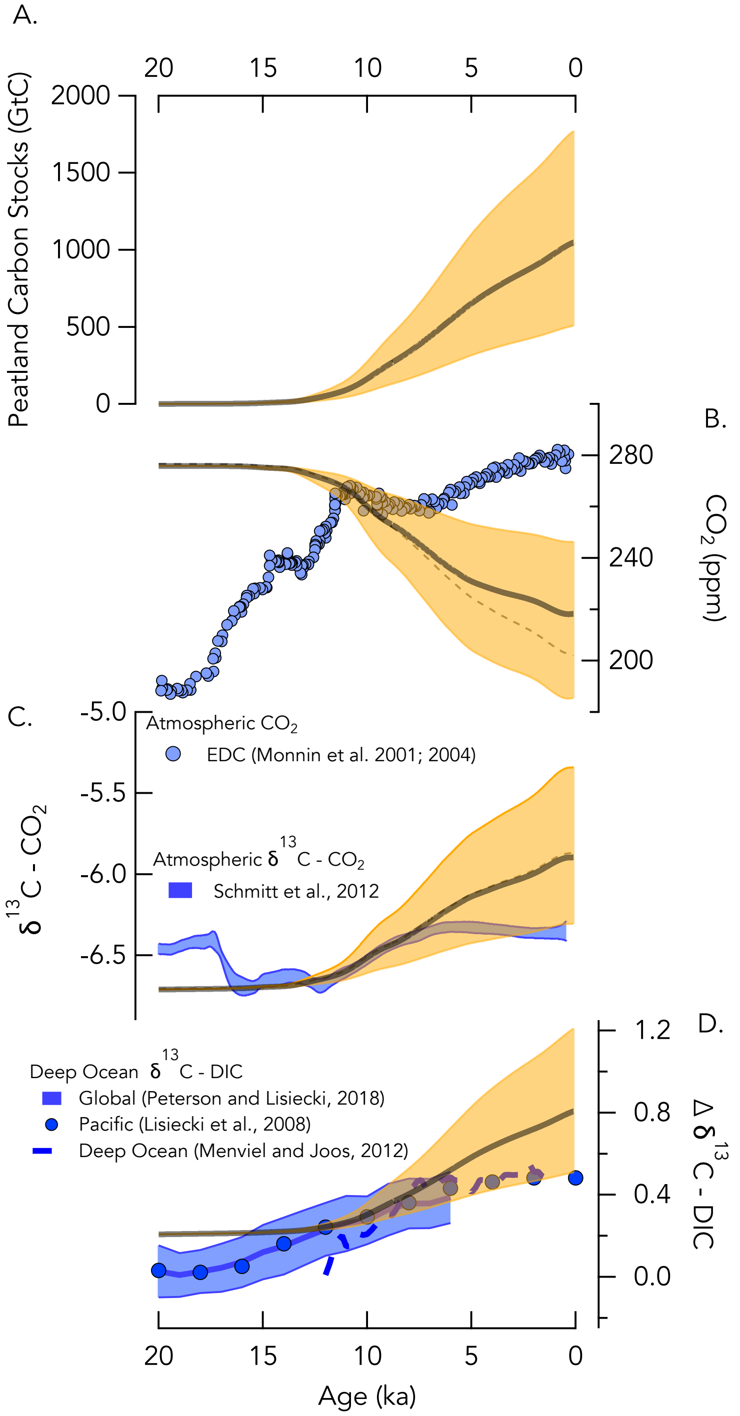

Fig. 1. Unrealistic consequences of large peat carbon storage. **A.** Peat carbon storage change (line) over time with uncertainties (orange band)[7]. **B.** Observed atmospheric CO_2 concentration from ice core (dots) and box-model calculated CO_2 concentration. **C.**

Observed atmospheric $\delta^{13}CO_2$ from ice core (blue shading) and model-calculated value. **D**. Observed deep ocean δ^{13}C-DIC from the global ocean (blue shading), deep Pacific (dashed blue line) and a stack of 33 deep-ocean cores[12] and model-calculated values. The δ^{13}C values are plotted as anomalies relative to model results. Dashed line in **B** represents the outcome without “carbonate compensation” mechanism in the model. See Suppl. Info. for additional references.

This is part of a non-peer reviewed preprint of a manuscript that is now under review at *Nature Geoscience.*

SUPPLEMENTARY INFORMATION

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

Comment on the paper by Nichols & Peteet (2019) in *Nature Geoscience* (**12**: 917-921)
[Revised version of Manuscript Ref. NGS-2019-11-02825A]

Zicheng Yu[1, 2,*], Fortunat Joos[3], Thomas K. Bauska[4], Benjamin D. Stocker[5,6], Hubertus Fischer[3], Julie Loisel[7], Victor Brovkin[8], Gustaf Hugelius[9], Christoph Nehrbass-Ahles[10], Thomas Kleinen[8] and Jochen Schmitt[3]

[1]Institute for Peat and Mire Research, School of Geographical Sciences, Northeast Normal University, 130024 Changchun, China (PeatHunter@gmail.com)
[2]Department of Earth and Environmental Sciences, Lehigh University, Bethlehem, PA 18015, USA
[3]Climate and Environmental Physics, Physics Institute, & Oeschger Centre for Climate Change Research, University of Bern, Sidlerstrasse 5, CH-3012 Bern, Switzerland (joos@climate.unibe.ch; hubertus.fischer@climate.unibe.ch; schmitt@climate.unibe.ch)
[4]British Antarctic Survey, High Cross, Madingley Road, Cambridge, CB3 0ET, UK (thausk@bas.ac.uk)
[5]Department of Environmental Systems Science, ETH Zürich, Switzerland (bestocke@ethz.ch)
[6]Swiss Federal Institute for Forest, Snow and Landscape Research WSL, Birmensdorf, Switzerland
[7]Department of Geography, Texas A&M University, 3147 TAMU, College Station, TX 77843, USA (julieloisel@tamu.edu)
[8]Max-Planck Institute for Meteorology, Hamburg, Germany (victor.brovkin@mpimet.mpg.de; thomas.kleinen@mpimet.mpg.de)
[9]Department of Physical Geography, Stockholm University, 106 91 Stockholm, Sweden (gustaf.hugelius@natgeo.su.se)
[10]Department of Earth Sciences, University of Cambridge, Downing Street, Cambridge, CB2 3EQ, UK (cn425@cam.ac.uk)

*Correspondence author:
Emails: PeatHunter@gmail.com

Data transparency and reproducibility concerns

To help ensure the reproducibility of research results, researchers should provide "clear, specific, and complete information about any computational methods and data products that support their published results"[1]. To date, we have not been provided with the list of sites and ^{14}C dates used in the paper by Nichols and Peteet (hereafter N&P)[2], despite multiple requests made directly to the corresponding author and through the journal editor. In response to our request, the corresponding author stated: "To the best of my knowledge I used all of the data publicly available and properly cataloged at the time of my data collection, 2-3 years ago. … I did, in fact, use all the sites in Neotoma (which includes the European Pollen Database) labeled as 'peatland' or synonyms. … My data collection resulted in a very large dataset. No selection criteria, other than reasonable public availability, were used to systematically eliminate any data." (J. Nichols, personal communication, 23 November 2019).

Without specific information about the exact sites and dates used, we cannot evaluate and reproduce the result presented in N&P[2]. One reason is that the Neotoma database is an open database that researchers continuously contribute data to. To the best of our knowledge, Neotoma has no database version keeping track of the exact number of data entries. In retrospect, it is therefore not possible to identify all data (i.e., peatland sites) used by N&P. In addition, in the case of N&P[2], the authors compiled the data sets from Neotoma likely in 2016 or 2017. The Neotoma database has grown rapidly since then, with a doubled number of unique occurrences for all different types of data (see the figure in ref. 3). Today, applying the same search criteria and the same keywords as the ones used in N&P ("bog, fen, peatland and synonyms") would certainly generate a very different set of sites. Therefore, without an explicit list of sites used in N&P, we cannot reproduce their results in detail.

Suitability of datasets in the Neotoma Paleoecology Database

While we do not mean to question the standard and quality control of the Neotoma Paleoecology Database (NPD), we just raise concern about how N&P[2] use the database. Below we provide additional information about why the uncritical inclusion of datasets from the NPD is problematic and how it biases N&P's estimate of peatland carbon storage. Indeed, N&P used "all sites" that were categorized as peatland, bog, fen or other synonyms; this selection includes a large number of sites that may well be peatlands today, but that started as mineral-deposition systems, such as lakes. Here we use a specific site from the NPD as an example to illustrate the type of error N&P's data selection has incurred.

Chatsworth Bog (Neotoma Site ID: 364) is a marl fen in an outwash channel; it is located in Illinois, USA. The >12-m long sediment core spans the last 14,000 years[4]. Chatsworth Bog was a lake during most of its 14,000-year history. At about 3000 years ago, lake sediment had almost completely filled the basin, and the site changed from a lake to a fen that started to deposit peat. Chatsworth Bog is a good example for the "lake infilling process" that may precede peat accumulation. This type of transition from lake to peat (terrestrialization) is widespread in Eurasia and North America. The site name and its categorization in the NPD indicate that it is a peatland, but peat has only accumulated for the last 3000 years, while the initial 11,000 years were lake sediments. It is extremely unusual for a peatland to accumulate more than 12 m peat during the postglacial time, that is, over the last 13,000 years, except perhaps in small kettle-hole setting. In any case, most of the sediment at Chatsworth Bog are clearly not peat, so it is erroneous to include the entire stratigraphic record in N&P's analysis; only the peatland portion could have been included. As the lower lake sediment section has a very high sedimentation rate—arguably much higher than what a peatland would—it contributes to inflate the early-Holocene sedimentation rate (cm yr^{-1}) in N&P's analysis (their Fig. 2c). As the exact list of sites that were used remains unavailable, we don't know how many occurrences—similar to this one—were included in N&P's analysis. It could be a major issue, since this lake-to-peat transition is common in deglaciated terrain.

Also, lake sediments often have much lower carbon content and lower carbon density than peat, so using a single median carbon density derived from boreal and subarctic peatlands, along with this high sedimentation rate, would greatly overestimate the carbon accumulation rate (j_C). N&P used a median value of peat carbon density (gC cm^{-3}) from measurements of carbon content (%) or organic matter content (%) and dry bulk density (g cm^{-3})[5,6]. However, N&P fail to account for the variability in carbon density among regions and among different types of peatlands[5]. For example, there is a two-fold difference in carbon 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)[5]. Also, peat undergoes different degrees of decomposition and compaction with age, resulting in highly variable carbon density often observed along a single peat profile. Fen peat and bog peat, just to name these two, also have different carbon densities[5]. Previous large-scale syntheses based on similar approaches[5,7] used ^{14}C-dated individual peat profiles to reconstruct their carbon accumulation history and excluded sites that did not have direct carbon density measurements. Those studies thus avoided these biases, but N&P did not. As mentioned above, applying one median peat carbon density value to mineral-rich deposits must have greatly inflated j_C calculations in N&P[2]. Their propagation estimates of uncertainties of carbon density would not resolve this root problem.

Furthermore, **t**he vast majority of these new data from Neotoma used by N&P[2] 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, the total peatland area in these regions is small, if not negligible, compared to the peatland area in boreal and subarctic regions[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.

Methodology issues

In addition to the problems with the datasets they used, we also find an inherent problem in N&P's algorithm that inflates the sedimentation rates and total carbon storage at the site level. Their probabilistic method was initially developed in a case study from an Alaskan peatland[9]. Using their data[9] and algorithm, we show that a composite stratigraphy of 197 cm in length (in their Table 2) would change to a 246 cm long core after calculating sediment-accumulation rates. We arrived at this 24.5% increase in core length by summing the product of the sedimentation rate (as annotated on their Fig. 3D) and time duration (shown in their Fig. 3E) for each of their 10 core intervals. We conclude that their algorithm violates the principle of mass conservation; in that case study, it “added” almost 50 cm to the real core data after calculating sedimentation rates. Using their algorithm, which integrates carbon accumulation rates over age duration of data in their Figs. 3E or 4, the observed peat carbon storage of 126.3 kgC m^{-2} (as calculated from their Table 2) would be inflated to 155.8 kgC m^{-2}—an increase of 23.4%. This case study demonstrates that the assumptions behind their probabilistic method artificially create additional carbon mass not present in reality.

Mass conservation would require the total amount of carbon per unit area integrated over the entire time period to remain unchanged, regardless of the algorithm used. As such, a peat core of a given length should result in the same peat carbon storage (in kgC m^{-2}), independent of the number of ^{14}C dates available, age-depth model, smoothing technique, or any other data manipulation procedure. Different age models or chronologies would only affect how that same amount of carbon is distributed over time, but it should not change the total integrated amount of carbon. This is a fundamental principle and requirement that any algorithm and methodology—no matter how complex and fancy they may be—should abide by; the algorithm used in N&P seems to fail this requirement. However, because we do not have access to the datasets used in N&P, we can only evaluate their methodology problem through visual inspection of their plotted results vs. plots that were built using conventional methods of the same or similar datasets[6]. Such comparison shows that the age-integrated area (in kgC m^{-2}) below the curve derived from their method[2] is much larger than the original calculation[6] (see Fig. S1 in N&P's Reply).

Lack of support from global carbon budget constraints

N&P speculate that carbon release from terrestrial cold steppe permafrost that accumulated during the glacial time could have compensated the large peat carbon uptake and thereby satisfy the isotopic $\delta^{13}C$ mass balance constraint. However, this release occurred mostly during the deglacial warming[10], not during the Holocene, when most of the present extratropical peat carbon storage grows.

In addition to the problems that we discuss in the main text on the impacts of exceedingly large peat carbon storage on deep ocean, here we comment on other oceanic processes. If any oceanic carbon source contributed to the Holocene CO_2 rise to compensate the large carbon sequestration by peatlands, it would likely be due to carbonate compensation after deglaciation[11] and surface-ocean processes, including shallow water carbonate accumulation such as coral reefs on newly exposed continental shelves[12]. 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 carbon uptake in the atmospheric $\delta^{13}C$ record, but, as demonstrated in our box model experiments (Fig. 1 in the main text), are insufficient to compensate for such a large peat carbon sink.

Furthermore, N&P relates 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[13] with their peak in peat initiation (Fig. 2b in N&P[2]). 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 more to total area of existing CH_4 emitting wetlands and climate-dependent rates of CH_4 emissions than the rates of initiation and peat area increase[14]. It is important to note that the strong increase of CH_4 at that time occurred likely much too quickly (within a century) 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[15] at the onset of the Holocene.

Unrealistic consequences of large peat carbon storage (Figure 1 caption with full references). **A.** Peat carbon storage change (line) over time with uncertainties (orange band) as reported in N&P[2]. **B.** Observed atmospheric CO_2 concentration from ice core (dots)[16,17] and box-model calculated CO_2 concentration. **C.** Observed atmospheric $\delta^{13}CO_2$ from ice core (blue shading)[18] and model-calculated value. **D**. Observed deep ocean $\delta^{13}C$ - DIC from the global ocean (blue shading)[19], from deep Pacific (dashed blue line)[20] and from a stack of 33 deep-ocean cores[11] 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.

In summary, N&P[2] have made an extraordinary claim of doubled carbon 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.

References

1. National Academies of Sciences, Engineering, and Medicine. *Reproducibility and Replicability in Science*. Washington, DC: The National Academies Press. (2019). https://doi.org/10.17226/25303.

2. Nichols, J.E. & Peteet, D.M.. Rapid expansion of northern peatlands and doubled estimate of carbon storage. *Nature Geoscience* **12**, 917-921 (2019).

3. Williams, J. Neotoma Paleoecology Database: Recent Updates. *Quaternary Times: The American Quaternary Association Newsletter* **41** (2, Fall Issue), 14-17 (2019). https://www.neotomadb.org/documents/157883/

4. King, J.E. Late Quaternary vegetational history of Illinois. *Ecological Monographs* **51**(1): 43-62 (1981).

5. Loisel, J. et al. A database and synthesis of northern peatland soil properties and Holocene carbon and nitrogen accumulation. *Holocene* **24**, 1028–1042 (2014).

6. Treat, C.C. et al. Effects of permafrost aggradation on peat properties as determined from a pan-Arctic synthesis of plant macrofossils. *J. Geophys. Res. Biogeosci.* **121**, 78–94 (2016).

7. Yu, Z., Loisel, J., Brosseau, D. P., Beilman, D. W. & Hunt, S. J. Global peatland dynamics since the Last Glacial Maximum. *Geophys. Res. Lett.* **37**, L13402 (2010).

8. Xu, J., Morris, P. J., Liu, J. & Holden, J. PEATMAP: Refining estimates of global peatland distribution based on a meta-analysis. *Catena* **160**, 134–140 (2017).

9. Nichols, J. E. et al. A probabilistic method of assessing carbon accumulation rate at Imnavait Creek Peatland, Arctic Long Term Ecological Research Station, Alaska. *J. Quat. Sci.* **32**, 579–586 (2017).

10. Ciais, P. et al. Large inert carbon pool in the terrestrial biosphere during the Last Glacial Maximum. *Nat. Geosci.* **5**, 74–79 (2011).

11. Menviel, L. & Joos, F. Toward explaining the Holocene carbon dioxide and carbon isotope records: Results from transient ocean carbon cycle-climate simulations. *Paleoceanography* **27**, PA1207, doi:10.1029/2011PA002224 (2012).

12. Brovkin, V. et al. What was the source of the atmospheric CO_2 increase during the Holocene? *Biogeosciences* **16**, 2543–2555 (2019).

13. Chappellaz, J. et al. Synchronous changes in atmospheric CH4 and Greenland climate between 40 and 8 kyr BP. *Nature* **366**, 443- 445 (1993).

14. Yu, Z. et al. Evidence for elevated emissions from high-latitude wetlands contributing to high atmospheric CH4 concentration in the early Holocene. *Glob. Biogeochem. Cycles* **27**,131–140 (2013).

15. Turetsky, M.R. et al. Short-term response of methane fluxes and methanogens activity to water table and soil warming manipulations in an Alaskan peatland. *J. Geophys. Res*. **113**, G00A10, doi:10.1029/2007JG000496 (2008).

16. Monnin, E. et al. Atmospheric CO_2 concentrations over the last glacial termination. *Science* **291**, 112–114 (2001).

17. Monnin, E. et al. Evidence for substantial accumulation rate variability in Antarctica during the Holocene, through synchronization of CO_2 in the Taylor Dome, Dome C and DML ice cores. *Earth Planet. Sci. Let.* **224**, 45–54 (2004).

18. Schmitt, J. et al. Carbon isotope constraints on the deglacial CO_2 rise from ice cores. *Science* **336**, 711-714 (2012).

19. Peterson, C.D. & Lisiecki, L.E. Deglacial carbon cycle changes observed in a compilation of127 benthicδ13Ctime series (20–6 ka). *Clim. Past* **14**, 1229–1252 (2018).

20. Lisiecki, L.E., Raymo, M.E. & Curry, W.B. Atlantic overturning responses to Late Pleistocene climate forcings. *Nature* **456**, 85-88 (2008).