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Peatlands and Their Role in the Global Carbon Cycle

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Global peatlands store a very large carbon (C) pool located within a few meters of the atmosphere. Thus, peatland-atmosphere C exchange should be a major concern to global change scientists: Will large amounts of respired belowground C be released in a warmer climate, causing the climate to further warm (a positive climate feedback)? Will more C be sequestered due to increased plant growth in a warmer climate? How will land use change, fires, and permafrost thaw affect the magnitude and direction of carbon dioxide (CO_2) and methane (CH_4) exchange with the atmosphere? These questions remain challenging, but some significant progress has been made recently.

Recent studies find that C sequestration rates have been highly variable during the Holocene (the past 12,000 years) and that peak C accumulation rates occurred during warmer climate intervals. This raises the possibility that northern peatlands, or at least significant portions of them, may serve as a negative feedback to climate change in the future, causing a cooling effect if hydrological and disturbance-induced surprises are avoided.

Carbon Hot Spots

Peatlands worldwide occupy about 3% of global land area and contain approximately 600 gigatons of C, almost all of which has accumulated since the last ice age [*Yu et al.*, 2010]. The majority of peatland area and C is located north of 45°N latitude. Northern peatlands occur mostly in boreal and subarctic regions, including extensive development in western Siberia, central Canada, northwestern Europe, and Alaska (Figure 1a). The highest C densities occur at 50°–70°N (Figure 1b).

The next largest concentration (~50 gigatons of C) is in tropical peatlands, primarily in Southeast Asia and perhaps South America [*Yu et al.*, 2010]. The tropical peatland C stock is very vulnerable to intense land use pressure [*Page et al.*, 2011].

Peat Carbon Accumulation Histories

The increase in peatland area over time can be estimated from ages obtained from basal peat layers. On the basis of more than 1500 basal dates, it was determined that northern peatlands spread rapidly in the early Holocene, around 10,000 years ago [*MacDonald et al.*, 2006] (see Figure 1a for site locations). Vertical C accumulation rates in many northern peatlands also show a peak in the early Holocene on the basis of 33 sites [*Yu et al.*, 2010] (see Figure 1a for site locations). High rates of expansion and C accumulation were likely in response to maximum solar irradiance in summer and possibly strong temperature seasonality, with warmer summers stimulating plant production and colder winters reducing winter decomposition. Climate cooling after the Holocene thermal maximum, around 8000–5000 years ago, appears to have slowed peat C accumulation. Peatlands in the warmest parts of western Siberia have accumulated the most C since 2000 years ago [*Beilman et al.*, 2009], and some peatlands in Alaska show increases in C sequestration during the Medieval Warm Period, about 900 years ago.

In the Southern Hemisphere, rapid expansion and C accumulation of Patagonian peatlands around 15,000 years ago [*Yu et al.*, 2010] were likely induced by a warm climate in the Southern Ocean 14,000–17,000 years ago [*Barker et al.*, 2009]. These extratropical observations suggest that C-rich, cold-region ecosystems can rapidly sequester C under warmer climates if the necessary moisture conditions can be maintained.

Modeled net C balance (NCB) for global peatlands suggests that peatlands have

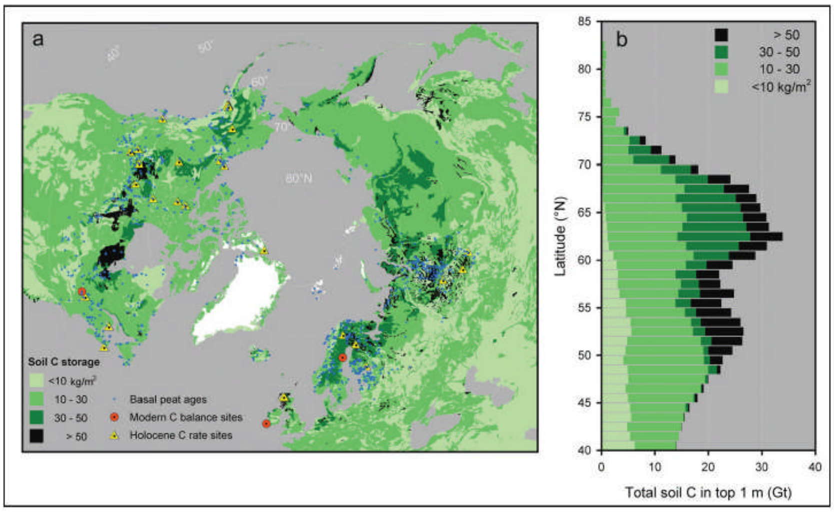

*Fig. 1. Soil and peatland carbon (C) distribution. (a) Map of peatland sites, with sites where basal ages were obtained [*MacDonald et al., *2006] and sites at which C accumulation rates for the past 12,000 years (the Holocene) were calculated [*Yu et al., *2010]. The map includes circum-Arctic distribution of soil C (from the International Geosphere-Biosphere Programme Data and Information System (IGBP-DIS) soil database). Note that peatlands dominate in grid cells with more than 30 kilograms of C per square meter in the top meter of soil. (b) Latitudinal distribution of total soil C, measured in gigatons (Gt), with different soil C density.*

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been a persistent, but variable, long-term C sink during the Holocene, ranging from 16 to 88 gigatons of C trapped every thousand years [*Yu*, 2011] (Figure 2a). Northern peatlands sequester C at a rate of 5.6–38 grams per square meter per year (Figure 2b). Global peatland C sequestration shows three phases during the Holocene that appear to correlate with atmospheric CO_2 concentrations and carbon isotope ratios in CO_2 ($\delta^{13}CO_2$; see Figures 2c and 2d), suggesting a major role for peatlands in the global C cycle. The slow decrease in CO_2 and sharp increase in $\delta^{13}CO_2$ (7000–11,000 years ago) reflect land biosphere C uptake, including forest growth and peatland development across the newly deglaciated north. The rapid CO_2 increase and stable $\delta^{13}CO_2$ (4000–7000 years ago) suggest a dominant role of ocean C release, with steady peatland uptake at a Holocene average rate of 50 gigatons of C every thousand years. A slow CO_2 increase and slightly decreasing $\delta^{13}CO_2$ (since 4000 years ago) may reflect C release from the aggregated land biosphere, when peatlands slow down their C sequestration rates. In several respects, peatlands act like a "terrestrial ocean" because of their large C stock and long-term buffering effect from continuous decomposition.

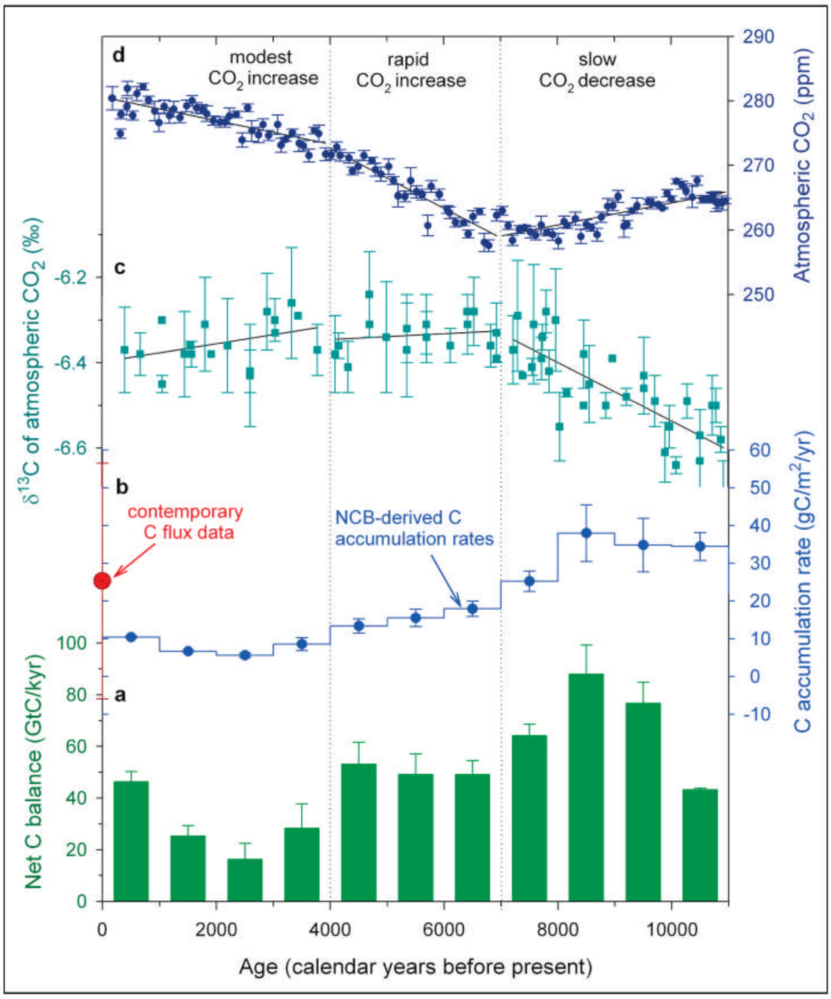

*Fig. 2. Holocene peatland C dynamics and the global C cycle. (a) Net global peatland C sequestration rates per millennium (gigatons C per kiloyear) modeled from observed peat core data [*Yu, 2011*]. (b) True instantaneous C accumulation rates from northern peatlands as derived from net carbon balance (NCB) in Figure 2a and peatland areas over time (error bars are standard errors of the means). These paleodata are from roughly 2000 basal peat ages and more than 70 peat C accumulation records, representing a 600-gigaton C pool. Red circle represents the average of NCB with a standard deviation of a total of 14 years of measurements from three peatland sites [*Roulet et al., *2007;* Nilsson et al., *2008;* Koehler et al., *2011*]. (c) C isotope composition from atmospheric carbon dioxide ($\delta^{13}CO_2$), as measured from the European Project for Ice Coring in Antarctica (EPICA) Dome C ice core in Antarctica [*Elsig et al., *2009*]. (d) Atmospheric CO_2 concentrations from EPICA [*Monnin et al., *2004*]. Note that high C sequestration in peatlands at 7000–10,000 years ago (Figures 2a and 2b) is likely responsible for the simultaneous CO_2 decrease (Figure 2d) and $\delta^{13}CO_2$ increase (Figure 2c); peatlands might have played secondary but noticeable roles during other time periods.*

Carbon Exchange Today

Multiyear C balance measurements, including CO_2, CH_4, and dissolved organic carbon, available from only a few northern peatlands, show a large weather-driven interannual variability from weak C sources to strong C sinks, responding to hydrological and temperature conditions (Figure 2b). Despite large interannual variations, site averages converge around 20–30 grams of C per square meter per year. An overall mean NCB of 25 (±31) grams of C per square meter per year is 2–3 times the rate of the last several millennia (≤10 grams of C per square meter per year; see Figure 2b). Is this higher C sequestration rate a response to recent global change—including climate warming, elevated CO_2, and increased nitrogen deposition—or the result of limited sampling? The scientific community does not yet know enough about peatland responses to global change factors to answer this question.

Possible Future Surprises and the Path Forward

Observational evidence showing higher C accumulation rates during past warmer climates suggests that northern peatlands may provide a negative climate feedback in a warming world. However, warming-induced permafrost thaw (itself difficult to forecast) will affect C cycling rates of many northern peatlands in ways that are difficult to predict, especially for CH_4 emission rates [*Christensen et al.*, 2004]. Rapid climate change to novel climatic conditions may have effects not easily seen in records of past ecosystem responses. Changing seasonality such as greater winter warming may tilt the balance between production and decomposition. Fires and other disturbances are also expected to increase over the next century in the boreal zone (between 50° and 70° latitudes) and some tropical areas, which could also release C that has been sequestered over millennia.

Five research themes would strengthen scientific understanding of peatland C dynamics:

1. Significant data and knowledge gaps exist in both paleo and modern C flux studies. Tropical peatlands and some remote northern regions have received little attention. To benefit global synthesis efforts and process-level understanding, selection of new study sites should be based on considerations of gaps in the records of present

and past environments and climates, including the uniqueness and relevance of climate controls, climate sensitivity, and climate histories.

2. C sequestration histories preserved in peat deposits provide a unique opportunity to directly link paleo and contemporary C dynamics. Also, decadal to centennial changes in C balance are most relevant to climate change impact assessments and mitigation policies, so new concepts and approaches for analyzing paleodata at this temporal scale and integrating paleo and contemporary observations are urgently needed to address this intermediate time scale.

3. Hydrology provides necessary conditions for peatlands to exist and survive, but temperature may play a more dominant role in C accumulation rates, as new data have suggested. There are clear research needs to reveal and quantify the relative roles of temperature and hydrology changes in peat C balance over different time scales (from interannual to millennial) and across peatland types (e.g., old versus young, shallow versus deep, bogs versus fens, etc.).

4. The C cycle consequences of permafrost peatland thawing and intense peatland fires are not well understood and are difficult to predict but represent a potentially large C flux term. More research is needed to understand the connections among climate change, changing disturbance regimes, and peatland C balance.

5. Models that represent peatlands as "complex adaptive systems" [*Belyea and Baird,* 2006], including both climate and internal feedbacks as peatlands adapt to changing conditions [*Frolking et al.*, 2010], are needed to understand threshold behaviors and nonlinear dynamics. An important goal is to incorporate dynamic peatlands into coupled climate–C cycle models for long-term simulations [e.g., *Lawrence and Slater,* 2008; *Kleinen et al.*, 2010].

Addressing these research needs and gaps not only will provide insight into the role of peatlands in the global carbon cycle in the past and future but will also generate new knowledge of carbon dynamics and biosphere interactions. Peatlands may serve as a model ecosystem in understanding the importance of time scales in the response of terrestrial carbon dynamics to future climate change over centuries to millennia.

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Author Information

Zicheng Yu, Lehigh University, Bethlehem, Pa.; E-mail: ziy2@lehigh.edu; D. W. Beilman, University of Hawai`i at Manoa, Honolulu; S. Frolking, University of New Hampshire, Durham; G. M. MacDonald, University of California, Los Angeles; N. T. Roulet, McGill University, Montreal, Quebec, Canada; P. Camill, Bowdoin College, Brunswick, Maine; and D. J. Charman, University of Exeter, Exeter, UK

Increasing depth of burial over time.