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 (CO₂) and methane (CH₄) 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.

**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 [Barber 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
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 CO₂ concentrations and carbon isotope ratios in CO₂ (δ¹³CO₂; see Figures 2c and 2d), suggesting a major role for peatlands in the global C cycle. The slow decrease in CO₂ and sharp increase in δ¹³CO₂ (7000–11,000 years ago) reflect land biosphere C uptake, including forest growth and peatland development across the newly deglaciated north. The rapid CO₂ increase and stable δ¹³CO₂ (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 CO₂ increase and slightly decreasing δ¹³CO₂ (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.

**Carbon Exchange Today**

Multiyear C balance measurements, including CO₂, CH₄, 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). This higher C sequestration rate a response to recent global change—including climate warming, elevated CO₂, 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 CH₄ 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 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 peat 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 responses of terrestrial carbon dynamics to future climate change over centuries to millennia.

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