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A comparative study of within-basin and regional peatland development: implications for peatland carbon dynamics

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A B S T R A C T

Northern peatlands are among the most carbon-rich ecosystems on Earth, but many unanswered questions remain regarding linkages between their long-term developmental processes and climatic variability. In this paper, we present a detailed paleoecological reconstruction of the developmental history of a kettle peatland in northern Wisconsin, USA (Fallison Bog) based on 21 coring locations and temporally constrained by 69 radiocarbon dates. This record of within-basin developmental history is compared to a regional dataset containing estimated ages of peatland establishment for 75 core samples collected from 37 depressional peatlands throughout the Great Lakes Region. Finally, our data are used to develop a spatially explicit model of whole-system carbon accumulation in Fallison Bog, which distinguishes between carbon pools stored in limnic sediments and peat deposits. Results indicate that peatland development in Fallison Bog was episodic and spatially complex. Peatland development was related to the morphology of the underlying basin and characterized by pulses of both terrestrialization and paludification. Major episodes of terrestrialization centered on 4980 and 3180 years before A.D. 1850 (cal yr BP), with less extensive episodes occurring around 3840, 1060, 670, and 410 cal yr BP. Extensive peatland area developed by paludification of shallow portions of the basin around 2040 cal yr BP. The timing of peatland development within Fallison Bog was correlated with the timing of peatland development in other depressional peatlands across the Great Lakes Region ($r = 0.70$), suggesting a common climatic driver. Comparison of peatland development in Fallison Bog and independent paleoclimate records suggested that both millennial-scale and sub-centennial-scale variability in moisture balance influenced spatiotemporal patterns of peatland development. Model results indicated that Fallison Bog accumulated ~6655 t of carbon during the Holocene, with 66% of this total stored in peat deposits that have accumulated in only the last ~5000 years. Collectively, model results and the strong correlation between the timing of within-basin and regional pulses of peatland establishment imply that depressional peatlands likely experienced climate-sensitive and episodic changes in carbon accumulation rates during the Holocene, and similar dynamics could be expected in response to ongoing and future climatic change.

1. Introduction

Northern peatlands have accumulated nearly 550 Gt of carbon (C) since the Last Glacial Maximum, placing them among the most C-dense ecosystems on Earth (Yu et al., 2010). Importantly, this sizable C pool is stored within a few meters of the atmosphere and maintained by shallow watertables, creating appreciable potential for feedbacks with the climate system. Recognition of this potential has motivated efforts to include peatland C cycling in global climate models (Frokling et al., 2009). However, these efforts are hampered by an incomplete understanding of the ecosystem processes that influence lateral and vertical growth of peat deposits, especially with respect to climatic influences on peatland expansion (Korhola et al., 2010; Yu et al., 2010, 2011). The importance of resolving linkages between peatland processes and climate is underscored by concerns over recent and anticipated future warming and enhanced climatic variability over many peat-rich regions (Meehl and Tebaldi, 2004; Schär et al., 2004; Meehl et al., 2007).

In contrast to boreal regions where much of the land surface is covered by expansive, interconnected veneers of peat (mean thickness = 2.3 m; Gorham, 1991), peatland ecosystems in previously glaciated zones of temperate North America and Europe are

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mostly confined to discrete depressions on the landscape (Kratz and Medland, 1989). Although depressional peatlands tend to be isolated and small in aerial extent (generally < 20 ha), they are often abundant at regional scales and occupy deep basins (up to 15 m), and thus can store large quantities of C in peat deposits and limnic sediments (Buffam et al., 2010). For example, recent estimates from a previously glaciated region of northern Wisconsin (USA) indicate that peat deposits and limnic sediments account for over 80% of the total fixed-C pool across thousands of heavily forested square kilometers, despite covering only 20% and 13% of the land area, respectively (Buffam et al., 2011). Despite the magnitude of these pools and their implications for long-term C cycling, surprisingly little is known about the rates at which they accumulated over the Holocene, the relative importance of different pathways of peatland development (i.e., terrestrialization or paludification), or the influence of climatic variability on ecosystem trajectory and C dynamics.

In depressional systems, peatland can develop following two primary pathways. *Terrestrialization* is the process by which peatland replaces formerly aquatic habitat through the combined effects of basin infilling by sediment accumulation and lakeward expansion of floating vegetation mats. In contrast, *Paludification* entails outward expansion of peatland directly over waterlogged mineral soils, resulting in the conversion of formerly dry upland to wetland habitat (Charman, 2002).

It is generally assumed that autogenic processes (i.e., vegetation succession and water retention by *Sphagnum* mosses) exert dominant control over the rate and pattern of peatland development along both of these pathways (Charman, 2002), which leads to predictions of gradual, climate-independent peatland development and accumulation of peatland C pools throughout the Holocene (Kratz and DeWitt, 1986; Anderson et al., 2003). However, several studies have documented non-linear patterns of peatland development in depressional systems and concluded that climate could influence which developmental pathway is followed and affect the rate at which peatland expands laterally over aquatic or upland habitat (e.g., Buell et al., 1968; Kratz, 1988; Winkler, 1988; Klinger, 1996). For example, pulses of terrestrialization have been linked to climate-driven water-level fluctuations (Campbell et al., 1997; Ireland and Booth, 2011; Ireland et al., 2012) and the occurrence of outward paludification has been documented during shifts toward relatively wet climatic conditions in the late Holocene (Brugam and Johnson, 1997; Filion and Begin, 1998). Contrasting climate-independent and climate-driven conceptual models of peatland development in depressional systems leads to dramatically different predictions for past and future C-accumulation rates (Ireland et al., 2012).

In this paper, we present a detailed reconstruction of peatland development in a northern Wisconsin kettle depression (Fallison Bog) based on 20 peat cores and one lake core, temporally constrained by 69 radiocarbon (^{14}C) dates. We demonstrate an episodic developmental history that included both terrestrialization and paludification pathways and compare these data to independent reconstructions of regional paleohydrology, demonstrating that data are consistent with a conceptual model of peatland expansion driven by climate-induced water-level variability (Ireland et al., 2012). The timing of peatland development within Fallison Bog is compared to peatland establishment ages from 75 core samples collected from 37 depressional peatlands throughout the Great Lakes Region. This comparison demonstrates that within-basin and regional episodes of peatland development were temporally coherent, further suggesting a common climatic driver. Finally, we use our data from Fallison Bog to develop a spatially explicit model of whole-system C accumulation, which illustrates the potential C-cycling implications of these results.

2. Study site and methods

2.1. Site description

Fallison Bog (45.995° N; 89.613° W) is located in northern Wisconsin, USA (Fig. 1). Regional surficial geology was structured by the most recent deglaciation, which deposited approximately 40 m of sandy outwash over granitic bedrock (Kratz and Medland, 1989). Subsequent melting of buried ice blocks formed a gently undulating landscape with abundant depressions and surface elevations ranging from 480 to 550 m above sea level. Regional uplands are generally covered by second-growth forest (53% of total land area) and contain minimal agricultural or urbanized land cover (Buffam et al., 2011). Between 1895 and 2008, precipitation averaged 81 cm annually and was distributed fairly evenly throughout the year while January and July air temperatures averaged −12 and

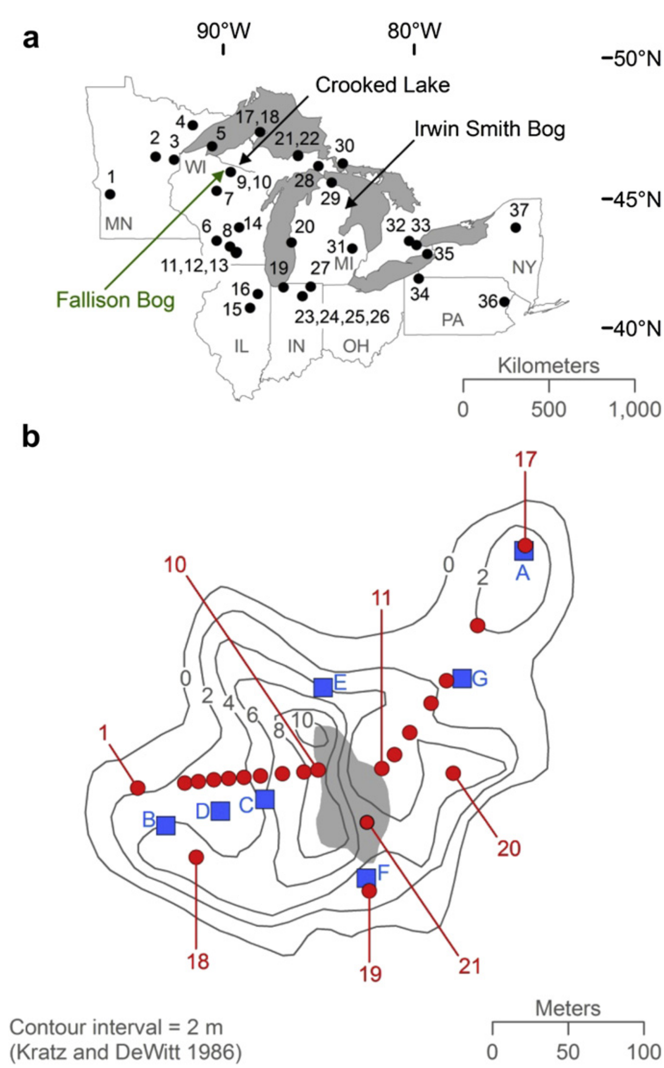

Fig. 1. Regional orientation map and detailed site map of Fallison Bog. **a**. Regional map depicting the locations of the Fallison Bog study site, Crooked Lake (Brugam et al., 1998), Irwin Smith Bog (Booth et al., 2012a,b), and 37 closed-basin peatland sites included in a regional dataset of estimated peatland establishment times (Appendix C). **b**. Detailed map of Fallison Bog basin depicting the location of core samples collected in this study (red circles) and those collected by Kratz and DeWitt (1986) (blue squares). The gray shaded region represents the modern extent of the remnant pond. For clarity, only the first and last core of each transect are labeled, but core identification numbers are sequential. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)