Association of postfire peat accumulation and microtopography in boreal bogs[1]

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Abstract: Peatlands accumulate organic matter as peat because of disproportionate rates of production and decomposition. However, peat accumulation heterogeneity has not been well studied along the microtopographic gradient (hummocks vs. hollows), particularly with respect to fire. Fire affects peatland species composition by differentially removing vegetation and resetting succession, resulting in peat accumulation changes. We examined peat accumulation and microtopography in two historically burned bogs in Alberta, Canada. Measurements of current and historic microtopography were made, and cores were collected along the gradient to identify depth of peat accumulated since fire, as well as to assess properties of the accumulated peat. Current microtopography is significant and correlated with the immediate postfire surface relief. However, differences in the magnitude of variability between sites suggests that differential rates of growth between features are exacerbated between sites and reflected in bog microtopography. Rates of organic matter accumulation, ranging from 156 to 257 $g \cdot m^{-2} \cdot year^{-1}$, were elevated but comparable to published rates of recent accumulation. Organic matter content and accumulation rate were greater for hummocks than hollows at Athabasca bog, but the difference between features diminished at Sinkhole Lake, suggesting that the pattern and properties of peat accumulation and microtopography postfire may be attributable to differences in site conditions.

Résumé : Les tourbières accumulent de la matière organique sous forme de tourbe à cause du déséquilibre entre les taux de production et de décomposition. Cependant, l'hétérogénéité de l'accumulation de tourbe n'a pas été bien étudiée le long d'un gradient microtopographique (buttes vs dépressions), particulièrement en relation avec le feu. Le feu affecte la composition des espèces dans les tourbières en éliminant de façon différentielle la végétation et en redémarrant la succession, ce qui se traduit par des changements dans l'accumulation de tourbe. Les auteurs ont étudié l'accumulation de tourbe et la microtopographie dans deux tourbières qui ont déjà brûlé en Alberta, au Canada. Des mesures de la microtopographie actuelle et passée ont été prises et des carottes ont été prélevées le long d'un gradient pour déterminer la profondeur de la tourbe qui s'est accumulée depuis le feu et évaluer les propriétés de la tourbe qui s'est accumulée. La microtopographie actuelle est significative et corrélée avec le relief de surface présent immédiatement après feu. Cependant, les différences dans l'ampleur de la variation entre les sites portent à croire que des taux différentiels de croissance correspondant aux différents éléments de relief sont exacerbés selon le site et reflétés dans la microtopographie des tourbières. Le taux d'accumulation de matière organique, qui variait de 156 à 257 $g \cdot m^{-2} \cdot an^{-1}$, était élevé mais comparable aux taux publiés dans le cas d'accumulations récentes. Le contenu en matière organique et le taux d'accumulation étaient plus élevés sur les buttes que dans les dépressions à la tourbière Athabasca mais la différence entre les éléments de relief diminuait au lac Sinkhole, ce qui indique que le patron et les propriétés de l'accumulation de la tourbe et de la microtopographie après feu sont peut-être dus aux différences dans l'état des sites.

[Traduit par la Rédaction]

Introduction

Bogs, like all peatlands, accumulate organic matter as peat because plant production exceeds decomposition. This is not due to high productivity rates, but to the depression of decomposition through colder temperatures (Clymo 1970; Silvola and Hanski 1979; Kuhry and Vitt 1996; Yu et al. 2001*a*), acidic and anoxic conditions (Clymo 1970; Rochefort et al. 1990; Kuhry and Vitt 1996; Yu et al. 2001*a*, 2001*b*), and the organic chemical compostion of peat-forming mosses (Turetsky 2002). Boreal peatlands sequester an estimated 23 g carbon (C)$\cdot m^{-2} \cdot year^{-1}$ and comprise a worldwide C pool holding 455 Pg C (Gorham 1991), with continental western Canadian peatlands collectively retaining 42 Pg C as peat and an additional 6 Pg C in live vegetation (Vitt et al. 2000). However, these are broad estimates and do not address what may be considerable within-site variability in the processes that lead to peat accumulation (Ohlson and Dahlberg 1991; Ohlson and Økland 1998). Knowledge of the nature of this variability is critical to making accurate assessments of peatland C cycling.

Bogs vary microtopographically, with high hummocks and low hollows with up to 0.5 m in vertical variation (Vitt and Slack 1984; Malmer 1986; Rydin 1986, 1993; Wallen and

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Malmer 1992). Microtopographic variation translates into differences in hydrology within the bog, with hummocks being drier than hollows because of increased distance from the water table (Vitt and Slack 1984; Malmer 1986; Rydin 1986, 1993; Wallen and Malmer 1992). Species that inhabit hummocks must be able to transport, retain, and utilize water more efficiently and resist desiccation to a greater degree than those living in the "water-rich" hollows (Foster 1984; Rydin 1986, 1993; Wallen and Malmer 1992). *Sphagnum fuscum* (Schimp.) Klinggr. is dominant on hummocks in western Canadian bogs, with *Sphagnum magellanicum* Brid. and *Sphagnum angustifolium* (C. Jens. ex Russ.) C. Jens. in Tolf dominating the lower hummocks, lawns, and hollows. The greater water transport and retention capacity of *S. fuscum*, made possible by mutualistic interactions of individuals in dense mats, allows them to survive on the drier hummocks, whereas hollow species (e.g., *S. angustifolium*), whose communities are more loosely arranged, are less able to retain water during drought and therefore are more prone to desiccation.

Peatland plant species have different photosynthetic capacities (Hayward and Clymo 1983; Vitt 1990; Wallen and Malmer 1992), resulting in differential rates of production between species. Rates of decomposition also differ between species, in part because of differences in organic chemical composition (Turetsky 2002). Turetsky (2002) found *S. fuscum* to decompose much more slowly than other peatland species because of a greater proportion of C in recalcitrant compounds (acid-insoluble material). The balance between production and decomposition results in different rates of peat accumulation for individual moss species, such that spatial accumulation differences can be related to local species dominance (Ohlson and Økland 1998). When site conditions also are factored in, production and decomposition rates are further complicated. Drier conditions result in decreased production and increased decomposition, whereas anoxic conditions created by water saturation decrease decomposition rates while increasing water availability for biomass production (Hayward and Clymo 1983; Vitt 1990; Wallen and Malmer 1992). Therefore, peat accumulation rate is a function of not only species characteristics, but also site and microsite conditions.

Wildfire is an important and prevalent factor affecting boreal peatlands. Turetsky et al. (2002) estimated that 1470 ± 59 km^2 of peatlands burn annually in continental western Canada (Alberta, Saskatchewan, Manitoba), releasing 3.1 ± 0.5 Tg C·year^{-1} to the atmosphere (Benscoter and Wieder 2003). However, combustion during fire is variable through bog peatlands, with hollows and lawns exhibiting greater combustion than hummocks (Benscoter and Wieder 2003), most likely because of differences in water retention ability between moss species characteristic of the respective features. Differences in burn severity influence the vegetation succession trajectory (Benscoter et al. 2005) and alter the microtopography of the affected bog. Benscoter et al. (2005) found hummocks to return to *S. fuscum* dominance and resume prefire conditions more quickly and consistentaly than hollows, which represent earlier successional stages and have a more variable recovery trajectory, therefore prolonging compositional and functional recovery. If less severely burned hummocks exhibit faster vegetation recovery to prefire conditions, then peat accumulation should return faster than in hollows, resulting in greater postfire accumulation on hummocks, at least early on after fire. However, as time increases after fire, successional changes, inherent differences between moss species in production and decomposition, and differences in peat properties (i.e., bulk density, organic matter content) between hummocks and hollows may modify the influence of microtopographic position and vegetation composition on peat accumulation and bog C cycling.

To assess if differences in postfire peat accumulation exist along the microtopographic gradient, we examined two historically burned bogs in Alberta, Canada. Peat accumulation is dependent on vegetation composition and successional trajectory, which are dependent on fire severity and are reflected in bog microtopography. Total peat accumulation should be lower in hollows at shorter time intervals because of more severe combustion and longer successional trajectories, but over time, greater rates of accumulation in established hollows relative to hummocks should result in almost equal postfire peat accumulation.

Materials and methods

Site selection

Our goal was to identify two historically burned ombrotrophic bog sites. Candidate sites were identified by overlaying peatland distribution maps (Vitt et al. 1996) and maps showing historical fire occurrence (Delisle and Hall 1987) to locate areas with a high incidence of ombrotrophic bogs within a historical fire perimeter, followed by aerial photograph examination (Alberta Sustainable Resource Development Air Photo Services, Edmonton, Alberta) to identify bog landforms that exhibited evidence of fire occurrence by the presence of visibly identifiable fire scars. Visual inspection of a "test peat core" was used to identify the occurrence of previous fire at the sites, as indicated by the presence of a charcoal or ash layer at a depth reasonable for 40–60 years of peat accumulation (30–50 cm).

Upon field verification, two suitable sites were chosen: Sinkhole Lake and Athabasca bog. Both sites exhibited present-day microtopographic variation, evidence of a past fire, and at least 20 cm of peat accumulation since the most recent fire. Sinkhole Lake (53°19′N, 115°13′W) is an ombrotrophic bog bordered by a large nonpatterned fen located approximately 120 km WSW of Edmonton, Alberta. According to historical fire records, this bog burned in a 1942 fire (Delisle and Hall 1987) that affected the entire bog landform, resulting in a relatively dense, even-aged stand (48–51 years based on tree ring analysis) of *Picea mariana* (Mill.) BSP. Hummocks are dominated by *S. fuscum*, with hollows composed of various lichens, true mosses, and wet-loving *Sphagnum* mosses (i.e., *S. angustifolium*). Test cores from hummocks showed a distinct charcoal layer around 25–30 cm from the surface, a depth consistent with approximately 60 years of postfire peat accumulation (cf. Turetsky et al. 2000).

Athabasca (54°43′N, 113°10′W) is a smaller bog also surrounded by a large nonpatterned fen located approximately 5 km east of Athabasca, Alberta, and 120 km north of Edmonton. Although exact records of a fire in this area are not available because of the small areal extent of the fire (<200 ha), there was evidence that a fire occurred in this landform more recently than at Sinkhole Lake based on a younger (28–32 years based on tree rings), less dense *P. mariana* stand and a charcoal layer depth of around 15–20 cm from the surface in hummock test cores, placing the time of fire approximately 40 years before present based on an expected 10-year postfire reestablishment lag for *P. mariana* (Zoltai et al. 1998). Like Sinkhole Lake, hummocks are dominated by *S. fuscum*, and hollows vary in composition from lichens to *S. angustifolium*.

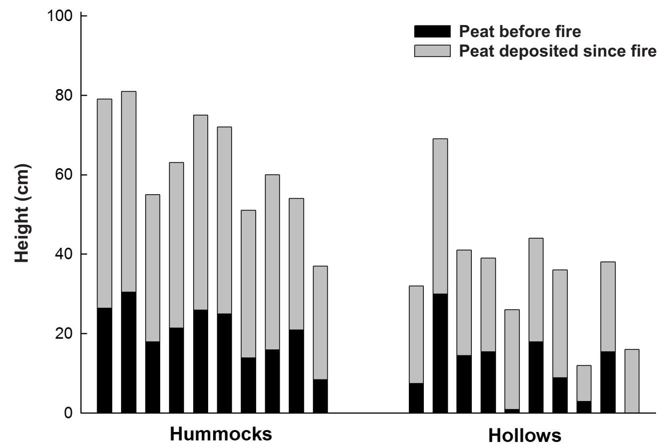
Experimental design

One randomly situated transect was established at the Sinkhole Lake and Athabasca bog sites with 10 plots positioned along each transect. Transects were positioned through the center of the bog, and two random numbers were used to designate the north–south and east–west positions of the random sampling points along the transects to maximize coverage of the entire bog. At each sampling point, a 0.5 m × 0.5 m plot was established on the nearest hummock and hollow. To quantify the vertical variation between hummocks and hollows, a level horizontal reference line was established along the transect using a rotating laser level. Measurements of deviation from this reference line to the vegetation surface were made for each plot (distance from set elevation, DSE). The difference between the hollow and hummock DSE represents the vertical variation at a particular sampling point, while the difference between DSE values of the respective microtopographic features across the entire transect represents the microtopographic variation throughout the site. For comparisons between sites, relief measurements were standardized by referencing them relative to the highest feature within the site.

Peat accumulation since the most recent fire was assessed by collecting a 10-cm diameter soil core from each subplot to a depth of 50 cm using polyvinyl chloride (PVC) pipe. Cores were frozen, followed by visual inspection to locate the most recent charcoal horizon through macrofossil analysis (see Benscoter et al. 2005 for vegetation analyses). The frozen cores were cut into 1-cm sections, dried at 65 °C for 72 h, weighed, homogenized using a Cyclotec sample mill (Foss Tecator, Inc., Eden Prairie, Minnesota), and organic matter content was determined by percent loss on ignition of an approximately 0.2-g subsample of each section at 450 °C for 4 h (Turetsky and Wieder 2001), combusting all organic C. Percentage of organic matter was multiplied by the section dry mass to give a measurement of organic matter content for the entire 1-cm section, which was summed by core for all sections above the most recent charcoal horizon to determine total organic matter accumulation since fire (OM). The overall rate of organic matter accumulation (OMR) since fire was determined by dividing the total accumulated organic matter by the time since fire (Sinkhole Lake, 60 years; Athabasca, 40 years). One-way ANOVAs were performed to assess variation in total organic matter accumulation since the most recent fire between sites and their respective microtopographic features, as well as variation in the overall rate of postfire peat accumulation.

Two-way ANOVAs were used to assess variation in microtopographic position of the current vegetation surface and corresponding position of the most recent charcoal layer (CHAR), as well as the depth of peat accumulated since the most recent fire for each subplot. Spearman's ranked correlation was used to assess the relationship between current and historic microtopographic position (DSE vs. CHAR, respectively). To determine if current microtopographic relief was more variable than on the immediate postfire landscape, the variance ratio test was used to compare the variance in DSE and CHAR for each site.

Fig. 1. Microtopographic position of the immediate postfire surface and current surface for hummocks and hollows (n = 10) from Athabasca bog. Top of black bar indicates position of charcoal layer, grey bar indicates postfire column depth, and top of grey bar indicates current surface position. Measurements were made from a uniform elevation above the surface and standardized relative to the lowest point of the charcoal horizon.



Bulk density (BD) was determined for each core at 1-cm depth intervals by dividing the section dry mass by the section volume (78.5 cm^3). Mean bulk density of the portion of the collected core above the most recent charcoal horizon was plotted for hummocks and hollows within each site, and a two-way ANOVA was performed to detect any variation between features within and between sites.

Results

A high degree of present-day microtopographic variability was found at each site (Figs. 1 and 2), with hummocks being 22 ± 9 cm higher, on average, than hollows (F = 78.85, df = 1, 34, p < 0.001; Athabasca 18 ± 9 cm higher; Sinkhole Lake 26 ± 9 cm higher). Significant historic microtopographic variability was found as well, with the charcoal horizon under current hollows being 9 ± 8 cm deeper from the surface than under current hummocks (F = 12.96, df = 1, 34, p = 0.001). Present and historic microtopographic positions were highly correlated (r = 0.79, p < 0.001), with historically low microtopographic positions being preserved in the present surface (Fig. 3). While no significant difference in historic versus current microtopographic relief was detected within features or within Athabasca bog, current microtopographic variability was significantly greater than immediately postfire in Sinkhole Lake (F = 2.39, df = 17, 17, p = 0.042).

Mean peat column depth above the most recent charcoal horizon was consistently greater for hummocks than for hollows at both sites (F = 55.73, df = 1, 34, p < 0.001; Fig. 4*a*).

Fig. 2. Microtopographic position of the immediate postfire surface and current surface for hummocks and hollows (n = 9) from Sinkhole Lake bog. Top of black bar indicates position of charcoal layer, grey bar indicates postfire column depth, and top of grey bar indicates current surface position. Measurements were made from a uniform elevation above the surface and standardized relative to the lowest point of the charcoal horizon. Note: The hummock and hollow cores from plot 3 were excluded because a reliable charcoal horizon was not identified.

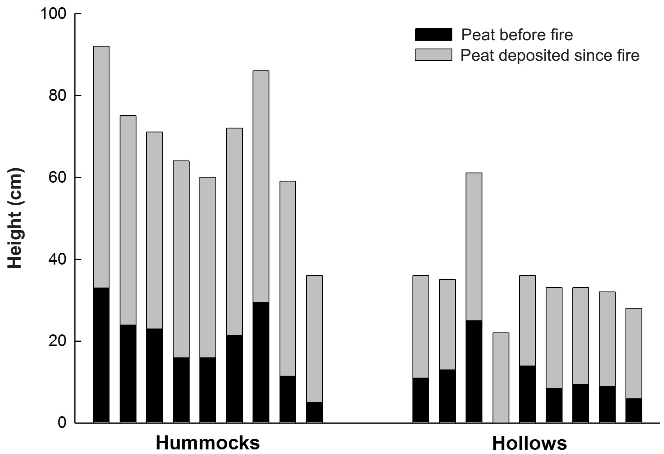
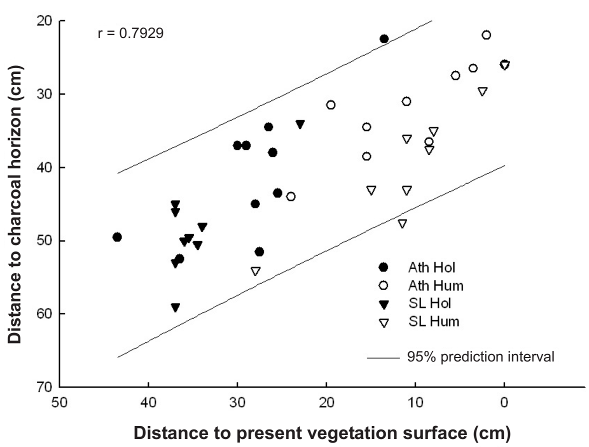


Fig. 3. Relationship between present microtopographic position and charcoal horizon position relative to a uniform elevation for 10 hummocks (hum) and hollows (hol) from Athabasca (Ath) and Sinkhole Lake (SL) bogs. Elevations standardized relative to the highest position along transect. Note: Two cores (a hummock and hollow) from Sinkhole Lake bog were excluded because a reliable charcoal horizon was not identified.



Bulk density, while not significantly different between features at Athabasca (Fig. 4*b*), showed the inverse at Sinkhole Lake, with the peat above the charcoal horizon from hollows having a greater mean bulk density than peat from hummocks (site × feature: F = 78.10, df = 1, p < 0.001). Mean total organic matter in the accumulated peat showed a significant site × feature interaction (F = 7.81, df = 1, p = 0.009). Athabasca hollows had significantly less organic matter accumulation above the most recent fire horizon than any other feature (Fig. 4*c*). A similar site × feature interaction was found for the overall net rate of organic matter accumulation since fire (F = 5.70, df = 1, p = 0.023), with Athabasca hollows having a lower accumulation rate than hummocks (161 ± 27 $g \cdot m^{-2} \cdot year^{-1}$ and 257 ± 23 $g \cdot m^{-2} \cdot year^{-1}$, respectively; Fig. 4*d*), although hollows and hummocks at Sinkhole Lake did not have significantly different rates of accumulation (188 ± 28 $g \cdot m^{-2} \cdot year^{-1}$ and 156 ± 15 $g \cdot m^{-2} \cdot year^{-1}$, respectively).

Discussion

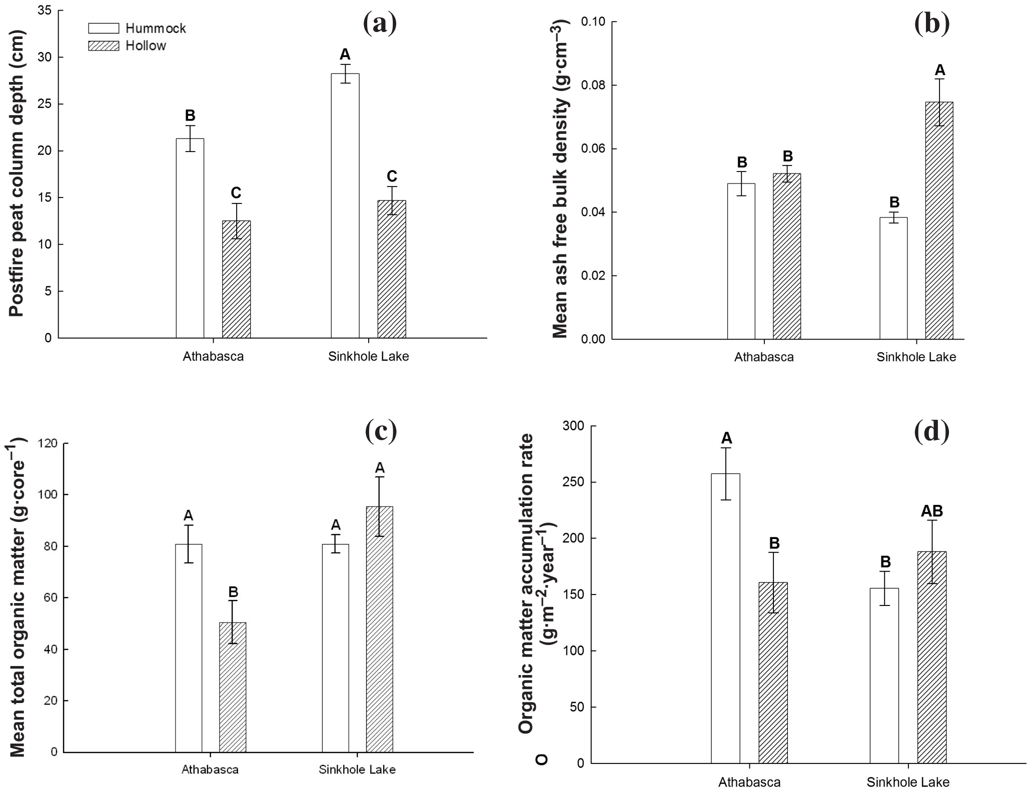
While many studies have examined long-term rates of organic matter or C accumulation in peatlands (Reader and Stewart 1972; Alm et al. 1993; Botch et al. 1995; Pitkanen et al. 1999; Turunen 1999), few have addressed recent accumulation rates or variability between microtopographic features. Turetsky et al. (2000) found average recent rates of organic matter accumulation from Canadian bogs of 100 $g \cdot m^{-2} \cdot year^{-1}$ over the last 100 years, which were within the range observed by Ohlson and Økland (1998) in Norwegian bogs averaged over the last 125 years (40–200 $g \cdot m^{-2} \cdot year^{-1}$). Alm et al. (1993) also found comparable average accumulation rates in Finland (162 $g \cdot m^{-2} \cdot year^{-1}$) corresponding with 180 years of accumulation. However, while comparable to the accumulation observed in this study, these previous estimates use dating methods (radiocarbon dating and dendrochronology), and their inherent margins of error, for determining the period of accumulation. Use of the charcoal horizon as a chronostratigraphic marker is a far more reliable dating technique at short time intervals, provided that fire occurrence records are available.

Combustion during fire is variable (Kuhry 1994; Zoltai et al. 1998), with some areas experiencing extensive combustion while others are only lightly burned, if at all. During the 2001 Chisholm, Alberta, fire, Benscoter and Wieder (2003) showed hollows to burn more intensively, on average, than hummocks. Severe disturbance increases the time required for vegetation and function to recover to prefire conditions, placing intensively burned hollows at a functional disadvantage.

For peat accumulation to recommence postfire, vegetation must become reestablished. However, the postfire successional trajectory varies along the microtopographic gradient. Benscoter et al. (2005) showed postfire vegetation changes to be dynamic and unpredictable in hollows, whereas hummocks had consistent and relatively quick returns to *S. fuscum* dominance postfire. As peat accumulation rates are species specific and dependent on vegetation return, hummocks surviving fire are capable of accumulating peat earlier than hollows, resulting in greater peat accumulation on hummocks at short postfire intervals.

Hollows, from a vegetation standpoint, represent an early succession environment and require more time to reach a community composition capable of significant peat accumulation (Benscoter et al. 2005). This reestablishment lag may be responsible for diminished organic matter content and column depth soon after fire. Greater decomposability of hollow species, particularly early successional species, also

Fig. 4. Bar graphs of mean peat column depth (*a*), mean bulk density (*b*), mean total organic matter content (*c*), and mean overall organic matter accumulation rate (*d*) for hummocks and hollows from two bogs in Alberta, Canada. Values are means ± SE. Bars with different letters are significantly different (comparison-wise α = 0.05) based on LSD a posteriori comparisons.



may contribute to lower peat accumulation as well as greater bulk densities.

A quick return to prefire conditions is most likely responsible for the greater column depths and peat accumulation observed in hummocks of Athabasca bog (40 years since fire) compared with hollows. Slower decomposition of *S. fuscum* (Rochefort et al. 1990; Turetsky 2002) accounts for the lower bulk densities in hummocks than in hollows and further promotes greater column depths through maintenance of interstitial spaces and physical integrity of the peat. This is not evident in Sinkhole Lake bog (60 years since fire) where extensive regeneration and succession has occurred, allowing the hollows to compensate for their reestablishment time lag through greater productivity. As succession proceeds, species such as *S. angustifolium*, which has much higher production rates than *S. fuscum* (Vitt and Slack 1984; Rochefort et al. 1990; Vitt 1990), become established in the hollows, while the *S. fuscum* hummocks become more and more water limited because of vertical accumulation (Vitt 1990), slowing the rate of hummock productivity. Presumably by 60 years since fire, the accumulation rate in hollows has increased and in hummocks has decreased to a point intermediate between their 40 years since fire rates, resulting in equal amounts of accumulated peat between features. Ohlson and Dahlberg (1991) found similar results in Swedish mires, in which hummock peat accumulation exceeded hollows in mires less than 50 years old, but the difference in accumulation between features decreased with age.

While the immediate postfire landscape is not devoid of microtopography, the current relief has a greater range for both sites. In general, the immediate postfire microtopography was maintained to present, as evidenced by the strong correlation between current and historic microtopographic position, but the degree of variability in the current surface relative to the postfire surface increased in Sinkhole Lake, suggesting that the greater recovery time has allowed for greater magnitude in microtopographic relief. This is supported by the greater column depth observed on Sinkhole Lake hummocks compared with their corresponding hollows or features from Athabasca bog.

We conclude that the pattern of peat accumulation after fire is topographical, and hence species dependent, and therefore changes over time as succession occurs. The rate of change is dependent on local fire severity and its effect on vegetation composition and succession. Therefore, maintenance of microtopography is controlled by succession, as microtopography is the end result of differential degrees of peat accumulation based on variability in species composition. As succession proceeds, patterns of net peat accumulation become more homogenous, although the microtopographic gradient is maintained because of differences in the physical properties of the accumulated peat. Given an extended disturbance-free period, the microtopographic gradient may be reduced or eliminated through the establishment of uniform plant community composition, although this is highly unlikely because of the frequency of disturbance, particularly wildfire (cf. Zoltai et al. 1998). Therefore, understanding patterns in microtopography and peat accumulation requires not only knowledge of the present community structure, but also the current successional stage of the bog.

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