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Hydrogeological controls on post-fire moss recovery in peatlands

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SUMMARY

Wildfire is the largest disturbance affecting boreal peatlands, however, little is known about the controls on post-fire peatland vegetation recovery. While small-scale variation in burn severity can reduce post-fire moss water availability, high water table (WT) positions following wildfire are also critical to enable the re-establishment of keystone peatland mosses (*i.e. Sphagnum*). Thus, post-fire moss water availability is also likely a function of landscape-scale controls on peatland WT dynamics, specifically, connectivity to groundwater flow systems (*i.e.* hydrogeological setting). For this reason, we assessed the interacting controls of hydrogeological setting and burn severity on post-fire moss water availability in three burned, *Sphagnum*-dominated peatlands in Alberta's Boreal Plains. At all sites, variation in burn severity resulted in a dichotomy between post-fire surface covers that: (1) exhibited low water availability, regardless of WT position, and had minimal (<5%) moss re-establishment (*i.e.* lightly burned feather mosses and severely burned *Sphagnum fuscum*) or (2) exhibited high water availability, depending on WT position, and had substantial (>50%) moss re-establishment (*i.e.* lightly burned *S. fuscum* and where depth of burn was >0.05 m). Notably, hydrogeological setting influenced the spatial coverage of these post-fire surface covers by influencing pre-fire WTs and stand characteristics (*e.g.*, shading). Because feather moss cover is controlled by tree shading, lightly burned feather mosses were ubiquitous (>25%) in drier peatlands (deeper pre-fire WTs) that were densely treed and had little connection to large groundwater flow systems. Moreover, hydrogeological setting also controlled post-fire WT positions, thereby affecting moss re-establishment in post-fire surface covers that were dependent on WT position (*e.g.*, lightly burned *S. fuscum*). Accordingly, higher recolonization rates were observed in a peatland located in a groundwater flow through system that had a shallow post-fire WT. Therefore, we argue that hydrogeological setting influences post-fire recovery in two ways: (1) by influencing vegetation structure prior to wildfire, thereby controlling the coverage of post-fire surface covers and (2) by influencing post-fire WT positions. These results suggest that post-fire moss recovery in peatlands isolated from groundwater flow systems may be particularly susceptible to droughts and future climate change.

1. Introduction

The boreal forest accounts for ∼29% of the Earth's forest cover (FAO, 2006) and stores ∼367 to 1716 Pg C (Bradshaw and Warkentin, 2015), primarily in peatlands (Bradshaw and Warkentin, 2015; NWWG, 1997). Wildfire is the largest disturbance affecting peatlands in this zone, areally accounting for >97% of all disturbances in these ecosystems (Turetsky et al., 2002). Although peatland wildfires typically result in complete stand mortality and the die-off of ground layer vegetation (Benscoter and Vitt, 2008; Zoltai et al., 1998), peatlands are generally resilient to wildfire in that they return to a net carbon sink status within ∼20 years post-fire (Wieder et al., 2009). However, given that climate change scenarios suggest that increases in evapotranspiration are likely to exceed increases in precipitation in northern latitudes (Collins et al., 2013), there is concern that peatlands will experience substantial drying (Roulet et al., 1992), thereby increasing their vulnerability to wildfire (Thompson and Waddington, 2013a; Turetsky et al., 2011), and shift to net sources of carbon to the atmosphere (Turetsky et al., 2004).

The potential impact of future drying and shifting wildfire regimes must be weighed against the recovery of peat-forming vegetation. In particular, peatland mosses (*e.g.*, *Sphagnum*) are critical in maintaining ecosystem resilience because of their role as

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ecosystem engineers (van Breeman, 1995) whereby they lower decomposition rates (Rydin et al., 2013), conserve water during drought (Kettridge and Waddington, 2014; Waddington et al., in press), and limit combustion during wildfire (Shetler et al., 2008). Previous studies have provided an understanding of the spatiotemporal patterns of post-fire moss recovery in peatlands (Benscoter, 2006; Benscoter and Vitt, 2008; Wieder et al., 2009); however, the underlying physical processes controlling this recovery have only recently been investigated (Sherwood et al., 2013; Thompson and Waddington, 2013b; Lukenbach et al., in press-a). These studies found that the re-establishment of peatland mosses after wildfire, through repsrouting and diaspores, was primarily dependent on hydrological factors (*i.e.* depth to water table, soil moisture) (Lukenbach et al., in press-a; Kettridge et al., 2015). Specifically, burn severity (*i.e.* depth of burn, the vertical and horizontal spatial extent of burn) affects post-fire hydrological conditions, such as soil moisture (Lukenbach et al., in press-a) and depth to water table (WT) (Kettridge et al., 2015; Sherwood et al., 2013), thereby altering water available to peatland mosses. However, these studies were limited in that they were site-specific, limited in temporal scope, or focused on plot-scale hydrological processes (Lukenbach et al., in press-a; Thompson and Waddington, 2013b). Therefore, there is an immediate need to examine these hydrological controls on post-fire recovery in peatlands at the landscape-scale. Given that hydrogeological setting is a first order landscape-scale control on peatland WTs (Aldous et al., in press; Demers et al., 2013; Devito et al., 2012; Duval and Waddington, 2011; Godwin et al., 2002; Winter, 1999) and has been shown to influence patterns of burn severity in peatlands (Hokanson et al., in press), we hypothesized that hydrogeological setting would also impart a strong control on the post-fire recovery of keystone peatland mosses (*i.e. Sphagnum*).

Hydrogeological setting is defined by both the mineral substrate composition (*i.e.* texture) and topographic position at a particular location on the landscape relative to groundwater (Winter, 1999). Consequently, hydrogeological setting controls peatland connectivity to groundwater flow systems, the magnitude and composition of hydrological fluxes (Winter, 1999), and thus the frequency of low WT positions in peatlands (Duval and Waddington, 2011; Winter et al., 2003). For example, on regional topographic lows in coarse-textured glaciofluvial outwashes, peatlands are commonly located in groundwater discharge zones, resulting in less dynamic and shallow WT positions (Winter, 2000). Because peatlands located in different hydrogeological settings exhibit differences in WT dynamics, hydrogeological setting is linked to peatland vegetation cover (Godwin et al., 2002). This is important because moss species exert a strong control on the spatial extent of burn (*i.e.* depth of burn) (Hokanson et al., in press; Benscoter et al., 2011; Shetler et al., 2008). In peatlands, feather mosses are prone to drying and typically undergo higher depth of burn (DOB) (>0.05 m) (Benscoter et al., 2011), whereas *Sphagnum* mosses (*e.g.*, *Sphagnum fuscum*) are able to efficiently retain water during dry periods and often limit DOB to <0.03 m (Shetler et al., 2008; Thompson and Waddington, 2013a). Such variability in burn severity alters the trajectory of post-fire moss recovery by influencing hydrological conditions, such as depth to WT (Hokanson et al., in press; Lukenbach et al., in press-a,b) and the presence of near-surface (top 0.10 m) water repellency (Kettridge et al., 2014). Indeed, peatlands with higher feather moss cover exhibit lags in post-fire recolonization due to reduced water availability after fire because feather mosses facilitate the development of near-surface water repellency (Kettridge et al., 2014; Lukenbach et al., in press-a). Moreover, because feather moss cover is controlled by canopy closure (*i.e.* shading) prior to fire (Bisbee et al., 2001; Kettridge et al., 2013), peatlands located in hydrogeological settings with lower average WT positions likely contain higher feather moss cover due to enhanced tree growth (Lieffers and Macdonald, 1990) and recruitment (Lieffers and Rothwell, 1986). Therefore, peatlands located in hydrogeological settings that are prone to drying, such as those that have water balances dominated by precipitation inputs (Winter, 2000), may be less resilient to wildfire because higher feather moss cover can both increase burn severity (Benscoter et al., 2011) and limit post-fire recolonization rates (see conceptual model in Lukenbach et al., in press-a).

While hydrogeological setting likely influences post-fire recovery through its control on peatland WT positions, peatlands also possess internal ecohydrological feedbacks that are critical for post-fire moss re-establishment (Waddington et al., in press). The presence of peatland microtopography, a form of self-organized spatial patterning (see Eppinga et al., 2008 for a review of microtopography development), is responsible for some of these ecohydrological feedbacks. In peatlands, species occupy hydrological niches along microtopographic gradients (Rydin et al., 2013) and, as a result, microforms (*i.e.* hummocks and hollows) exhibit differences in their water retention properties (Thompson and Waddington, 2013a). Because hummock species (*i.e. S. fuscum*) retain water more efficiently during drought, DOB is lower in hummocks (<0.03 m) than hollows (Shetler et al., 2008). This variability in depth of burn maintains peatland microtopography over long-time scales (Benscoter et al., in press), which can increase ecosystem stability by increasing habitat heterogeneity (Tilman et al., 2006). This ecosystem stability is further enhanced by ecohydrological feedbacks that affect peatland water balances. For example, while the amount of energy available for evaporation increases after wildfire due to the combustion of the tree canopy (Thompson et al., in press), evaporation and WT drawdowns are limited through the water table depth—moss surface resistance feedback (Waddington et al., in press) where moss surface resistance increases due to a reduction in capillary flow from the deeper WT (Kettridge et al., 2014). While this and other ecohydrological feedbacks are critical in peatlands, the importance of certain feedbacks is dependent on a peatland's hydrogeological setting. In particular, peatlands located in groundwater discharge zones have water balances dominated by groundwater fluxes, thus a post-fire reduction in evaporation is unlikely to affect post-fire WT positions. As such, there is a need to integrate the current understanding of post-fire ecohydrological processes with landscape-scale properties (*i.e.*, hydrogeological setting) to better understand post-fire recovery in peatlands.

Here, we present the first inter-annual, multi-site measurements of post-fire hydrological conditions in peatlands that are linked to landscape-scale properties (*i.e.* hydrogeological setting) in Alberta's Boreal Plain. First, we examined how hydrogeological setting affected post-fire moss water availability. We hypothesized that peatlands located in hydrogeological settings isolated from groundwater sources would exhibit lower post-fire moss water availability due to their deeper and more dynamic WTs. Second, given the strong control that vegetation imparts on post-fire moss water availability and recovery in peatlands (Benscoter and Vitt, 2008; Lukenbach et al., in press-a), we examined how hydrogeological setting affected pre-fire vegetation structure and how this interacted with post-fire hydrological processes (*e.g.*, WT dynamics). We hypothesized that peatlands located in hydrogeological settings that were isolated from groundwater sources would have greater feather moss cover prior to fire (due to tree shading)