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Fire pattern in a drainage-affected boreal bog

Tiina Ronkainen[1)2)]*, Minna Väliranta[1)] and Eeva-Stiina Tuittila[2)3)]

[1)] *Environmental Change Research Unit (ECRU), Department of Environmental Sciences, P.O. Box 65, FI-00014 University of Helsinki, Finland (corresponding author's e-mail: tiina.m.ronkainen@helsinki.fi)*
[2)] *Peatland Ecology Group, Department of Forest Sciences, P.O. Box 27, FI-00014 University of Helsinki, Finland*
[3)] *current address: School of Forest Sciences, University of Eastern Finland, P.O. Box 111, FI-80101 Joensuu, Finland*

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Similarly to drainage caused by land-use change, the predicted climate warming may cause a moderate water-level drawdown in northern peatlands due to increased evapotranspiration. This is likely to alter the frequency and severity of peatland fires. We surveyed the fire pattern in drainage-affected and unmanaged parts of a boreal raised bog using three sampling transects reaching from drainage-affected area to an unmanaged bog area. Throughout the bog, dry hummock surfaces provided spreading routes for fire while hollows remained intact. Drainage promoted succession that lead to the dominance of hummock vegetation close to the drained area. Consequently, drainage succession favoured fire. The results suggest an increase in fire impact as a consequence of lowered water levels. In warmer climate with increased evapotranspiration bogs are likely to become more vulnerable to fires.

Introduction

Fires are an important natural disturbance element throughout the boreal zone, especially in the forested areas. In Siberia, Canada and Alaska, 10–15 million hectares are estimated to burn annually (Flannigan *et al*. 2009, Turetsky *et al*. 2011). Warm and dry weather conditions, and abundant fire fuel availability, i.e. dry or dead plant material, favour fire occurrence (Reinhardt and Holsinger 2010). In the future, under a predicted warmer climate, possibly introducing extreme and prolonged seasonal droughts (IPCC 2007), more severe and frequent fires may occur in boreal regions (Flannigan 2006).

Although peatlands are naturally wetter ecosystems than forests they are frequently affected by wild fires (Foster and Glaser 1986, Pitkänen *et al*. 1999, Sillasoo *et al*. 2011). Fire-susceptibility differs among different types of peatlands, depending on the fire fuel loading and moisture conditions (Flannigan *et al*. 2009). Peatland fires are globally a significant source of direct carbon emissions to the atmosphere. Total peat combustion in North America is estimated to be nearly 10 Tg C year^{-1} (Zoltai *et al*. 1998) while in an individual peatland, carbon loss can be of the order of 3 kg m^{-2} per fire event (Pitkänen *et al*. 1999, Benscoter and Wieder 2003). Following a fire event, peatlands can act as a net carbon source for around the next ten years, i.e. until the vegetation recovery process returns the peatland to a net carbon-sink state (Wieder *et al*. 2009).

Raised bogs are peatlands that typically rise above the surrounding landscape and are surrounded by forested margins. In northern Europe,

Editor in charge of this article: Jaana Bäck they are characterized by distinct microhabitat forms: dry hummocks (surface 20–50 cm above the water table), intermediate lawns (5–20 cm above the water table) and wet hollows where the water table is at the surface (Rydin *et al.* 2006). Hummocks support dwarf shrubs, lichens and *Sphagnum* species (e.g. *S. fuscum* and *S. capillifolium*) able to grow well above the water-table level due to their proficient capillary water transport, while in hollows, there are only few vascular plant species and surfaces are characterized by *Sphagnum* species (e.g. *S. cuspidatum* and *S. majus*) lacking the water transport trait. Lawns are intermediate habitats which can support both hummock and hollow plant species (Rydin *et al.* 2006, Laine J. *et al.* 2009).

Study results from the northeastern coast of Canada demonstrated that bog fires proceed along the dry hummocks, burning the lichen cover and killing the above-ground portion of vascular plants, while ground layer Sphagna are killed by heat rather than by burning *per se* (Foster and Glaser 1986). In contrast to this pattern, Benscotter and Wieder (2003) reported from continental bogs of Canada, that the most severe fire damage occurred on hollows while hummocks were only lightly scarred or remained intact. This pattern was explained by the high water retention capacity of hummocks and the dryness of the hollows after a prolonged period of dry weather.

In the long term, climate change, with warmer climate associated with possible changes in effective moisture conditions, is expected to have an impact on peatlands (Moore 2002). In northern peatlands, climate warming has been predicted to cause a moderate water-level drawdown due to increased evapotranspiration (Roulet *et al.* 1992) which, in turn, promotes succession towards drier vegetation (Laine *et al.* 1995, Moore 2002). Increased amount of dry vegetation alter the loading of fire fuel and sufficiency of peatlands in supporting combustion. Therefore, depending strongly on future spatial and temporal changes in precipitation regimes, climate induced drying may increase frequency and severity of fires in boreal peatland (Camill *et al.* 2009) leading to increased carbon release to the atmosphere and altered internal carbon dynamics (Zoltai *et al.* 1998, Lavoie *et al.* 2005, Turetsky *et al.* 2011).

The existing knowledge on pristine peatland fires agree that the distinct bog microtopography leads to uneven spatial fire patterns (Foster and Glaser 1986, Benscotter and Wieder 2003, Benscotter *et al.* 2005, Ohlson *et al.* 2006). However, studies comparing fire patterns between natural and drained mire conditions are so far lacking. Also, as far as we know, the knowledge on fire patterns in northern Europe is based only on palaeoecological studies with small spatial resolution.

In this study, we aimed to compare fire patterns on unmanaged bog surface *vs.* drainage-affected bog surface in a relatively maritime climate region where bogs have conspicuous microtopography. We hypothesized that drainage increases fire intensity through altered water-table level (WT) and consequent change in vegetation. Because drainage can simulate possible future changes in vegetation caused by changes in effective moisture conditions (Laine *et al.* 1995, Strack *et al.* 2004, Riutta *et al.* 2007, Chivers *et al.* 2009, Laine A. *et al.* 2009), we use results to discuss the impact of warming climate on fire intensity.

Material and methods

Study site

The study site was located in western-central Finland in the Siikajoki commune (64°34´N, 25°20´E). Studied peatland was a patterned raised bog, with a variety of microtopographical features: hummocks, lawns, and hollows. The southern side of the peatland complex was under peat extraction. Ditching of the area was carried out in the mid-1980s and most of the peat in the extraction site had already been mined and therefore extraction area lies at a lower level than the neighbouring unmanaged area (Fig. 1). Next to the studied area was a bordering ditch with a peat bank which were located between the extraction area and unmanaged area. These constructions prevent horizontal seepage from the unmanaged peat body to the peat extraction area.

In May 2009, a human-induced fire spread out to the surrounding forest, peat extraction field, and to the unmanaged part of the raised bog. We conducted the survey in August 2009 two months after the fire. Water tables at the site were measured in August 2009 and once in July 2010. No data was collected from the studied site before the fire.

Weather conditions

The mean May temperature in 2009 was two degrees higher than the long-term May average (Table 1). Prior to the fire, the monthly May precipitation was similar to the long-term average. However, the weather conditions during the previous four months (January to April) were drier than the long-term average. From January to April 2009, the precipitation was three quarters of the long-term average and the mean temperature was a half a degree higher than the long-term average. Also, there were small differences in weather conditions between the years 2009 and 2010. The period January–August in 2010 was wetter and colder. The weather conditions differed between the WT measuring months: August 2009 was wetter and colder than July 2010 (Table 1).

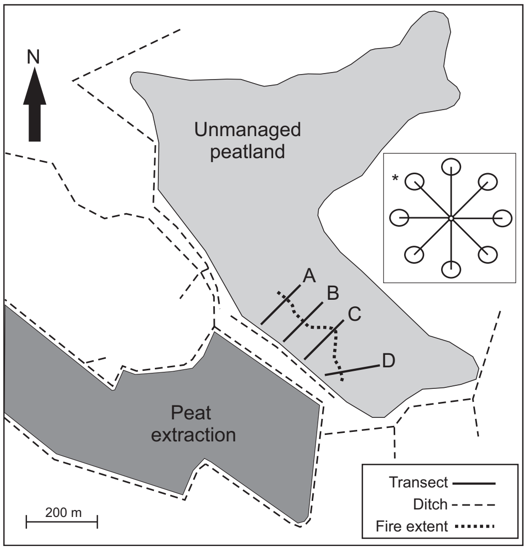

Fig. 1. The map of the peatland area, drainage ditches, sampling transects A, B, C and D and estimated fire extent at transects. Surrounding area is mainly drained peatland forest. Most peat deposit has been already extracted and peat extraction area lies in a lower position than the unmanaged peatland and its surroundings. * = sampling cluster of eight circle shape sample points (diameter 30 cm) situated two metres apart from the water table well in the middle.

Sampling

To define the fire pattern, and the impact of fire on vegetation under drainage-affected and unmanaged conditions of the bog, we established three 160-m-long survey transects (A, B and C) 80 m apart from each other. The transect length was selected so that each transect comprised at least one unburned sampling point. The transects started at the vicinity of the closed ditch and continued towards the centre of the non-managed part of the peatland. To avoid sampling on the ditch bank, the first sampling points (0 m) of

Table 1. Temperature and precipitation in 2009, 2010 and 1971–2000. Source: Finnish Meteorological Institute weather station Ruukki–Revonlahti, 64°43´N, 24°58´E.

	Temperature (°C)			Precipitation (mm)		
Month	1971–2000	2009	2010	1971–2000	2009	2010
January	–9.4	–8.0	–14.6	35.5	25.4	10.9
February	–9.0	–9.0	–12.3	26.0	34.2	41.0
March	–4.4	–4.3	–6.6	26.7	14.1	66.7
April	1.0	1.3	2.6	24.0	10.1	37.1
Average	**–5.5**	**–5.0**	**–7.7**	**28.1**	**21.0**	**38.9**
May	7.6	9.7	10.9	35.4	39.2	33.5
June	13.1	13.0	12.1	51.9	14.0	34.5
July	15.5	15.3	18.6	68.6	67.1	59.4
August	13.0	14.5	13.6	72.1	77.0	71.7

each transect were established 10 m away from the ditch nearby.

In order to describe the characteristic habitat-specific bog vegetation in the unmanaged part of the studied bog, we established one additional 160-m-long transect (D) outside the area affected by the fire (Fig. 1). Due the extent of the fire, we were forced to use the partly burned sampling points and the remains of the burned plants for the description of the drainage-affected area.

All transects (A, B, C and D) included nine sampling clusters situated every 20 metres along the transects. Each cluster formed a sample plot where eight sampling points were situated to cardinal and half-cardinal points at a two metres distance from the centre. According to the micro-topography, each sampling point (0.07 m^2 with diameter of 30 cm) was described as a hummock, lawn or hollow. Vegetation of sampling points was surveyed by estimating the projection cover of each plant species using on a scale 0%–100%. The fire intensity of the sampling points was estimated separately for ground and field layers by using the following scale: burned = no identifiable plant parts, scorched = plants still recognisable but parts of the plants burned, mosses up most part burned, unburned = all plants recognisable, nothing burned.

To define the extent of the area impacted by the drainage, we measured water-table level (WT) in relation to the moss surface from wells established in summer 2009. We express WT below the moss surface as negative. Wells (1-m long and 2 cm in diameter plastic pipes) were installed into the peat in the centre of each sample plot, regardless of the differences in microtopography between the plots. WT was measured in each well once at the end of July 2009 and once at the beginning of August 2010. We also measured the relative altitude of the centre of each sample plot, to define whether the surface of the bog had compressed due to drainage. Furthermore, the number of trees within a three-metre radius from the centre of the plot was counted in each sample plot, to support the division of the study site into drainage-affected and non-managed parts. Trees were divided into two height groups: < 1.3 m and > 1.3 m. The basal area of the trees was estimated using the sampling method described in Eid (2001).

Data analyses

Normality of the data was assessed by evaluating skewness and kurtosis, and with Shapiro-Wilk's *W* test (SPSS ver. 19). Since the distributions proved normal, to evaluate how far from the ditch the effect of drainage can be detected, we compared mean WT among the sample plots during the two measurement years using repeated measures ANOVA followed by Tukey's post-hoc test (PASW Statistics 18). The relative altitude of surface and the number of trees were compared between the sample plots using one-way ANOVA.

We used the WT results to divide the bog into drainage-affected and unmanaged parts. Altitude and tree frequency data were used for supporting the decision. The proportion of different micro-habitats and the fire intensity in different micro-habitats were calculated as a mean of the three transects (A, B and C) in the fire-impacted area. To test the hypothesis that drainage increases fire intensity through altered water table level (WT) and consequent change in vegetation, we compared microhabitat distribution and fire intensity between drainage-affected and unmanaged area with a chi-square (χ^2) test (SPSS ver. 19) that does not have assumptions regarding normality of the data (Dytham 2011).

Results

Division of the drainage-affected and unmanaged area

As expected, distance from the ditch had an impact on WT (repeated measures ANOVA: $F_{8,27} = 10.009$, $p < 0.001$). According to Tukey's post-hoc test, WT was significantly lower ($p < 0.05$) at sample plots located closest to the ditch (0 m) as compared with that at the rest of the plots (Fig. 2). Neither WT of the sample plots, nor the effect of distance differed between the years 2009 and 2010 ($F_{1,27} = 0.786$, $p = 0.383$; and $F_{8,27} = 0.417$, $p = 0.900$; respectively). Peat close to the ditch had been compressed due to the drainage (one-way ANOVA: $F_{8,27} = 3.155$, $p = 0.012$). According to Tukey's post-hoc test, sample plots 0 and 20 were located significantly lower ($p < 0.05$) than plots 40–160.

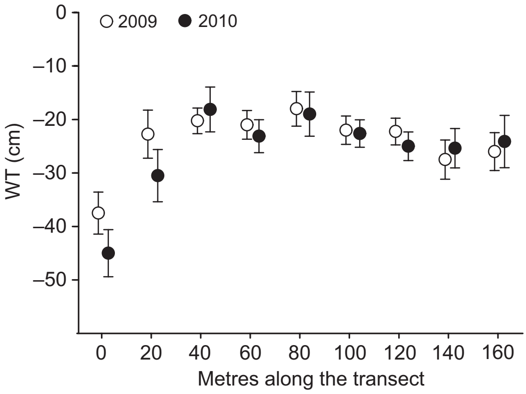

Fig. 2. Mean ± SD summer 2009 and 2010 water-table depths at the sampling points along the transects; $n = 8$.

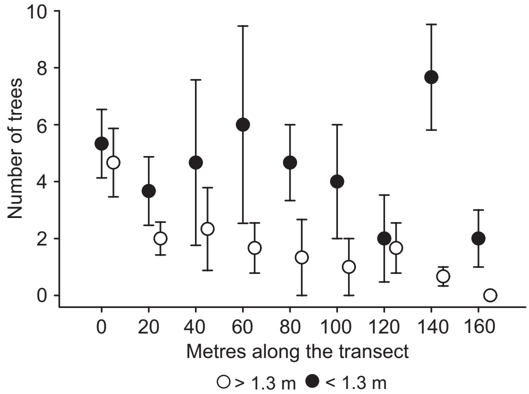

Fig. 3. Average ± SD number of trees per sample plot (trees > 1.3 m and seedlings < 1.3 m); $n = 4$.

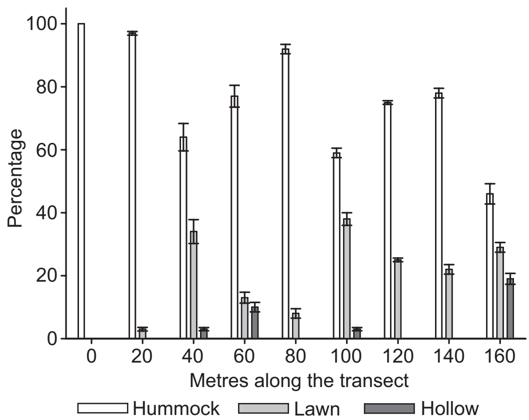

Fig. 4. Mean coverage ± SD of different microhabitats along the three transects in the peatlands impacted by fire (A, B and C); $n = 32$.

The only tree species present was pine (*Pinus sylvestris*), whose basal area at each sampling point was less than 1 m^2 per hectare. Although there was no pattern in the number of tree seedlings (< 1.3 m in height), the number of taller trees (> 1.3 m in height) was highest in the vicinity of the ditch (Fig. 3) although the difference was not significant ($p = 0.229$). The difference between WT, the relative altitude and the density of taller trees were used as a basis to divide the bog into two different parts: drainage-affected area, including the first sample plots (at 0 m), and unmanaged areas, including the rest of the sample plots (20–160 m).

Microhabitat distribution and vegetation composition

First sampling points (0 m) of transects were in the drainage-affected area; as hypothesised they were strongly altered in comparison with the unmanaged part ($\chi^2_2 = 13.371$, $p = 0.001$) being purely covered by hummocks (Fig. 4). Although hummocks dominated also in the unmanaged part of the peatland, lawns appeared already at the second-sample-plot distance (20 m), which was the first sample plot in the unmanaged area. Hollow microhabitats appeared in the third sample plot (40 m). Hollows were most abundant in the last sample point (160 m) closest to the centre of the unmanaged bog (Fig. 4).

In the unmanaged bog area, the most common bryophyte species in hummocks were *S. fuscum* and *S. angustifolium* (Table 2). Hummocks were characterised by sparse layer of dwarf shrubs such as *Andromeda polifolia* and *Empetrum nigrum*. In lawns, the most common bryophyte species was *S. balticum*. *Andromeda polifolia* and *Eriophorum vaginatum* were dominant in the field layer. Hollows were dominated by *S. majus*, and the vascular-plant coverage was scarce.

In the drainage-affected area, the ground-layer vegetation was severely burned but traces of *Digranum* spp., *Cladonia* spp. and *Pleurozium shcreberii* were detected. The field layer was dominated by *Vaccinuim uliginosum* (max. 10%), *Myrica gale* and *Betula nana* and burned remains of *Empetrum nigrum* and *Eriophorum vaginatum* were also detected.

Impact of fire

In agreement with our hypothesis, fire frequency was higher in the drained than in the unmanaged area (χ^2_1 = 35 839, p < 0.001). The hummock vegetation covering the drainage-affected area suffered most from the fire: over 60% of the ground and field layers were burned (Fig. 5). In addition to the completely burned area, about a third of the field and ground layers were scorched. No unburned field layer surfaces remained and only 8% of the ground layer remained unburned.

Table 2. Mean vegetation coverage ± SE (%) (showing plants over 1% coverage) in different microhabitats in the unburned area of the bog.

	Mean vegetation coverage ± SE (%)
Hummocks (n = 25)	
Sphagnum angustifolium	28 ± 5
Sphagnum fuscum	23 ± 6
Mylia anomala	8 ± 2
Sphagnum balticum	8 ± 2
Sphagnum magellanicum	5 ± 2
Cladina arbuscula	1 ± 1
Dicranum bergeri	1 ± 0
Andromeda polifolia	2 ± 0
Rubus chameamorus	2 ± 0
Empetrum nigrum	1 ± 0
Eriophorum vaginatum litter	1 ± 0
Myrica gale	1 ± 0
Vaccinium oxycoccos	1 ± 0
Drosera rotundifolia	1 ± 0
Lawns (n = 38)	
Sphagnum balticum	37 ± 4
Sphagnum angustifolium	28 ± 5
Sphagnum magellanicum	7 ± 2
Sphagnum majus	6 ± 3
Mylia anomala	5 ± 1
Cladina rangifera	1 ± 1
Sphagnum fuscum	1 ± 0
Andromeda polifolia	2 ± 0
Eriophorum vaginatum litter	1 ± 0
Rubus chameamorus	1 ± 0
Eriophorum vaginatum living	1 ± 0
Drosera rototundifolia	1 ± 0
Vaccinium oxycoccos	1 ± 0
Hollows (n = 6)	
Sphagnum majus	53 ± 13
Sphagnum balticum	26 ± 12
Sphagnum magellanicum	3 ± 2
Andromeda polifolia	2 ± 0
Schuezeria palustris litter	1 ± 0
Eriophorum vaginatum litter	1 ± 0

In contrast to the drainage-affected area, around 40% of hummock vegetation remained unburned at the unmanaged part of the peatland (Fig. 5). Of the hummocks that were impacted by fire, around 30% were burned and around 30% scorched. Only a minority of lawns were impacted by fire; 2% of the lawn vegetation was burned, but the scorched area varied between 24% (field layer) and 10% (ground layer). Vegetation in the hollows remained unburned throughout (Fig. 5).

Discussion

Our study that first time compared the impact of fire in drainage-affected and unmanaged parts of the same peatland pointed out the vulnerability of the drainage-affect area. As we hypothesized, the fire was more extensive in the drainage-affected area; on the unmanaged bog surface there was only sparse fire damage that was restricted mainly to hummock surfaces. The effect of the drainage had the most drastic impact in the first sampling plots, ten meters from the ditch, although the influence of natural drought on the peatlands' water table can be expected to be more gradual. The artificial water-level drawdown and the consequent vegetation changes may simulate possible future conditions where, due to a warmer climate and prolonged dry seasons, water levels remain low and the surface vegetation composition alters dryer, resulting in more fire fuels.

Climate predictions for the northern regions forecast warmer weather, prolonged dry periods, but also increased precipitation (IPCC 2007). The amount of precipitation is, however, suspected to vary greatly both spatially and seasonally, which complicates interpretation and implications of future moisture scenarios. However, as a result of possible increased evapotranspiration and consequent water-level drawdown, northern peatlands may become drier environments (Roulet *et al*. 1992), at least temporarily during the predicted prolonged dry periods. This makes peatlands, as well as upland areas, more prone to fire and the impact of fire on peatlands may become more severe (Lavoie & Pellerin 2007, Flannigan *et al*. 2009). In this study, the preceding four months before the fire that had been warmer and dryer than long-term average, may have favored the fire fuel conditions on the studied bog (Roulet *et al*. 1992, Flannigan *et al*. 2009). Some analogy to past climate and fire frequencies can be found from palaeoecological studies: during the Holocene (ca. 11 600 years to present) the natural fire frequency on Canadian peatlands (without anthropogenic influence) was highest during the warm and dry mid-Holocene climate phase, ca. 8000–5000 years ago (Kuhry 1994). However, no link between climate and fire frequency was detected in the recent study of two bogs from the Baltic region (Sillasoo *et al*. 2011). There, throughout the last ca. 5000 years, bog fires occurred repeatedly with an interval of less than 300 years. Modern human-induced landscape management can further enhance the effect of change in the climate regime.

Our results which show a patchy fire spreading pattern and the influence of burning on peatland vegetation are consistent with the general view suggested by earlier studies on pristine peatlands (Foster and Glaser 1986, Benscoter and Wieder 2003, Ohlson *et al*. 2006). The peatland fire proceeded along dry surfaces, while wet depressions remained intact. The pattern contradicts the results derived from continental Canadian peatlands (e.g. Benscoter and Wieder 2003). The reason probably is that in continental bogs the microtopography is less pronounced and hollows support for instance *S. angustifolium* (Benscoter *et al*. 2005), i.e. species that in Fennoscandia inhabits dry hummock surfaces together with *S. fuscum*. One reason could also be the generally lower water table in continental bogs which makes them more prone to desiccation and consequently more prone to fire during prolonged dry periods (Benscoter *et al*. 2005) when compared with truly wet hollows of Fennoscandian bogs. Since even during dry periods, continental *S. fuscum* hummocks may be able to retain their independent moisture, they may be protected from burning. The hummocks in the present study area contained dwarf shrubs and lichen, which may have resulted in greater fuel loading and combustion potential as compared with a solid moss layer.

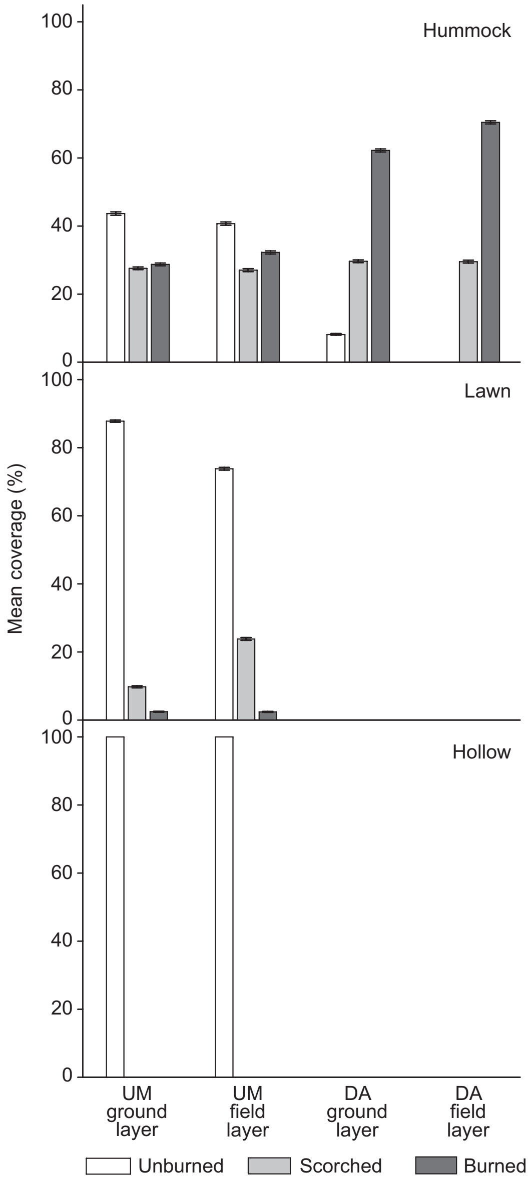

Fig. 5. Fire damage to the ground and field-layer vegetation in different microhabitats in unmanaged (UM) and drainage-affected (DA) parts of the bog. Standard error of the mean in every bar is 0.1% or less.

As wildfires are globally a significant source of direct carbon emissions to the atmosphere, the possibility of increased peatland fires must be taken into consideration when estimating future carbon budgets. Peatland fires do not only release carbon during the fire event, but fires can also have long-term general effects on peatland carbon dynamics. For several years after a severe fire event, a peatland can act as a carbon source instead of being a carbon sink because of fire-mediated changes in local hydrology and vegetation (Väliranta *et al*. 2007, Wieder *et al*.

2009). In the future, drier peatland surfaces — either due to climate change or increased human-induced peatland drainage — are likely to increase peatland fire occurrences and extent in the boreal zone.

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