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Invited review

Insights and issues with estimating northern peatland carbon stocks and fluxes since the Last Glacial Maximum

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In this review paper, we identify and address key uncertainties related to four local and global controls of Holocene northern peatland carbon stocks and fluxes. First, we provide up-to-date estimates of the current northern peatland area (3.2 M km^2) and propose a novel approach to reconstruct changes in the northern peatland area over time (Section 2). Second, we review the key methods and models that have been used to quantify total carbon stocks and methane emissions over time at the hemispheric scale, and offer new research directions to improve these calculations (Section 3). Our main proposed improvement relates to allocating different carbon stock and emission values for each of the two dominant vegetation assemblages (sedge and brown moss-dominated vs. *Sphagnum*-dominated peat). Third, we discuss and quantify the importance of basin heterogeneity in estimating peat volume at the local scale (Section 4.1). We also highlight the importance of age model selection when reconstructing carbon accumulation rates from a peat core (Section 4.2). Lastly, we introduce the role of biogeomorphological agents such as beaver activity in controlling carbon dynamics (Section 5.1) and review the newest research related to permafrost thaw (Section 5.2) and peat fire (Section 5.3) under climate change. Overall, this review summarizes new information from a broad range of peat-carbon studies, provides novel analysis of hemispheric-scale paleo datasets, and proposes new insights on how to translate peat-core data into carbon fluxes. It also identifies critical data gaps and research priorities, and many ways to consider and address them.

Contents

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1. Introduction

1.1. The role and importance of northern peatlands in the global carbon cycle

The terrestrial biosphere plays a key role in the global carbon (C) cycle, mostly through C uptake via photosynthesis and C release via respiration. Peat-accumulating wetlands are arguably the most effective terrestrial ecosystems at sequestering C over millennial timescales. These peatlands are characterized by a water-saturated soil layer consisting of at least 30% (dry mass) organic material. Most definitions require a minimum peat thickness of 30 cm for an ecosystem to be considered a peatland (National Wetlands Working Group, 1997; Joosten and Clarke, 2002). Carbon-rich peatlands cover about 3% of the global land area and account for >50% of the wetland area worldwide (Rydin and Jeglum, 2006). Most peatlands (80–90%) are distributed across the northern mid- and high-latitude regions (~45–70°N), with significant development starting around 16,000 calibrated years before present (cal. BP). Their expansion across the northern landscapes approximately tracked the retreating ice sheets following the Last Glacial Maximum (e.g., Harden et al., 1992; Vitt et al., 2000; Glaser et al., 2004; Gorham et al., 2007), with peak peatland initiation occurring between 11,000 and 8000 cal. BP (MacDonald et al., 2006; Korhola et al., 2010; Yu et al., 2010; Ruppel et al., 2013). Other significant peatland-rich areas of the world include the Amazon River Basin, Congo, Indonesia, the Tibetan Plateau, and southern Patagonia. Peatlands worldwide support important biological diversity (including species at risk of extinction), regulate water flow, and constitute substantial water, nitrogen, and C stores (Joosten and Clarke, 2002; Keddy and Fraser, 2005; Keddy et al., 2009).

Peatlands are very efficient at sequestering C over millennial timescales. These organic landforms currently store 500 ± 100 gigatons of carbon (Gt C), which accounts for a substantial fraction of the global soil C pool (Gorham, 1991; Yu et al., 2010; Loisel et al., 2014). In peat soils, dead plant material accumulates over time due to incomplete decay, resulting in a positive C balance. This process is mainly attributable to (1) cold, waterlogged, and acidic conditions that limit soil microbial activity, and (2) plant and peat recalcitrance to decomposition (Rydin and Jeglum, 2006). Over centennial and millennial timescales, decaying plant biomass can accumulate into thick peat deposits characterized by very high soil C densities (up to >250 kg C/m^2; Sheng et al., 2004). Northern peatland complexes have probably been a persistent atmospheric carbon dioxide (CO_2) sink and a methane (CH_4) source over the Holocene, with an overall negative radiative impact (i.e., a cooling effect) on the global climate (Frolking and Roulet, 2007; Ciais et al., 2013; Kleinen et al., 2015; Brovkin et al., 2016).

The stability of the northern peatland C pool remains uncertain under projected global changes. Alarmingly, a general agreement has yet to be met regarding the direction and magnitude of the impact of global warming on the peatland C sink capacity. On one hand, several studies have suggested enhanced peat decomposition and subsequent C emission to the atmosphere in a warmer and drier world (Ise et al., 2008; Dorrepaal et al., 2009; Wu and Roulet, 2014). Model simulations have also shown that CH_4 emissions could increase considerably (+120–200%) by 2100 under the RCP 8.5 scenario (Stocker et al., 2014), potentially shifting the net C balance of peatlands from sink to source. Conversely, warmer temperatures would prolong the growing season for peatland vegetation, and could thus increase net primary production (NPP) and C accumulation in regions that are not water-limited (Beilman et al., 2009; Stelzer and Post, 2009; Charman et al., 2013; Loisel and Yu, 2013). Other studies suggest that peatlands overall could keep functioning as large C sinks, albeit a possible redistribution in the strength of sinks and sources at the regional scale (Frolking et al., 2011; Neubauer, 2014; Petrescu et al., 2015). Large uncertainties remain regarding the net radiative budget of peatlands because of the generally opposite directions of CO_2 (uptake) and CH_4 (release) fluxes, as well as the different atmospheric lifetimes of these gases (Petrescu et al., 2015). For example, the impact of drought on fire severity, intensity, and recurrence on CO_2 emissions are not well understood (Turetsky et al., 2011a). Likewise, the impact of warming temperature on permafrost thaw and subsequent peatland collapse on CH_4 emissions remain uncertain (Turetsky et al., 2007; Tarnocai et al., 2009; Sannel and Kuhry, 2011; Treat et al., 2016). That being said, very few studies point towards runaway scenarios where peatland C stocks would rapidly decompose and emit vast quantities of greenhouse gases to the atmosphere under a warming climate (but see Ise et al., 2008).

1.2. Holocene peatland carbon dynamics: from the local to the global scale

Several internal and external factors control C cycling in peatlands at the local scale. The main factors of importance are: (1) basin geomorphology, slope, and substrate impermeability (Glaser et al., 2006; Yu et al., 2009; Ireland and Booth, 2010); (2) long-term climatic conditions such as effective moisture, growing season length, air temperature, and the presence of permafrost (Charman et al., 2013, Schuur et al., 2015; Treat et al., 2016); (3) short-term weather events such as floods and droughts (Lafleur et al., 2004; Roulet et al., 2007); (4) disturbance, including human activity, fire, and permafrost thaw (Camill et al., 2009); (5) peatland hydrology, influenced by site-specific characteristics that determine the inputs, outputs, and storage components of the regional water balance (Belyea and Baird, 2006), and (6) peatland ecology, including microbial communities, plant species, and vegetation succession (Vitt et al., 2000; Hughes and Barber, 2003; Fenner and Freeman, 2011). All of these factors also interact via internal feedback mechanisms such as flow networks that, in the end, impact peat growth rates through self-regulating feedback mechanisms (Frolking et al., 2010; Swindles et al., 2012a).

Comprehensive compilations of peatland data (Fig. 1) have recently provided us with new means to estimate peatland C stocks and fluxes from around the world. In a recent synthesis, 151 peat core records from the northern peatland domain were combined to estimate long-term changes in peat accumulation (Fig. 1; Loisel et al., 2014). The