

J.E. Nichols and D. M. Peteet Reply

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The quantification of northern peatland carbon stocks is vital to our understanding of the global carbon cycle, and we welcome the opportunity to respond to the comments submitted in the preceding “Matters Arising” (Yu et al., Ratcliffe et al.). In response to Yu et al., we provide additional clarification of how data from the Neotoma Paleoecological Database (NPD) are stored and used. We also repeated our quantification of northern peat carbon stocks using only radiocarbon data vetted by other publications. However, our conclusions are unchanged by the elimination of the additional data. We respond to Ratcliffe et al. by addressing the conflict between the “time-history” and “inventory methods.” We calculated northern peatland carbon stocks by the inventory method using our dataset and carefully quantify the uncertainties. We find that while the mean values for carbon stock differ by twofold, the uncertainties around those means are larger than previously acknowledged and are overlapping. This result emphasizes the need for continued work by the carbon cycle science community to understand and quantify uncertainty in terrestrial carbon stock estimates.

Radiocarbon measurements from Neotoma

Both sets of authors in their respective “Matters Arising” expressed concern about the quality of the data stored in the Neotoma Paleoecology Database (NPD). Radiocarbon ages stored in Neotoma are a well-curated resource, and they can be used without additional individual screening, but only if the database is queried appropriately. We did not use any assumed

geochronological information from pre-radiocarbon publications nor any obsolete calibrations. Here we will further clarify how data is entered and stored in Neotoma as well as how we retrieved it. Additionally, we include in the supplement the results of our NPD query—a list of dataset identification numbers (Dataset IDs). These Dataset IDs can be used to directly access the data, metadata (including depth and location), and references for all 553 sets of radiocarbon ages we used. This can be done (as we did in our original publication) in an automated fashion using the “neotoma” package for the R statistical computing environment¹.

Neotoma stores age information in two ways. “Geochronologic datasets” contain only raw measurements of age and have their own associated metadata. “Chronologies” contain modeled ages for all samples in a core, either assigned by the original authors of the dataset or algorithmically by Neotoma¹. When Ratcliffe et al. queried Neotoma for peatlands older than a particular threshold, the search algorithm based the returned result on the “chronologies” not on measurements stored in “geochronological datasets.” In contrast, we queried only Neotoma’s geochronologic datasets. These data came from samples positively identified as peat in the dataset-level metadata. This returned more datasets than could practically be reviewed individually, but, importantly, such a review would be redundant. All datasets and metadata stored in the NPD are carefully quality checked by a subject-area expert—a critical fact that sets Neotoma apart from other public data facilities. We ignored any derived “chronologies,” and calculated new calibrated age probability distributions for each date using the IntCal13 calibration curve². Another crucial detail of our analysis is that peat depth is assigned by the depth of the deepest radiocarbon measurement on peat. Therefore, even though our mean peat depth is deeper than that of Ratcliffe et al., we are confident that the depths we report are not skewed by the inclusion of non-peat sediment laid down at the site before peatland initiation. We are also confident that our initiation age compilation is not likely to be contaminated with old carbon by the hard water effect, nor with non-peat sediment from below the bottom of the peat.

We are acutely aware of these potential pitfalls, and our results (Fig. 2 of the original publication³) show us that such contamination is undetectable, if present at all. The core-bottom age density curve rises sharply at two intervals, once at the start of the Bølling warming, and again at the start of the Holocene. If the initiation age dataset contained erroneous ages, we would expect that the density curve would have slopes leading into warm periods rather than the sharp rises at known climatic transitions we observe.

Comparing different applications of the time-history method

Yu et al. contend that the increased estimate of peatland carbon is due to the fact that we included peatlands in our analysis that were outside the typical zones where peatlands are located. We endeavored to include all peatlands that do in fact exist, not ones that conform to an ideal. The contrasts between our new estimate of peat carbon stock are not due to our inclusive data policy but to our removal of biases inherent to previous methods of compositing j_C (the carbon flux to peatlands, typically expressed in $\text{g C m}^{-2} \text{ yr}^{-1}$). The age modelling methods used in previous composites have two levels of smoothing applied; The first is when site-specific age models are produced using “Bacon,” an age modelling algorithm that purposely and explicitly dampens rapid accumulation rate changes⁴, and the second is when time resolution is reduced for compositing^{5,6}.

To demonstrate the sensitivity of carbon stock calculations to j_C smoothing, we apply the same probabilistic method of calculating a composite record as in our original publication, but use only the available data from Treat et al., 2016 and Loisel et al., 2014 (Fig. 1). The reduced variability that distinguishes the time-binning method is stark when comparing the Younger Dryas cold period (12.5 – 11.7 ka) with the Early Holocene (11.7 – ~7 ka) (Fig. 1). The time-binned record obscures this abrupt change. This smoothing is much less important for a single site, as abrupt

changes are typically apparent in paleoecological data. However, when calculating carbon flux and sink from a smoothed age model, strong biases are introduced. In the present case, the contrast in peat carbon accumulation between the early Holocene, when accumulation should be rapid, and the Younger Dryas, when accumulation should be slow, is strongly attenuated by smoothing. This distinction would be unimportant if the area of peatlands remained constant. However, because peatland area also rapidly increases across this interval, the redistribution of flux in time produces an artificially reduced total stock of peatland carbon when the product of two records is integrated for the final stock estimate.

The depression of the total peatland stock caused by smoothing bias is very large. Using our probabilistic method of j_C record compositing and the cumulative peatland area curve of MacDonald et al.⁷, we arrive at a median value of 955 Gt of peat carbon, only slightly less than the value we report using the full dataset and area-weighting methods, but quite different from the approximately 550 Gt previously reported⁵. We conclude that the discrepancy is due not to data policy, but to our removal of smoothing bias in the record of peat carbon flux.

The inventory method with uncertainty estimation

Ratcliffe et al., in their “Matters Arising,” contend that the time-history method inherently overestimates peat carbon stock. To address this concern, we recalculated the stock of northern peatland carbon as they suggest, using the inventory method⁴. The inventory method estimates the stock of Northern Peatland carbon as the product of carbon density, peat depth, and peatland area extent. Our estimates for these three parameters and their uncertainty are shown in Fig. 2 (a-c). The mean and median estimates of carbon stock using the inventory method were 659 Gt and 463 Gt respectively (Table S2), similar to that of Ratcliffe et al. However, the $\pm 1 \sigma$ range of these estimates, is 101–1,883 Gt and fully encompasses the $\pm 1 \sigma$ range of our

gridbox-weighted time-history method estimate, 477–1,664 Gt (Fig. 2d, Table S2). The apparent twofold difference in the means is nearly meaningless, given the overlapping uncertainty.

We advocate for the use of the time-history for the insights it provides as to the timing of peatland carbon accumulation. The inventory method has no temporal component and therefore cannot comment on changes in carbon flux from the atmosphere to peatlands or its relationship with climate.

The Global Carbon Budget Constraints and Uncertainty

Yu et al. assert that the global carbon cycle cannot accommodate the stock of peatland carbon that we estimate. However, these authors' comments do not properly account for the quantified uncertainties in the data and model results reported, nor do the comments acknowledge the unquantified uncertainties arising from the carbon cycle components the models do not simulate, and the data do not measure.

The box model of the global carbon cycle presented by Yu et al., based on the $\delta^{13}\text{C}$ of atmospheric CO_2 , does not differentiate among terrestrial stores of carbon nor transfers among them. Northern peatlands are but one deposit of carbon on the terrestrial landscape. Others include living biomass, mid-latitude lakes and swamps, tropical peatlands, coastal and riparian peatlands, and shallow lake sediments. Hence, as Bauska et al.⁸ conclude, “many possible scenarios can explain the evolution of CO_2 and $\delta^{13}\text{C}\text{-CO}_2$ during the deglaciation.” This holds for the Holocene as well. For example, there is ample evidence of permafrost collapse throughout the western Arctic and subarctic during the first half of the Holocene⁹⁻¹¹. Carbon release from permafrost soils with reuptake by peatlands during the Holocene Thermal Maximum is just one of the many possible ways of reorganizing terrestrial carbon without invoking oceanographic mechanisms.

Yu and others further present a compilation of measurements of $\delta^{13}\text{C}$ of deep ocean carbonate. Based on those data, they conclude that the deep ocean contained insufficient CO_2 during the glacial to account for all the peat we estimate accumulated in the Holocene. However, large uncertainties exist in these estimates as well^{12,13}, particularly due to data gaps in the Southern Ocean. The data we cited^{14,15} show continued outgassing of CO_2 from the Southern Ocean well into the middle Holocene. The studies Yu et al. cited also explicitly exclude CO_2 release from shallow waters, another potentially important carbon source¹⁶. Considering still other methods of estimating the change in deep ocean carbon between the Glacial and the Holocene reveal more uncertainty. For example, a range of modeling experiments were used to estimate deep ocean organic-derived CO_2 based on the efficacy of the biological pump. Depending on the parameters used, there was more than 1000 Gt of difference in the estimates¹⁷. Clearly, there is enough uncertainty in our understanding of the Glacial and Holocene carbon cycle to accommodate a larger, and similarly uncertain, peatland stock.

Yu et al. conclude their “Matters Arising” with the admonition that our “extraordinary” conclusions require extraordinary evidence. However, when our quantified, and explicitly stated uncertainties are considered as context, the differences between our conclusions and those of other investigators become much less “extraordinary.” Despite important advances made by carbon cycle science, much remains uncertain about the carbon inventory of terrestrial environments and the ocean, as well as the myriad processes by which carbon is transferred between and within them. Our community should embrace these uncertainties and continue to carefully define and quantify them.

Competing Interests Statement

The authors declare no competing interests.

References

1. Williams, J. W. et al. The Neotoma Paleoecology Database, a multiproxy, international, community-curated data resource. *Quaternary Research* **89**, 156–177 (2018).
2. Reimer, P. J. et al. IntCal13 and Marine13 Radiocarbon Age Calibration Curves 0–50,000 Years cal BP. *Radiocarbon* **55**, 1869–1887 (2013).
3. Nichols, J. E. & Peteet, D. M. Rapid expansion of northern peatlands and doubled estimate of carbon storage. *Nat. Geosci.* **12**, 917–921 (2019).
4. Blaauw, M., Bakker, R., Christen, J., Hall, V. & van der Plicht, J. A Bayesian Framework for Age Modeling of Radiocarbon-Dated Peat Deposits: Case Studies from the Netherlands. *Radiocarbon* **49**, 357–368 (2007).
5. Yu, Z., Loisel, J., Brosseau, D. P., Beilman, D. W. & Hunt, S. J. Global peatland dynamics since the Last Glacial Maximum. *Geophysical Research Letters* **37**, L13402 (2010).
6. Loisel, J. et al. A database and synthesis of northern peatland soil properties and Holocene carbon and nitrogen accumulation. *The Holocene* (2014) doi:10.1177/0959683614538073.
7. Macdonald, G. M. et al. Rapid Early Development of Circumarctic Peatlands and Atmospheric CH₄ and CO₂ Variations. *Science* **314**, 285–288 (2006).
8. Bauska, T. K. et al. Carbon isotopes characterize rapid changes in atmospheric carbon dioxide during the last deglaciation. *Proceedings of the National Academy of Sciences* **113**, 3465–3470 (2016).

9. Kaufman, D. S. et al. Holocene thermal maximum in the western Arctic (0–180°W). *Quaternary Science Reviews* **23**, 529–560 (2004).
10. Peteet, D. M., Nichols, J. E., Moy, C. M., McGeachy, A. & Perez, M. Recent and Holocene climate change controls on vegetation and carbon accumulation in Alaskan coastal muskegs. *Quaternary Science Reviews* **131**, 168–178 (2016).
11. Nichols, J. E., Peteet, D. M., Frolking, S. & Karavias, J. A probabilistic method of assessing carbon accumulation rate at Imnavait Creek Peatland, Arctic Long Term Ecological Research Station, Alaska. *Journal of Quaternary Science* **45**, 300 (2017).
12. Peterson, C. D., Lisiecki, L. E. & Stern, J. V. Deglacial whole-ocean $\delta^{13}\text{C}$ change estimated from 480 benthic foraminiferal records. *Paleoceanography* **29**, 549–563 (2014).
13. Peterson, C. D. & Lisiecki, L. E. Deglacial carbon cycle changes observed in a compilation of 127 benthic $\delta^{13}\text{C}$ time series (20–6 ka). *Climate of the Past* **14**, 1229–1252 (2018).
14. Studer, A. S. et al. Antarctic Zone nutrient conditions during the last two glacial cycles. *Paleoceanography* **30**, 845–862 (2015).
15. Studer, A. S. et al. Increased nutrient supply to the Southern Ocean during the Holocene and its implications for the pre-industrial atmospheric CO_2 rise. *Nature Geoscience* **11**, 756–760 (2018).
16. Davies-Walczak, M. et al. Late Glacial to Holocene radiocarbon constraints on North Pacific Intermediate Water ventilation and deglacial atmospheric CO_2 sources. *Earth and Planetary Science Letters* **397**, 57–66 (2014).
17. Schmittner, A. & Somes, C. J. Complementary constraints from carbon (^{13}C) and nitrogen (^{15}N) isotopes on the glacial ocean's soft-tissue biological pump. *Paleoceanography* **31**, 669–693 (2016).

Figure Captions

Figure 1: We recalculated j_C for Holocene peats using only data from T16 and without using any area-weighting schemes to directly compare only our probabilistic j_C compositing method with the 500-year age binning j_C compositing method that is traditionally used. The results of the probabilistic method are shown in red and the age binning method in black. Both records show a 1.96σ (95% confidence) envelope. Note the y-axis is on a log scale.

Figure 2: Data used to estimate peat carbon stocks using the inventory method and a comparison of stock estimates using both the inventory method and the time-history method. In A-C, gray bars indicate a histogram of measurements of each parameter, and black lines describe the model used to estimate the parameter. Hatched areas indicate the $\pm 1 \sigma$ range of the measurements. **A:** Log-transformed peat carbon density. **B:** Cube root-transformed mean peat depth in each 90,000 km² gridbox. **C:** Estimated peatland extent. **D:** A comparison of peat carbon stock estimates by two methods. Diamonds indicate the median value; circles indicate the mean. Black areas span the interquartile range, and hatched areas (as in **A-C**) indicate the $\pm 1 \sigma$ range.