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Historical burn area in western Canadian peatlands and its relationship to fire weather indices

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[1] Peatlands store the majority of soil carbon in many northern regions, yet their vulnerability to fire remains poorly understood. We used large-scale mapping of fire and peatland distributions to explore patterns of burning at two spatial scales. On a landscape scale in central Alberta, we used spatially explicit distributions of peatlands and 50 years of fire perimeter maps to determine whether uplands burn more preferentially than peatlands. Burn area and ignition localities in central Alberta did not occur preferentially in uplands relative to bogs and fens. Extrapolating this result at a regional scale, we used the Peatlands of Canada database and 20 years of historical fire records to estimate annual burn areas for Alberta, British Columbia, Northwest Territories, and Saskatchewan peatlands. Peatland burn areas varied tremendously over time, with high fire activity in the early 1980s and mid-1990s. On average, fires impacted 1850 km^2 of peatland annually across this region of western Canada. Positive relationships between the area of peatland burned and weather variables calculated for each fire event using the Canadian Fire Weather Index, including maximum air temperatures and the duff moisture code, suggest that drier and/or warmer conditions likely would increase the burning of peatlands in western Canada. *INDEX TERMS:* 1615 Global Change: Biogeochemical processes (4805); 1620 Global Change: Climate dynamics (3309); 1640 Global Change: Remote sensing; 1890 Hydrology: Wetlands; *KEYWORDS:* fire, peatlands, wetlands, boreal, carbon, climate change

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1. Introduction

[2] The boreal biome represents ~10% of the Earth's land area, covering approximately 14 million km^2. Today, boreal regions around the globe are estimated to contain more than 700 Pg of carbon (C), representing almost 40% of the terrestrial C pool [*Apps et al.*, 1993; *McGuire et al.*, 2001]. Between 300 and 500 Pg C in boreal regions lies in belowground materials, and much of this carbon stock is located in the saturated/frozen soil layers of permafrost and peatland ecosystems [cf. *Gorham*, 1991; *Dixon et al.*, 1994; *Vitt et al.*, 2000; *Bhatti et al.*, 2002]. Soil carbon tends to accumulate in areas of poor soil drainage because of moisture controls on plant production and decomposition [*Harden et al.*, 2000]. Additionally, both the frequency and intensity of fire control fuel abundance and C storage across northern landscapes [*Kasischke et al.*, 1995; *Kurz and Apps*, 1999; *Kasischke et al.*, 2000]. Fires release gaseous and particulate C to the atmosphere immediately through organic matter combustion, and also influence longer-term ecosystem processes by reducing autotrophic respiration and potentially altering heterotrophic respiration through changes in soil climate, substrate quality, and/or microbial populations [*Pietikainen and Fritze*, 1996; *Burke et al.*, 1997; *O'Neill et al.*, 2002]. Between 5 and 12 million ha of boreal forest burn every year, directly releasing an estimated ~10–40 t C ha^{-1} yr^{-1} to the atmosphere [*Kasischke et al.*, 2000; *Levine and Cofer*, 2000; *Stocks and Kaufman*, 1997; *Alaska Fire Service*, 1998].

[3] Fires in the boreal region are highly variable, and area of forest burned is related to seasonal variations in temperature, precipitation [*Flannigan and Van Wagner*, 1991; *Flannigan and Wotton*, 1991] and atmospheric circulation patterns [*Skinner et al.*, 1999; *Hess et al.*, 2001]. The relationship between climate/weather and fire suggests that both fire frequency and severity will increase if northern regions experience warmer and drier climates in the future [*Wotton and Flannigan*, 1993; *Stocks et al.*, 1998; *Flannigan et al.*, 2001]. Area burned has increased over the past several decades in North America [*Kasischke and Stocks*, 2000; *Podur et al.*, 2002], most likely due to a combination of changing climate, more sensitive detection, and increased human activities in formerly remote areas.

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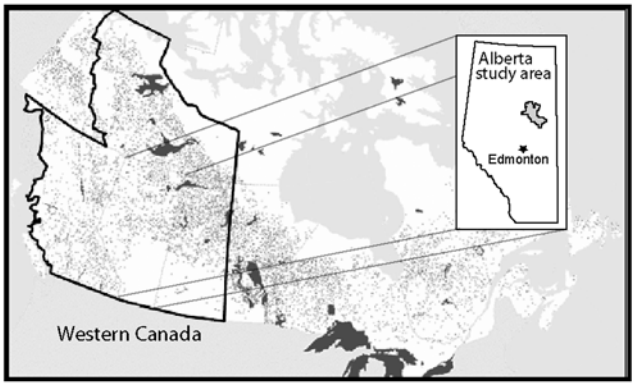

Figure 1. Map of large fires in Canada, 1980–2000, from the Large Fire Database [after *Stocks et al.*, 2002]. The points are fire start locations. The thick black line is a rough outline of our study region across western Canada, and includes British Columbia, Alberta, Saskatchewan, and the North West Territories. The expanded area in gray shows the location of our more intensive study region in central Alberta.

For example, about twice as much area burned in Canada during the 1980s and 1990s compared to the previous 2 decades [*Stocks et al.*, 2002].

[4] Wildfire severity and extent are sensitive to the amount, continuity, and flammability of fuels, which include the thick layers of organic soils that accumulate in many boreal ecosystems. Fires in tropical peatlands have received attention in recent years, as El Niño events and land-use have triggered severe burning [cf. *Goldhammer*, 1999; *Nepstad et al.*, 1999; *Page et al.*, 2002]. Northern peatlands comprise large areas of the boreal forest, which generally is prone to burning, and contain large terrestrial carbon stocks. However, the vulnerability of boreal peatlands to burning remains poorly understood. Fire return intervals range from 50 to 500 years in boreal upland ecosystems [*Laberge and Payette*, 1995], while estimates for fire return intervals range from 200 to 1100 years in continental peatlands [*Kuhry*, 1994; *Zoltai et al.*, 1998]. Though generally drier than oceanic peatlands, continental peatlands are thought to experience fires less frequently than uplands due to saturated surface fuels and sparse tree canopies. Nonetheless, in western Canada, fires reduce net ecosystem productivity or total C storage in peatlands [*Kuhry*, 1994; *Zoltai et al.*, 1998; *Robinson and Moore*, 2000; *Turetsky et al.*, 2002].

[5] We hypothesized that burn area would be lower in landscapes dominated by peatlands than those dominated by uplands. However, boreal peatlands have large organic matter stocks in vegetation and surface soil layers that may become susceptible to burning during dry weather periods. Here we capitalize on large-scale data sets of historic burn areas [*Amiro et al.*, 2001; *Stocks et al.*, 2002] and peatland distributions [*Tarnocai et al.*, 2000] to explore patterns of burning across northern peatlands. Our main goals were to (1) determine whether annual burn area and/or ignition locality occur preferentially in uplands relative to peatlands (bogs and fens), (2) explore the relationship between peatland abundance and fire size, and (3) investigate the controls of fire weather indices on peatland burning. We approach these objectives using detailed data sets for a smaller intensive region in Alberta, as well as a coarser data set for most of boreal western Canada.

2. Methods

2.1. Large Fire Database

[6] We used fire perimeter maps and point ignition locations compiled from data provided by the Province of Alberta for fires greater than 200 ha in size. Large fire events are particularly important in Canada, where 2–3% of all fire events account for more than 97% of the total area burned [*Stocks et al.*, 2002]. The polygon version of the database can link to a point database with attributes on the timing, perimeter, and ignition locations of fire events mapped in a geographical information system (GIS). Fires were mapped from aerial photographs, ground surveys, and more recently from global positioning system mapping from aircraft and satellite imagery.

2.2. Intensive Study Region: Central Alberta

[7] We examined landscape composition in fire perimeters for a 1.2 million ha area near Wabasca, central Alberta (Figure 1). This area was selected because detailed maps of landscape composition were mapped by the Province of Alberta from 1:40,000 to 1:60,000 aerial photographs. More than 11,000 landscape polygons were mapped, denoting the perimeter of individual upland or wetland features (bogs, fens, marshes, swamps). Additional information, including whether the landscape polygons are treed or underlain by permafrost, also were compiled. This area is within the Boreal Plains ecozone, and has features typical of this ecozone. It has deep soils and moderate topographical relief. In recent years, fire frequency has been less frequent here than in the Boreal Shield and Taiga ecozones farther north. Fires have been actively suppressed during the study period (1950–2000).

[8] The central Alberta study area comprises 55% upland and 45% wetland. Approximately 40% of the region is peatland (19% bog, 21% fen) while about 5% is non-peat accumulating wetlands (0.5% marsh, 4.5% swamp). Here we consider patterns of burning only in the dominant landscape types, including uplands, bogs, and fens that comprise about 95% of the landscape. Bogs are ombrotrophic systems that receive all of their nutrient and water inputs from the atmosphere alone. Bogs in western Canada usually are treed with sparse canopies of black spruce (*Picea mariana*). Fens are minerotrophic systems that receive water and nutrients from ground and/or surface water inputs. Fens in western Canada can be open (no trees) or have a sparse canopy of black spruce or larch (*Larix laricina*). In this study area, 82% of the fens were treed, while 18% of fens were open. We did not have information on the abundance of rich (alkaline fens dominated by brown mosses) versus poor (acidic fens dominated by *Sphagnum* species) fens.

[9] We overlaid all landscape polygons with fire perimeter maps from 1950–1999. Fire polygons included distributions

of unburned islands mapped within each fire perimeter. We excluded these unburned islands from our analyses (i.e., they are not considered burned). Within each fire perimeter, we created a new polygon for each burned landscape class (upland, bog, fen). We used these new spatial polygons to compile the total area burned annually in each landscape class. Where available, we also documented the landscape class at each ignition locality.

[10] To determine whether fires occur preferentially in uplands relative to peatlands, we used chi square goodness of fit tests to compare ratios of observed (i.e., the total area of land burned in each landscape type from 1950–2000) and expected values for area burned in each landscape type. Expected values assumed an even distribution of burn area in each landscape class (upland, bog, fen) in proportion to their availability on the landscape. To calculate expected burn areas, we summed observed burn areas from 1950–2000 across landscape classes (upland, bogs, fens), and multiplied this value by the area of each landscape class. A similar chi square test was used to explore the distribution of ignition locality in each landscape type to determine whether ignitions occur preferentially in uplands relative to peatlands.

[11] We used a general linear model [*Insightful Corporation*, 2001] that included fire weather index variables (see Appendix A for description of variables) to explore controls on the area of peatland burned in each fire over the 50-year period (n = 46 fires). Briefly, the fire weather data used here were interpolated from Environment Canada surface observation stations to each fire location (for the start date and the following 20 days) using a thin-plate cubic-spline technique [*Amiro et al.*, 2001; *Flannigan and Wotton*, 1991]. We started with a saturated model and removed nonsignificant factors sequentially to determine our final model.

2.3. Extensive Study Region: Western Canada

[12] We explored patterns of burning in the Boreal and Taiga ecoregions of four western Canadian provinces and territories, including Alberta, British Columbia, Saskatchewan, and the Northwest Territories (Figure 1). Peatland distributions across Canada have been inventoried from 1:40,000 to 1:60,000 aerial photographs, transferred to 1:250,000 base maps, and coverage of peatland types were calculated in ARC/INFO for 0.25° latitude and 0.5° longitude grid blocks. Data are summarized in the Peatlands of Canada database [*Tarnocai et al.*, 2000; *Vitt et al.*, 2000]. Grid blocks in this database do not delineate peatlands explicitly, but include information on the average percentage of each landscape class (upland, bogs, fens) in a spatial unit. We overlaid fire polygons from the polygon version of the Large Fire Database with grid blocks from the Peatlands of Canada database to estimate the average percentage of upland, bog, and fen burned. This approach assumes that burning occurred randomly with landscape composition (i.e., peatland and upland availability). Data are summed across fires within a year and represent average annual burn areas in peatlands.

[13] Year was a significant factor in a general linear model [*Insightful Corporation*, 2001] predicting log transformed fire size, suggesting that fire size was more similar within years than across years. Thus our final model was a general linear mixed effects model with year as a random factor to account for non-independence of fire sizes within years. Starting with a saturated model that included the month of ignition, percentage of peat in each fire polygon, and fire weather index variables (Appendix A), we removed nonsignificant factors sequentially to determine our final model.

[14] The distribution of fire sizes was not normal but was skewed toward smaller fire events (47% of the greater than 200-ha fires were less than 1000 ha); log transformations normalized these data. Percentages of peatland in each fire polygon were arcsine transformed. A spline fit was used to explore the relationship between fire size and peatland abundance across the full range of fire sizes using the generalized additive module in S-Plus [*Insightful Corporation*, 2001]. The spline fit showed no change in fire size with peatland abundance until fires exceeded about 100,000 ha, above which there appeared to be a positive relationship between peatland abundance and fire size. To further explore how the relationship between peatland abundance and fire size changed across fire sizes, we performed linear regression analyses with progressively smaller subsets of the data corresponding to larger fire sizes. Specifically, each repetition of the analysis excluded an additional 10,000 ha of fire size. Above 200,000 ha, there was no significant relationship between fire sizes and peatland abundance (p > 0.05). This approach suggested that the linear relationship between peatland abundance and fire sizes is strongest for fires >140,000 ha. We used a separate general linear mixed effects model (using the same approach outlined above) for fires >140,000 ha to explore potential landscape and fire weather controls on the extent of large fire events.

3. Results

3.1. Burning in Central Alberta

[15] From 1950 to 2000, there were 9 years in the central Alberta study region in which burning exceeded 10,000 ha (Figure 2). Six of those nine severe years occurred since 1980, and the largest area burned occurred in 1995. On average, 5887 ± 746, 1843 ± 390, and 2405 ± 378 ha yr^{-1} burned in upland, bog, and fen, respectively. Chi-square goodness-of-fit tests suggest that the total area burned in central Alberta across the entire 50-year period was dependent on landscape type ($\chi^2 = 641$; $p < 0.001$). Bogs burned less than expected (observed/expected: 0.91), while fens burned slightly more than expected (observed/expected: 1.08). The area of upland burned in the study region did not vary from expected values (observed/expected: 1.00). A similar analysis of just two landscape classes (peatland, upland) suggests that each class does not burn more than expected ($\chi^2 = 0.64$; $p > 0.25$). Seven ignitions occurred in bogs, 13 in fens (10 in treed fens and 3 in open fens), and 21 in uplands. The total number of ignitions occurring in each landscape class from 1950 to 2000 also was independent of landscape type ($\chi^2 = 2.33$; $p > 0.25$).

[16] Two fire weather variables explained 41% of variation in the annual peatland burn area in the central Alberta

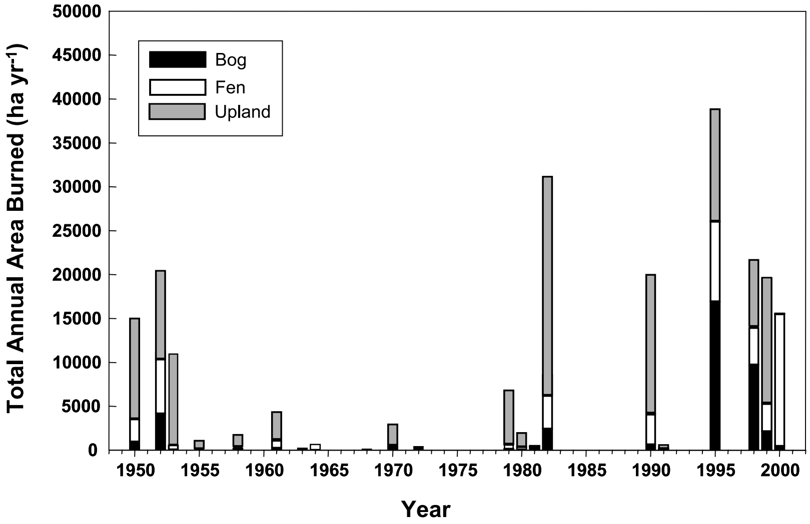

Figure 2. Annual area burned (1950–2000) for the various landscape classes mapped from aerial photography in central Alberta.

study region (Table 1). Values for the maximum air temperature and maximum duff moisture code (DMC) for each fire were positively related to the area of peatland burned.

3.2. Burning Across Western Canada

[17] Across western Canada, average peatland areas of 110,600, 4600, 23,000, and 55,000 ha burned annually from 1980 to 1999 in the NWT, BC, AB, and SK, respectively (Figure 3). However, annual burn area varied tremendously among years. For most provinces and territories, the early 1980s and early to mid-1990s were periods of high fire activity. Burn area in Saskatchewan peatlands was more constant through time, perhaps due to drier climatic conditions in the central prairies.

[18] Across all fires in this region, there was a significant but weak relationship between fire size and peatland abundance (Table 1, Figure 4; $n = 1200$; $R^2 = 0.006$; $F = 7.59$; $p = 0.006$). Coefficients of determination (R^2) between fire size and peatland abundance increased with fire size, with the highest values occurring between 140,000 and 150,000 ha (Figure 5). Above 140,000 ha, fire size increased positively with peatland abundance (Figure 4; $n = 19$; $R^2 = 0.43$; $t = 3.18$; $p = 0.007$).

[19] Across all fires, four variables were significant predictors of total fire size across western Canada, including month of ignition, the percentage of peat in each fire polygon, the maximum duff moisture code (DMC), and the maximum drought code (DC) (Table 1). Month of ignition was negatively related to total fire size, suggesting that larger fires occur earlier in the growing season. The percentage of peatland on the landscape and the two fire weather component variables were positively related to total fire size across western Canada. Our final model, however, explained only 9% of the variation in fire size.

[20] Peatland abundance and maximum temperatures (Appendix A) also were significant predictors for the total extent of large fires (exceeding 140,000 ha; Table 1). Maximum values for the duff moisture code (DMC) during fires were weakly related to total fire size. These predictors explained 63% of the variance in total fire size for large fires across western Canada.

4. Discussion

4.1. Burn Area in Peatlands

[21] We explored the relationship between area burned and landscape composition (uplands versus peatlands) on two spatial scales. On a landscape scale, detailed mapping of landscape composition across ~1.2 million ha of central

Table 1. Results of a General Linear Model Predicting Deviation in the Area of Peatland Burned in All Fires From 1950 to 1999 in the Central Alberta Study Region (n = 46 Fires) and Results of Two General Linear Models Predicting Deviation in Log Transformed Fire Sizes (1980–1999) Across Western Canada

Variables	Slope ± Std. Error	t	*p*
	Intensive Study Region[a]		
Max temperature	1334.82 ± 644.41	2.07	0.05
Max DMC	606.39 ± 287.65	2.11	0.04
	Extensive Study Region[b]		
All Fires			
Month	−0.06 ± 0.02	0.02	0.01
Max DMC	0.01 ± 0.01	<0.01	<0.01
Percent peatland	1.09 ± 0.35	0.35	<0.01
Max DC	0.001 ± 0.000	<0.01	0.02
Fires > 140,000 ha			
Percent peatland	0.80 ± 0.26	22.09	<0.01
Max temp	0.27 ± 0.01	0.01	0.01
Max DMC	0.0004 ± 0.0002	1.91	0.07

[a] Significant variables include maximum temperature and maximum duff moisture code (DMC; Appendix 1).

[b] Including all fire events in the model (n = 1200), significant predictors of fire size included month of ignition, arcsine transformed percentage of peatland in each fire polygon, maximum DMC, and maximum drought code (DC; Appendix 1). Including only fires greater than 140,000 ha (n = 17 fires), significant predictors of fire size included arcsine transformed percentage of peatland in each fire polygon and maximum temperature.

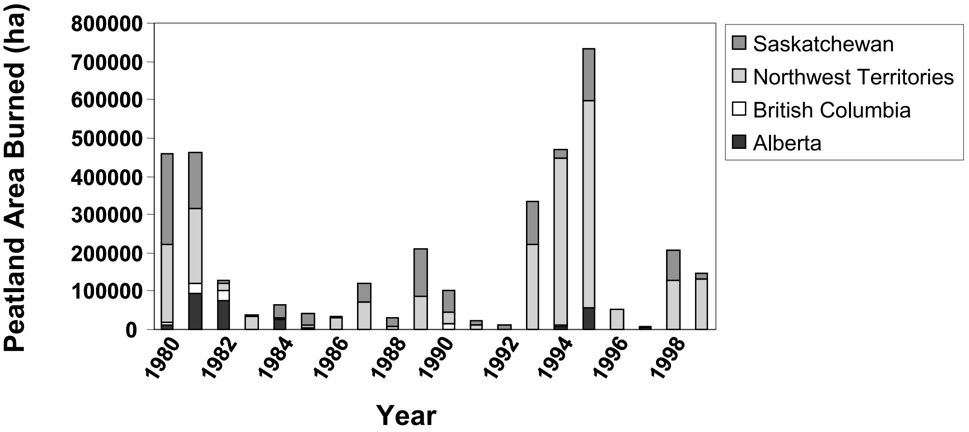

Figure 3. Average annual burn area in peatlands from 1980–2000 in the four western Canadian provinces and territories. Areas of each province are 661,137, 948,527, 1,171,918, and 651,900 ha for Alberta, British Columbia, the Northwest Territories, and Saskatchewan, respectively.

Alberta allowed us to investigate patterns of fire occurrence in well-drained (upland) versus poorly-drained (peatland) ecosystems. While we expected to find evidence for decreased levels of burning in peatland systems, chi square analyses suggest that burn area does not occur preferentially in uplands relative to peatlands. Burn area in bogs was slightly smaller than expected, given the abundance of bogs on the landscape. However, burn area in fens was larger than expected. Ignition localities were independent of landscape type. These data suggest that both fire ignition and burn area occur equally in uplands and peatlands, at least in this central Alberta region. This supports many other anecdotal observations of fires spreading across large peatlands. Similarly, *Harden et al.* [2003] overlaid historical burn perimeters over the past 50 years with soil drainage maps across Alaska. They report positive correlations between the area of poorly drained soil classes and burn areas. Together, these results show that fires do not preferentially influence upland ecosystems in the boreal forest region, and that permafrost and peatland areas may be more vulnerable to burning than previously appreciated.

[22] There are several explanations for why these large-scale approaches to understanding peatland burning do not agree with some previous generalizations. One hypothesis is that peatland fire return intervals have been overestimated in the past. Our traditional understanding of fire activity in peatlands has been based on macroscopic charcoal layers buried in peat. This approach depends on the genesis of combustion products during burning as well as their subsequent preservation in soils. Peatland ecosystems may experience more smoldering or scorching than uplands, and it is not clear how fire severity influences the generation of ash or charcoal layers in peat. Recent work in northern forests suggests that black carbon generated during northern wildfires is vulnerable to transport or degradation [*Czimczik et al.*, 2003]. Loss of charcoal/ash layers for any of these reasons will bias paleoecological reconstructions of fire history toward longer fire return intervals.

[23] These various approaches also reconstruct fire history on very different spatial scales and time frames. While charcoal analysis in peat cores explores fire histories over thousands of years, our large-scale mapping considers burn

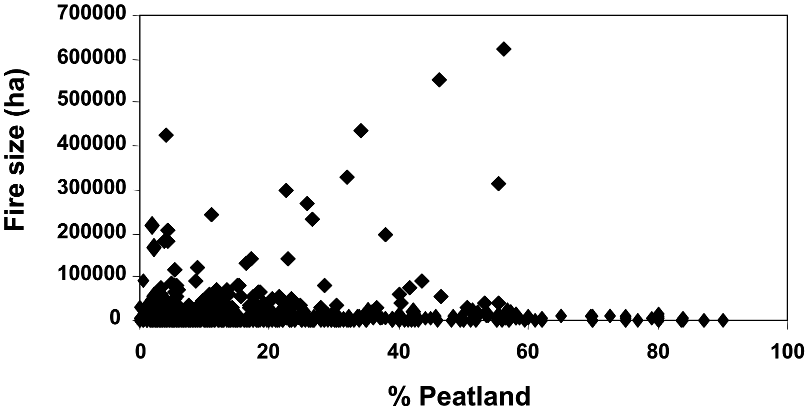

Figure 4. Relationship between fire size and peatlands abundance in western Canada from 1980–2000. For each fire mapped in the Large Fire Database, we estimated the average composition of uplands, bogs, and fens.

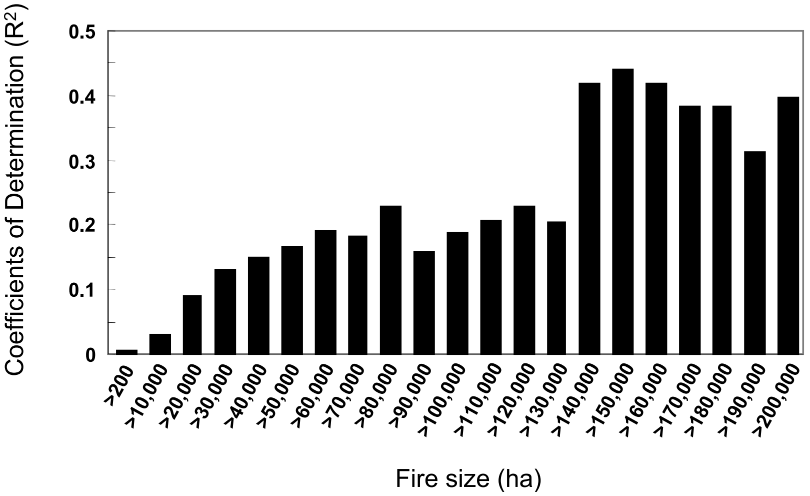

Figure 5. Coefficients of determination (R^2) for the relationship between peatland abundance and fire size based on linear regression analyses using progressively smaller subsets of fire size. Each repetition excluded an additional 10,000 ha up to a fire size of 200,000 ha.

areas over the past several decades. Charcoal analyses are fairly time consuming, and paleoecological studies tend to focus on detailed reconstructions of one or several peat cores. This approach may not adequately capture the spatial heterogeneity of peatland burning, which could lead to overestimates or underestimates of fire return intervals. Future paleoecological studies should strive to collect random samples on the landscape and increase spatial replication in addition to temporal replication.

[24] Alternatively, remote sensing and mapping efforts tend to ignore fine-scale processes, such as landscape configuration, fragmentation, and vegetation structure that may influence fire behavior [cf. *Bessie and Johnson*, 1995; *Flannigan et al.*, 2001; *Hély et al.*, 2001]. For the 1.2 million ha study area in central Alberta, landscape composition was mapped in more than 11,000 polygons. Though they may be important to fire behavior, we did not address any heterogeneity operating on finer spatial scales than these polygons. At a coarse level, we excluded unburned islands mapped within fire perimeters from estimates of peatland or upland burn area. However, combustion processes also exhibit considerable heterogeneity at smaller spatial scales. This could be important to our results if combustion tended to be patchier in peatlands than in upland ecosystems.

[25] Errors associated with mapping peatlands from aerial photography across western Canada are estimated at about 4% [*Vitt et al.*, 2000]. Spatial errors from the central Alberta wetland database are likely smaller than 4% due to the greater spatial resolution of the polygons. Errors associated with mapping fire perimeters have decreased in recent time due to technological advances in satellite imagery and geographical positioning systems. *Amiro et al.* [2001] estimated that this error represents about 5% for the fire polygons. However, rounding of spatial polygons during either fire or wetland mapping does cause some uncertainty, but this was minimized in our study by only using data across western Canada from the most recent 20 years.

[26] We estimated burn area in peatlands across the Northwest Territories, British Columbia, Alberta, and Saskatchewan. For these analyses, we assumed that fires do not occur preferentially in boreal uplands, as found in the central Alberta region. This assumption allowed us to overlay fire polygons with the Peatlands of Canada database, in which polygons (nonspatial) report the average abundance of uplands, bogs, and fens, without correcting our data for preferential fire spread in uplands. This approach could be misleading if central Alberta is not representative of the western Canadian region. Generally, the central Alberta region has more peatlands (45%) than the region as a whole (peatlands cover ~21% of Alberta, Saskatchewan, and Manitoba [*Vitt et al.*, 2000]). Within each province and territory, peatlands encompass 41, 23, 16, and 11% of Alberta, British Columbia, the Northwest Territories, and Saskatchewan, respectively. However, the ratio of the average annual peatland burn area to the total provincial/territorial area is highest for the Northwest Territories (0.51) and Saskatchewan (0.25) compared to Alberta (0.12) and British Columbia (0.03).

[27] Our results suggest that wet areas of boreal landscapes are burning more than previously appreciated. To understand this discrepancy in our understanding of peatland burning, additional work should resolve methodological differences between paleoecological and remote sensing/mapping approaches. Full integration of paleoecological information into spatial analyses will allow us to assess whether peatlands are burning more than they did in the past, perhaps due to climatic shifts over recent decades.

4.2. Fire Weather Controls on Burn Area

[28] Given the large C stocks currently stored in boreal peatlands, understanding climatic controls on peatland fires will be important for future C budgets at regional or national scales. General circulation model (GCM) estimates based on a tripling of CO_2 levels indicate about a doubling of area burned across all of Canada, with most boreal regions showing an increase in area burned [*Flannigan et al.*, 2002]. Historical charcoal records also show a strong relationship between climate and fire activity in Canada,

with more frequent fire events in boreal peatlands during the warm Hypsithermal period (around 6000–7000 years BP) than today [*Kuhry*, 1994].

[29] Within our intensive study region in central Alberta, we investigated whether area burned in peatlands was related to weather variables calculated within the Canadian Fire Weather Index System. Two fire weather variables, including maximum air temperatures and the duff moisture code (DMC), explained about 40% of variation in peatland burn area (Table 1). Not surprisingly, this model suggests that warm and dry conditions lead to increasing areas of peatland burning. Maximum air temperatures were positively related to total burn area across several Canadian ecozones [*Flannigan et al.*, 2004]. While the Canadian Fire Weather Index System has not been explicitly tested for peatlands, our results suggest that fire weather, specifically air temperature and soil moisture conditions, control patterns of burning in Alberta peatlands.

[30] We also explored patterns of area burned in peatlands across western Canada (including Alberta, British Columbia, Saskatchewan, and the Northwest Territories; Figure 1). Fire weather variables, month of ignition, and the percent peatland burned were significant predictors of total fire size in western Canada (Table 1). These relationships were not sufficiently strong to be used as predictive tools, but do suggest that both fire weather and landscape composition are important to the spatial extent of burning in boreal regions. Similarly, peatland abundance and maximum temperature during fires were significant predictors of the total extent of large fires (>140,000 ha). Thus, while the relationship between total fire size and peatland abundance is not linear, these models suggest that there are similar landscape and fire weather controls on the extent of burning across fire size. These variables, however, are much stronger predictors of fire size during large fire events.

[31] Generally, the relationship between weather and fire behavior is important in boreal and subarctic regions, where severe weather often is needed for soil and vegetation to dry sufficiently to serve as flammable fuels. We believe that peatland fires are affected by the season of burn, fuel condition, and fire weather. In our intensive region, about half of the fires occurring from 1950 to 2000 were spring fires. Across western Canada, month was negatively related to fire size, suggesting that spring fires tend to be larger than fire activity later in the growing season. Spring fires typically burn rapidly through dry, cured vegetation (with low values for the drought code index (DC)) but may not burn into deeper soil layers that remain saturated or frozen until well into the growing season (see section 4.3 for additional discussion on fire severity). Peatlands that have cured or dry biomass, such as sedges and grasses, exposed during spring months are susceptible to these burning events. These fires are likely to occur as surface fires, without combustion of deeper soil layers that tend to remain frozen well into the growing season. This is a different set of conditions than summer fires in which other vegetation and soils become dry and create deeper burning conditions. Hence it is difficult to derive a single set of weather conditions that would describe peatland burning across both surface and peat fires.

[32] The area of peatland burned increases with fire size, particularly during very large fires (>140,000 ha) that likely occur during extreme fire conditions (Figures 4 and 5). Our regression analyses (Figure 5) were designed to differentiate between small and large peatland fires, and showed a breakpoint at fires exceeding 140,000 ha. Our correlative approach is exploratory by nature, but indicated that peatlands are particularly affected by these large fires. The occurrence of fires exceeding 140,000 ha is relatively rare, as only 19 fires (representing ~1.6% of fires >200 ha) in the western Canadian study region exceeded this area over the past 20 years. However, these very large fires can represent a significant amount of the total area burned on a regional basis, particularly in Canada where typically 2–3% of all fires are responsible for 97% of the total area burned [*Stocks et al.*, 2002]. While our results show that peatlands burn more extensively in very large fire events (Figure 4), additional work will reveal the actual mechanism responsible for this spatial pattern. Burn area will increase similarly across all terrestrial ecosystems with fire size if burning truly occurs randomly on the landscape. However, burn area will increase preferentially in peatlands relative to other terrestrial systems if organic matter stocks in peatlands actually fuels fire activity during extreme fire weather conditions. Detailed (spatially explicit) mapping of landscape composition and configuration across large spatial scales is needed before this issue can be adequately addressed.

4.3. Hypotheses on Fire Severity

[33] While burn area is one aspect of fire patterning, spatial heterogeneity in combustion severity also is extremely important to C losses during fire [*Harden et al.*, 2004; *Benscoter and Wieder*, 2003; *Turetsky et al.*, 2002]. Our results suggest that areas of poor soil drainage still burn extensively (Figure 4), although we do not have information on intensity or severity. There may be a tendency toward less severe burning in peatlands relative to uplands, though published rates of peat combustion can be severe [*Turetsky and Wieder*, 2001; *Benscoter and Wieder*, 2003]. However, these studies likely have targeted severe fire areas where peat was known to burn. Future work documenting differences in burn severity between upland stands and peatlands will provide a more complete understanding of how soil drainage and/or landscape position influence losses of carbon during fire. Published rates of organic matter combustion (vegetation and soil) in peatlands average 3.2 ± 0.4 kg C m^{-2} per fire event (summarized by *Turetsky and Wieder* [2001] and *Turetsky et al.* [2002]). Using this average combustion rate, we estimate that up to 5.9 Tg C is released annually to the atmosphere as a result of peatland burning in our study region of western Canada. Fires annually release 27 ± 6 Tg C yr^{-1} across Canada through direct combustion emissions plus additional large losses in the post-fire environment [*Amiro et al.*, 2001]. Though more work is needed to better understand large-scale variations in emissions from peatland fires, these preliminary numbers suggest that peatland burning can represent a large component of total fire emissions from Canada and a significant source of C to the atmosphere. It seems clear that increased

fire activity under future climate change will reduce peatland C stocks and at least temporarily diminish peat accumulation. Regional C budgets suggest that small increases in fire activity would be sufficient to switch peatlands in continental Canada from net C sinks to sources to the atmosphere [*Turetsky et al.*, 2002]. Thus, more frequent and/or more severe burning potentially will lead to a landscape where terrestrial C stored in wetter fuels and soils are less ‘‘protected’’ from burning.

Appendix A

[34] The fire weather parameters tested [*Van Wagner*, 1987] were as follows:

[35] 1. FFMC (Fine Fuel Moisture Code) represents the moisture content of litter and other fine fuels in a forest stand, in a layer of dry weight about 0.25 kg m^{-2} (time constant about 2/3rd days). It is an indicator of sustained flaming ignition and fire spread.

[36] 2. DMC (Duff Moisture Code) represents the moisture content of loosely compacted, decomposing organic matter weighing about 5 kg m^{-2} when dry (time constant about 12 days). It relates to the probability of lightning ignition and fuel consumption.

[37] 3. DC (Drought Code) represents a deep layer of compact organic matter weighing about 25 kg m^{-2} when dry (time constant about 52 days). It relates to the consumption of heavier fuels and the effort required to extinguish a fire.

[38] 4. ISI (Initial Spread Index) is a combination of wind and FFMC representing rate of spread without the variable influence of fuel.

[39] 5. BUI (Build-up Index) is a combination of DMC and DC representing total fuel available to the spreading fire. It is correlated with fuel consumption.

[40] 6. FWI (Fire Weather Index) is a combination of ISI and BUI representing intensity of the spreading fire as energy rate per unit length of fire front. It is often used as a single integration of fire weather.

[41] 7. DSR (Daily Severity Rating) is a power function of FWI representing a measure of control difficulty for a fire.

[42] Max temp is the maximum temperature occurring during the first 20 days of fire activity.

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