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Peatland permafrost thaw and landform type along a climatic gradient

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ABSTRACT: Recent change in the areal extent of permafrost at the individual peatland scale was determined from aerial photographs and Ikonos satellite imagery. Nine peatland sites were mapped from across the Discontinuous Permafrost Zone (DPZ) of western Canada, from the southern limit of permafrost in the prairie provinces to the northern part of the DPZ in the Mackenzie Valley, NWT. Sites span a mean annual air temperature (MAAT) gradient from 0.2 to –4.3°C. At five southern sites between 30 and 65% of localized permafrost has degraded over the last 100-150 years. Total thaw is significantly correlated to MAAT and stability appears positively related to the size of remaining permafrost landforms. At four northern sites as much as 50% of peat plateau permafrost has thawed over 50 years, and total thaw can be greater than in the south. Results suggest that localized permafrost at the southern limit of the DPZ respond more directly to climate, whereas response of peat plateaus in the north may be more complex.

1 INTRODUCTION

Northern circumpolar air temperatures have warmed in the recent past, as evidenced by the instrument record over the last 30-100 years (Serreze et al. 2000) and by annual-resolution proxy data spanning the last 400 years (Overpeck et al. 1997). In western Canada, ground temperatures reconstructed from borehole temperature logs have warmed more than air temperatures over the same period (Majorowicz and Safanda 2001). As a ground temperature phenomenon, permafrost is sensitive to such changes. Although data are limited, available long-term records show that permafrost temperatures have generally changed in the same direction, if not the same magnitude, along with mean annual air temperatures in Alaska, Canada and Russia (Serreze et al. 2000). Instrumental records for several locations in the Mackenzie Valley indicate an increase in mean annual air temperature of 2.0°C since 1948. Temperature records for northern Alberta and Saskatchewan indicate warming by 1.7°C over the same period (Environment Canada, 2001).

In the Discontinuous Permafrost Zone (DPZ) of western Canada, permafrost is found predominantly in peatlands (Zoltai et al. 1988). Peatlands are wetland ecosystems with cold waterlogged soils and low decomposition rates that result in thick organic deposits. In this region, peatland landforms with permafrost follow a climate-correlated pattern of peat plateaus in the north grading into localized frost mounds in the south (Vitt et al. 1994). Permafrost has been thawing and sometimes completely disappearing from many northern peatlands across western North America from Alaska (Jorgensen et al. 2001) and the Northwest Territories (NWT), Canada (Robinson and Moore 2000), to the boreal and subarctic regions of the Canadian prairie provinces (Zoltai 1972; Thie 1974; Vitt et al. 1994). A natural cycle of permafrost aggradation and degradation has been noted in this area by Zoltai (1993), however, a dominance of degradation over aggradation is likely indicative of a climatic effect. Resulting thermokarst areas affect peatland ecosystem structure and function, e.g. vegetation (Camill 1999), plant diversity (Beilman 2001), hydrology (Woo et al. 1992), carbon accumulation (Robinson and Moore 2000; Turetsky et al. 2000), and gas efflux (Liblik et al. 1997). Given these impacts, documenting the extent and rate of permafrost thaw is important to determine its relationship with climate, and to more accurately anticipate future thaw (Gorham 1994).

Peatlands are one of the only permafrost landforms readily mapped for the presence and absence of permafrost, owing to a large affect on peatland vegetation. In this paper, we investigate changes in permafrost-underlain area in peatlands by large-scale (individual peatland) vegetation mapping. We determine permafrost areal change in 11 peatlands at nine sites across the DPZ in western Canada. As a first look at permafrost change at these sites, we limit our present analysis to comparing change in the areal extent of permafrost between landform types and sites to their position along a mean annual air temperature (MAAT) gradient.

2 METHODS

Changes in permafrost area at four peat plateau sites in the Mackenzie Valley, NWT were mapped from a pair of time-series images; 1:40,000 aerial photographs taken between 1947 and 1950, and from recent Ikonos satellite imagery from 2000 (Table 1). Peat plateaus underlain by permafrost in western Canada are treed by open-canopied *Picea mariana* (black spruce) and have ericaceous shrub and *Sphagum*-dominated surfaces that produce dark-toned islands on images (Vitt et al. 1994), in contrast to lighter tones of unfrozen peatland (Fig. 1A).

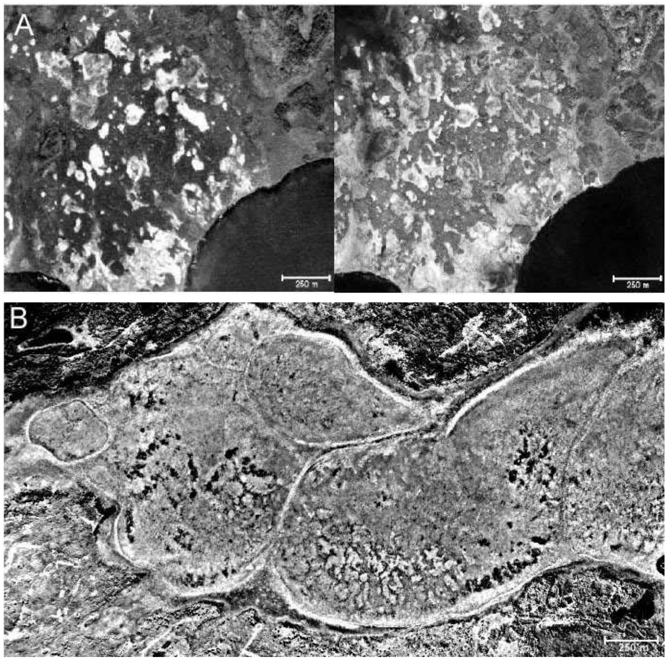

Figure 1. Examples of images mapped for vegetation showing permafrost presence and absence. A - Liard River #2, NWT site, aerial photograph (1947; left pane) and Ikonos image (2000; right pane). B - Moose Lake, MB site, aerial photograph (1996). Scale bars on all images indicate a distance of 250 m.

Changes in frost mound area in the southern sites were mapped from single images; the most recently available 1:10,000 to 1:16,000 aerial photographs (Table 1; Fig. 1B). Frost mounds in boreal peatlands of western Canada have dense, closed canopies of black spruce that in peatlands occur only when underlain by localized permafrost. In contrast, non-permafrost-affected bogs have open black spruce canopies that create an intermediate tone on images, and treeless internal lawns (recently thawed) have reflective surfaces of water and sedges that create the lightest tones (Vitt et al. 1994). The initial area of previously existing permafrost at each site was calculated as the sum of present permafrost (frost mound) and thawed (internal lawn) area. Dendrochronology of black spruce affected by permafrost thaw show that in this region degradation has occurred in the last century (Vitt et al. 1994). This timing is consistent with the end of the Little Ice Age, around 150 years ago (Halsey et al. 1995). We conservatively consider permafrost changes evident in the vegetation on these images to have occurred within the last 100-150 years. Degradation has been ongoing over the 100-150 period, as much of the currently visible internal lawn development is evident on 1948 aerial photographs (Vitt et al. 1994).

Within the main peatland area of each site, total peatland extent and enclosed permafrost features were digitized in either MapInfo or ArcInfo GIS. Mapped permafrost occurrence was ground truthed with a steel rod probe during site visits. The amount of permafrost thaw that has occurred in each peatland was calculated as (1-[current permafrost area/initial permafrost area]) x 100. Differences in mean size of localized permafrost landforms between sites and between frost mounds and internal lawns were determined by two-way ANOVA.

3 RESULTS

Nine mapped sites from across the DPZ span a MAAT gradient of 0.2 to –4.3°C (Table 1). Two peatlands were mapped at the Liard River (Site C) and Trout Lake (Site E). For all sites, between 0.214 and 7.078 km^2 total area was mapped and coverage by permafrost was between 2 and 89%. An average of 22% of peat plateau area in six peatlands has degraded over the last 50 years, ranging from 10 to 51% (Fig. 2A). On average, 56% of frost mound area has degraded over the last 100-150 years, ranging from 32 to 70% (Fig. 2B).

Mean frost mound and internal lawn size (area) were significantly different between both sites and landforms ($P < 0.05$), and a significant interaction was detected between site and landform type. No relationship was evident between area and MAAT, and the largest landforms were found at the warmest site (Fig. 3).

Table 1. Details and mapped characteristics of 11 peatlands investigated at nine sites.

Site	Unofficial Name	#	MAAT	Landform Type*	Location	Mapped Area (km^2)	Permafrost Area (km^2) (year of image) Initial	Current
A	Eentsaytoo Lake, NWT		-4.3	pp	64.6°N, 124.2°W	0.214	0.190 (1945)	0.171 (2000)
B	Wrigley Ferry, NWT		-3.8	pp	62.3°N, 122.6°W	1.797	1.285 (1948)	1.110 (2000)
C	Liard River, NWT	1	-2.7	pp	61.4°N, 121.8°W	0.615	0.276 (1947)	0.136 (2000)
		2				1.321	0.723 (1947)	0.478 (2000)
D	Buffalo Head Hills, AB		-2.7	fm	57.9°N, 116.1°W	3.519	0.206	0.140 (1996)
E	Trout Lake, NWT	1	-2.0	pp	60.5°N, 120.7°W	0.618	0.519 (1950)	0.467 (2000)
		2				0.757	0.601 (1950)	0.531 (2000)
F	Moose Lake, MB		-1.2	fm	55.1°N, 100.0°W	4.240	0.174	0.081 (1996)
G	Patuanak, SK		-1.0	fm	55.8°N, 107.7°W	1.429	0.094	0.033 (1990)
H	Anzac, AB		-0.4	fm	56.5°N, 110.0°W	7.078	0.111	0.044 (1988)
I	Goodwin Lake, AB		0.2	fm	55.5°N, 111.8°W	3.192	0.354	0.105 (1993)

* pp – peat plateaus, fm – frost mounds

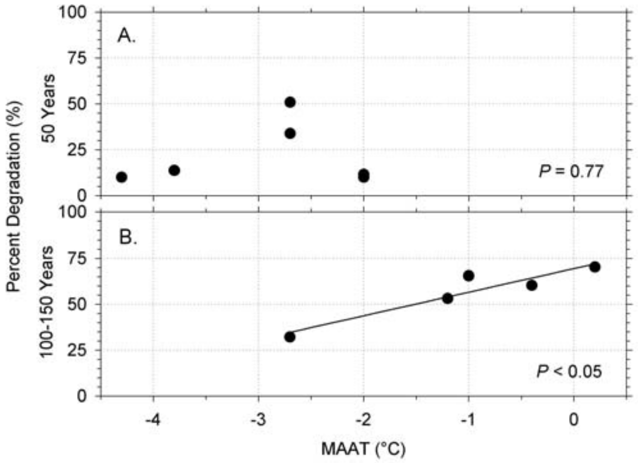

Figure 2. Relationship between recent changes in permafrost-underlain area for (A) peat plateaus and (B) frost mounds and MAAT in eleven mapped peatlands in western Canada. Best-fit line: degradation (%) = 69.4 +12.8*MAAT, $r^2 = 0.88$.

4 DISCUSSION

Detailed mapping of peatland permafrost change indicates that substantial recent degradation has occurred throughout the DPZ of western Canada. Permafrost degradation in peatlands occurs in response to disturbance (fire; Zoltai, 1993), overmaturity (Zoltai and Tarnocai 1975), and changes in thermal balance due to climate. At these sites climate has been the dominant trigger for change; complete stand replacing fire has not occurred within the period of observation, and no signs of overmaturity (open fissures and cracks in the peat surface) are present.

Although permafrost can contemporaneously aggrade and degrade in frost mound peatlands, small amounts of aggradation have only been observed in colder regions than the frost mound sites considered here (Laberge and Payette 1995). No evidence for permafrost aggradation following thaw exists in our sites.

4.1 *Extent of Degradation vs. MAAT*

Climate is predicted to warm in the next century in the permafrost peatland region of Canada (Moore et al. 1998). Frost mound thaw in the south has been more extensive in the warmer MAAT sites than in colder sites (Fig. 2B). The response of permafrost thaw to warming over the last 150 years has been shown to be complex and behave in disequilibrium fashion, with substantial time lags owing to locally

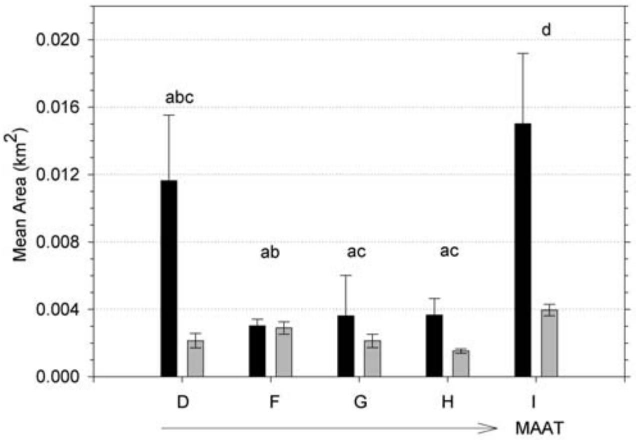

Figure 3. Mean size of frost mounds (solid bars) and thawed internal lawns (shaded bars) in five peatland sites. Bars show standard errors. Sites are ordered by increasing mean annual air temperature (MAAT); upper-case site letters follow Table 1. Lower-case letters above bars indicate equivalent mean landform size between sites (pooled frost mounds and internal lawns) following two-way ANOVA and Tukey's HSD test.

mediated soil thermal regimes (Halsey et al. 1995; Camill and Clarke 1998). Regardless, the relationship shown in Figure 1B suggests that a warmer western Canada may promote predictably more frost mound thaw over century time scales. Our individual-peatland scale results support similar quantified predictions of permafrost change based on regional peatland type distributions across western Canada (Vitt et al. 2000).

There is no relation between the mean size of localized permafrost landforms in each site and MAAT (Fig. 3). Either local factors are more important in determining the extent of initial permafrost aggradation, or MAAT patterns were significantly different from present when permafrost aggraded. Remaining frost mounds in these thawing permafrost peatlands are typically larger than degraded features (Fig. 3), which suggests that larger frost mounds are more resistant to thaw. In addition to surface vegetation/peat factors not addressed here, this may be related to the permafrost lens surface area to volume ratio, and larger permafrost features may be expected to 'outlast' smaller features when permafrost is in disequilibrium with climate. Soil thermal modelling could further address the importance of size as a local stability factor.

It is generally believed that the most extensive and important permafrost thaw is occurring in the southernmost regions of the DPZ. In contrast, recent degradation of peat plateaus is shown here to be substantial (Table 1; Fig. 2A), averaging 22% over 50 years. It is noteworthy that the total area affected is typically greater in the peat plateau than in the frost mound sites, even though the proportional areas are smaller and the time considered is shorter. For example, 0.245 km^2 (34%) of the permafrost at Liard River #2 (Site C) degraded over 53 years, compared to 0.061 km^2 (66%) at Patuanak (Site G) over 100-150 years, the mapped area of both sites being similar (Table 1). The extent of permafrost degradation in the peat plateau sites is unrelated to MAAT (Fig. 2A) and, although likely triggered by regional climate, the manner in which degradation proceeds may be more strongly moderated by local factors. In particular, changes in local hydrology induced by thaw can be large in degrading peat plateau peatlands, e.g. over 53 years, Liard River #2 changed from a permafrost-dominated site with disrupted drainage to a pattern of isolated permafrost and interconnected hydrology (Robinson, 2002).

4.2 *Landform Type and Future Thaw*

Two of our sites have similar MAAT but have different permafrost landforms: frost mounds in the Buffalo Head Hills, AB, and peat plateaus at Liard River, NWT. At the frost mound site 32% of permafrost has thawed over 100-150 years. In contrast, a greater proportion of thaw has occurred at Liard River, where 44% of permafrost (mean of two sub-sites) has thawed in the last 50 years – more than three times the total area degraded at Buffalo Head Hills. Comparison of these two sites further illustrates the potential for future thaw to be affected by conditions that vary by landform. Large regions of western Canada have both peat plateaus and frost mounds within the same local (50 km^2) area (Beilman et al. 2001). If future degradation follows patterns observed here, then landform differences are important for understanding how permafrost degradation may proceed, even locally. Consideration of future thaw should be mindful of the geomorphologic types affected in permafrost peatlands.

5 CONCLUSIONS

These results are preliminary, and ongoing mapping of additional sites will help verify trends observed here. Particularly, 50-year changes will be mapped for frost mound peatlands in the south of the Discontinuous Zone with time-series images. Our present results from nine sites across western Canada indicate:

1. Substantial permafrost degradation has occurred in peatlands throughout the DPZ of western Canada. In individual peatlands, 10 to 51% of initial

peat plateau area has degraded over 50 years, and 32 to 70% of initial frost mound area has degraded over 100-150 years at sites between 0.2 and –4.3°C MAAT.

2. The degree of frost mound thaw is significantly related to MAAT, with more thaw at warmer sites. However, the mean size of pooled frozen and thawed landforms is not related to temperature between sites; frost mounds are typically larger than internal lawns within sites.

3. Extent of permafrost degradation does not follow MAAT differences between four peat plateau peatlands.

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