

Localized Permafrost Peatlands in Western Canada: Definition, Distributions, and Degradation

David W. Beilman,
Dale H. Vitt, and
Linda A. Halsey

Department of Biological Sciences,
University of Alberta, Edmonton,
Alberta, Canada, T6G 2E9.
dbeilman@ualberta.ca

Abstract

Detailed inventory of peatlands by aerial photography shows that peatlands with climatically sensitive localized islands of permafrost cover 17,505 km² within a broad band of occurrence in continental western Canada (Alberta, Saskatchewan, and Manitoba). Within this zone, 37.5% of the total area covered by bog, and 9.1% of total area covered by fen have localized permafrost landforms (frost mounds and/or internal lawns). Regional distribution of the presence/absence of localized permafrost peatlands relative to expansive peat plateaus (peatland completely underlain by permafrost) shows that a north to south landform gradient exists that is dominantly controlled by mean annual temperature. Percent cover of localized permafrost peatland in an area is best explained by the amount of total peatland cover that can support it. Localized permafrost is associated with collapse forms (internal lawns) throughout the range of its occurrence in western Canada. In some locations permafrost has completely melted, moving the current southern limit of permafrost north by 39 km on average, and by as much as 200 km.

Introduction

Permafrost is a thermal condition of surface earth materials that remain below 0°C for two or more years (Muller, 1945; Harris et al., 1988). At the continental scale, the distribution of permafrost is considered in terms of continuity; the Continuous Permafrost Zone in Canada's north where permafrost occurs within all exposed land and is often hundreds of meters thick, and the Discontinuous Permafrost Zone where local factors determine the existence of perennially frozen ground that becomes increasingly thinner and less cold towards the south (Heginbottom, 1995). Within the Discontinuous Zone, permafrost is most common in peatlands (Brown, 1968). Peatlands are bryophyte-dominated wetlands where depressed decomposition rates result in the accumulation of organic matter over time (Zoltai, 1988). Peatlands are a major component of boreal and subarctic landscapes, covering about 21% of Alberta, Saskatchewan, and Manitoba (referred to here as continental western Canada). Modern peatland distributions in western Canada follow climatic gradients (Halsey et al., 1997, 1998), and generally no peatlands occur where precipitation is less than 500 mm and where evapotranspiration exceeds precipitation (Gignac and Vitt, 1994). Thus, peatlands are found in cooler climates that promote waterlogged soil conditions typical of the Discontinuous Permafrost Zone (Vitt et al., 1994). Peatlands can be divided into two general types based on hydrology: fens are geogenous peatlands that have surface waters that have been influenced by contact with mineral soil (ground or surface flow water), and bogs are ombrogenous peatlands that have surface waters derived from precipitation alone. Continental bogs in western Canada are characterized by oligotrophic nutrient status, tree cover of black spruce (*Picea mariana* [Mill.] B.S.P.), ground cover of *Sphagnum* spp. and a dry surface elevated well above the water table with a lack of open pools (Vitt et al., 1994). Fens are wetter, have a ground cover of brown mosses (rich fens) or *Sphagnum* spp. (poor fens), and are treed (black spruce and/or *Larix lari-*

cina [Du Roi] K. Koch) or treeless (*Betula* or *Salix* shrubs or *Carex* spp.).

Peatland surface vegetation and soils promote the aggradation and maintenance of permafrost due to their dynamic physical and ecological effects on surface energy balances. Near-surface organic soils are insulative when dry during summer and become highly conductive when wet and frozen during the fall and winter, their thermal conductivity increasing by an order of magnitude (Brown and Williams, 1972; Oke, 1987) promoting deeper, colder winter freezes. The expansion of water upon freezing elevates surfaces above the water table (Zoltai, 1971) and can change ground cover vegetation from wetland *Sphagnum* spp. to nonwetland lichen and feathermoss communities (Belland and Vitt, 1995), that also promotes dense vigorous growth of black spruce on localized frost mounds in the south (Zoltai and Tarnocai, 1971). This dramatic vegetation change further maintains a negative or neutral energy balance through increased shade (forest cover) and ground surface albedo (lichen cover) during summer, as well as increased snow interception by the forest canopy during winter, thinning the ground snowpack that normally insulates the soil. These factors contribute to the aggradation and stability of perennially frozen soils, allowing them to occur at warmer latitudes and elevations than in other soil types or under different vegetation. Thus, at its southern limit in continental western Canada permafrost is limited exclusively to peatlands.

Discontinuous permafrost in peatlands of subarctic and boreal Canada has long been recognized as occurring as two general landform types; large expansive areas of peatland underlain by permafrost called peat plateaus, and small isolated permafrost occurrences usually less than 100 m² in area (palsas) in otherwise unfrozen peatlands (Brown, 1968; Zoltai, 1971). Peat plateaus have low relief, usually elevated less than 1 m above surrounding unfrozen wetland, and individuals are expansive in spatial extent covering up to many square kilometers (Zoltai, 1972). Localized forms that occur as isolated small, treed frost mounds

in peatlands require more discussion and careful definition to avoid confusion in the use of the term "palsa" (see review by Nelson et al., 1991). The term was originally borrowed from the Lappish/Finnish and refers to "a peat hummock with a frozen core rising out of the surface of a mire" (Seppälä, 1988: 249). While the original meaning is simply descriptive and nongenetic, its adaptation into periglacial geomorphology has also included mineral cored mounds, and generally refers to treeless arctic/alpine forms that emerge out of saturated wetlands (Seppälä, 1988). In Canadian subarctic and boreal peatlands small permafrost features of this scale have also been called palsas, though these "invariably occur as islands or peninsulas in very wet fens or ponds" (Zoltai and Tarnocai, 1975: 34) as well as being differentiated from peat plateaus by their internal structure of frozen cores that extend into mineral substrata (Zoltai, 1971). In addition, the *Glossary of Permafrost and Related Ground Ice Terms* (Harris et al., 1988) defines palsas as "peaty permafrost mound(s) possessing a core of alternating layers of segregation ice and peat or mineral soil material," further stating that "ice segregation in mineral soil beneath peat is the process responsible for growth." Visible ice layers do not always occur in the peat of localized frost mounds in boreal peatlands (Zoltai and Tarnocai, 1975), and permafrost does not always extend into mineral soil (Zoltai and Tarnocai, 1971) particularly at its southern limit.

Because localized permafrost in boreal western continental Canada is not restricted to wet fens, commonly occurring in ombrotrophic dry bogs as well (Vitt et al., 1994), and that the internal structure of every permafrost mound cannot be inventoried in regional surveys, we feel that using the term palsa adds confusion to the nature of permafrost in this region. Though a more general definition and usage for the term has been suggested (Washburn, 1983; Nelson et al., 1991), we avoid the term palsa herein, instead referring to localized treed frost mounds in peatlands as simply "localized permafrost." However, localized permafrost or treed frost mound can be interchanged with "wooded palsa" (cf. Zoltai, 1972) if considered nongenetically and strictly as a morphological size description (*sensu* Washburn, 1983). Peat plateaus and localized permafrost have long been considered as morphological variations of the same process (Brown, 1968), thus the occurrence of localized permafrost signals a limit to local permafrost aggradation before peat plateau magnitude is attained due to interaction between climate and local factors (Seppälä, 1994). This together with the location of localized permafrost at the southern limit of the discontinuous zone, makes localized permafrost in peatlands likely the newest and most sensitive perennially frozen ground in Canada.

Permafrost is degrading at many locations within the Discontinuous Permafrost Zone. Many authors have reported thermal degradation and disappearance of true palsas in the discontinuous zone for some time (Sollid and Sorbel, 1974; Kershaw and Gill, 1979; Brown, 1980). In continental western Canada, peat plateaus and localized permafrost in peatlands also show evidence of extensive melt. Most peat plateaus have areas of internal degradation called collapse scars, and localized permafrost almost always has associated completely degraded forms termed internal lawns (Vitt et al., 1994). Internal lawns are treeless depressions of carpet or lawn cover by *Sphagnum* spp. and have surfaces depressed about 50 cm below nonpermafrost peatland, often with tilted partially buried black spruce snags from the pre-existing permafrost mound (Vitt et al., 1994). We use the phrase "localized permafrost landform" in general reference to either existing localized treed frost mounds or internal lawns, and "localized permafrost peatland" to describe peatlands with

both/either of these features. Localized permafrost landforms can occur in either bogs or fens (Vitt et al., 1994), that we call "localized permafrost bog" or "localized permafrost fen." The extensive degradation in this area, recently estimated to account for 9% (2627 km²) of the total previously existing permafrost (Vitt et al., 2000a), has been attributed to natural climatic warming over the last 150 yr since the end of the Little Ice Age (Halsey et al., 1995). The utility of monitoring characteristics and changes in such localized permafrost features as climate-change indicators has been advocated by numerous authors (Washburn, 1980; Seppälä, 1988; Solid and Sorbel, 1998; Nelson et al., 1991). Given the sensitivity of localized permafrost to climate, as well as the important physical and ecological changes that have occurred within their distribution in the recent past, a detailed exploration of the distribution of permafrost landforms in peatlands, particularly localized permafrost, is necessary to further understand the Canadian permafrost environment and how it is changing.

Objectives

Vitt et al. (1994) presented a qualitative overview of localized permafrost and peat plateau distributions for continental western Canada, with occurrences from rare to abundant for various bog types. The goal of the present paper is to expand upon their initial work to determine the spatial distribution and quantify cover of permafrost peatlands (peat plateau and localized permafrost peatland) at the regional scale, explore the relationship that these distributions have with climate and landscape, and determine how permafrost distributions have changed. Specifically, we will address the following questions: (1) What is the spatial distribution of a) the presence/absence of localized permafrost peatland relative to peat plateau, and b) landscape cover of localized permafrost peatland? (2) What climate/landscape factors are related to these distributions? and (3) What is the spatial distribution of complete degradation of localized permafrost (distribution of peatlands with internal lawns only, without treed frost mounds or peat plateau)?

Methods

LOCALIZED PERMAFROST PEATLAND DISTRIBUTION

Permafrost landforms in peatlands were inventoried by aerial photograph interpretation for the Discontinuous Permafrost Zone of continental western Canada following Vitt et al. (1994). Permafrost occurrence is inventoried as either (1) peatland completely underlain by permafrost (peat plateaus), or (2) as predominantly nonpermafrost peatlands containing isolated permafrost landforms (localized permafrost peatlands) (Fig. 1). A minimum mappable unit of 0.6 km² ensures that only expansive permafrost peatland is recorded as peat plateau. Information from the photos was transferred to 1:250,000 NTS base maps, digitized and summarized for 15' latitudinal by 30' longitudinal (NTS) gridcells in Arc/Info for Alberta and Saskatchewan and by the raster method (see Halsey et al., 1997) for Manitoba. Data are in the form of peatland area per gridcell for both permafrost landform types—peat plateau and localized permafrost peatland.

To determine the spatial distribution of localized permafrost relative to peat plateau, gridcells were classified into four types based on the presence/absence of permafrost peatland types and peatland coverage: (1) localized permafrost peatland only, (2) both localized permafrost peatland and peat plateau, with local-

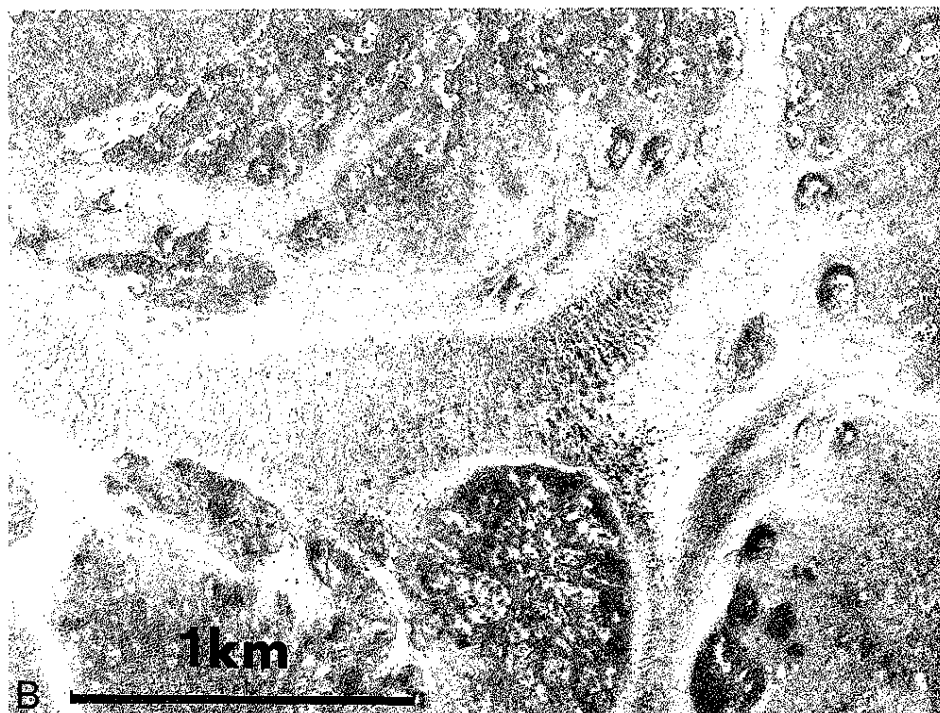
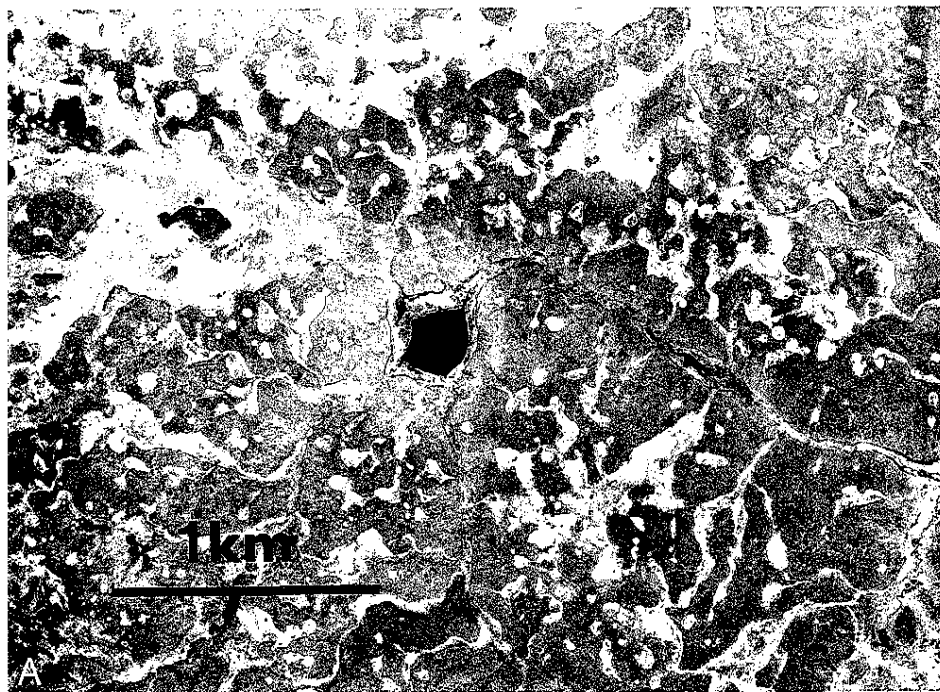


FIGURE 1. Aerial photographs of permafrost peatlands in continental western Canada. *A.* Extensive peat plateaus with collapse scars from Birch Mountains, Alberta (57°48'N, 112°31'W). *B.* Localized permafrost peatland with frost mounds and internal lawns near Algar Lake, Alberta (56°17'N, 112°28'W).

ized permafrost peatland dominant (>50% of total peat plateau and localized permafrost peatland cover), (3) both peat plateaus and localized permafrost, peat plateaus dominant, and (4) peat plateau only. To determine the spatial distribution of localized permafrost peatland, cover values were broken down into five cover classes: <0.49%, 0.5–4.9%, 5–14.9%, 15–24.9%, 25–50%. Classified gridcells were mapped in Arc/Info.

CLIMATE AND LANDSCAPE FACTORS

A number of climatic and landscape characteristics were estimated for each localized permafrost gridcell. Mean annual temperature derived from climate normals (1951–1980) was linearly interpolated between available climate stations, correcting for elevation effects following Vitt et al. (1994). The combined

effects of May–August precipitation and temperature are represented by a summer aridity index (based on precipitation – potential evapotranspiration) following Pettapiece (1995). Total peatland cover and the proportion of ombrogenous peatland (percent of total peatland that is bog) was estimated by the same technique as permafrost landform cover. Maximum peat depth values were modeled from data from 818 peatland sites following Vitt et al. (2000b). Physiographic characteristics of topography and mineral soil texture were estimated for each cell following Halsey et al. (1998). To determine how climatic and landscape character of gridcells in each permafrost landform class differed, data were submitted to canonical discriminant analysis (SAS, 1990). The significance of climate/landscape variables in explaining localized permafrost peatland coverage was determined by stepwise multiple regression (Zar, 1984).

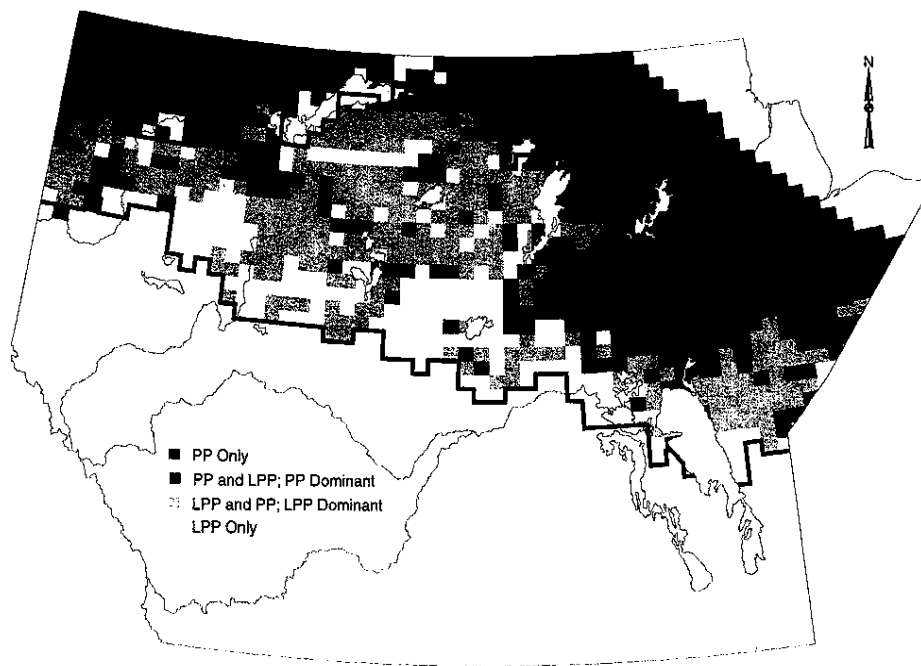


FIGURE 2. Distribution of permafrost landforms in boreal continental western Canadian peatlands by landform class. PP = peat plateau, LPP = localized permafrost peatland. The northern and southern limits of the zone of localized permafrost peatland occurrence is demarcated by heavy lines. Cells within the Continuous Permafrost Zone (Heginbottom, 1995) of northeastern Manitoba are excluded.

DEGRADATION

The spatial distribution of localized permafrost gridcells that contain only internal lawns (without treed localized frost mounds or peat plateaus), indicates the complete melt of permafrost that existed in the recent past. Spatial distribution of these cells demonstrate how distributions of localized treed frost mounds have changed.

Results

LOCALIZED PERMAFROST PEATLAND DISTRIBUTION

Spatial distribution of gridcells classified by the presence/absence of permafrost landform types indicate a north to south latitudinal zonation with exclusive peat plateau occurrence in the north, typically exclusive localized permafrost peatland in the south, and a large area of overlap where both permafrost landform types co-occur (Fig. 2). The northern half (48%) of these permafrost cells contain peat plateaus exclusively, whereas exclusive localized permafrost peatland in the south account for 12% of the gridcells shown. The remaining permafrost cells have a co-occurrence of peat plateaus and localized permafrost containing peatland. One-third of all cells that contain permafrost have dominant or exclusive localized permafrost peatland. The

TABLE 1

Summary of total permafrost landform and peatland type cover (km^2) by province for the region of localized permafrost peatland (Fig. 2)

	Saskatche-			Total
	Alberta	wan	Manitoba	
Peat plateau	3439	709	11,795	15,943
Localized permafrost peatland	6451	2328	8726	17,505
Localized permafrost bog	3972	1868	1796	7636
Localized permafrost fen	2479	460	6929	9868
Total bog (non-peat plateau)	8755	6663	4934	20,352
Total fen	37,301	24,438	46,308	108,047

bounds of the zone of localized permafrost peatland occurrence were set by the northernmost and southernmost gridcell of the mostly contiguous localized permafrost cells (shown in Fig. 2). Outliers occur in the subarctic of northeastern Manitoba and at higher boreal elevations south of the zone in eastern Saskatchewan/western Manitoba. Within the zone, localized permafrost peatland covers 17,504 km^2 , or 12.7% of total peatland area (Table 1). Cover is greatest in central and northeastern Alberta, northwestern Saskatchewan and central Manitoba, with the majority of cover being up to 5% of the land area in a broad band of occurrence (Fig. 3). About 56% of the total localized permafrost peatland cover is localized permafrost fen, concentrated mostly in central Manitoba. However, in Alberta and Saskatchewan, localized permafrost bog has greater cover than localized permafrost fen (Table 1). When considered relative to cover by peatland type within the zone, 37.5% of total (non-peat plateau) bog area is localized permafrost bog. Localized permafrost fen accounts for 9.1% of total fen cover.

CLIMATE AND LANDSCAPE FACTORS

Permafrost peatland classes 1-3 (gridcells with localized permafrost peatland) are characterized by significantly different regional characteristics following canonical discriminant analysis ($F = 19.1$; $P < 0.0001$). Canonical axes 1 and 2 explain 32% and 3% of the variance in the climate and landscape data, with mean annual temperature and bog cover most strongly correlated with the first canonical axis (Table 2). The climate and landscape character of gridcells in these three classes show considerable overlap in the ordination diagram (Fig. 4), suggesting a continuum of conditions between classes. Stepwise multiple regression of climatic and landscape variables against localized permafrost peatland cover per gridcell resulted in a model wherein only total peatland cover and mean annual temperature were significant (adjusted $R^2 = 0.316$; $F = 133.0$). Peatland cover accounted for the bulk of variability, as mean annual temperature increased the model R^2 by less than 0.01.

DEGRADATION

Of the gridcells with only localized permafrost peatland (Class 1 on Fig. 2), 40% of these have internal lawns only (with-

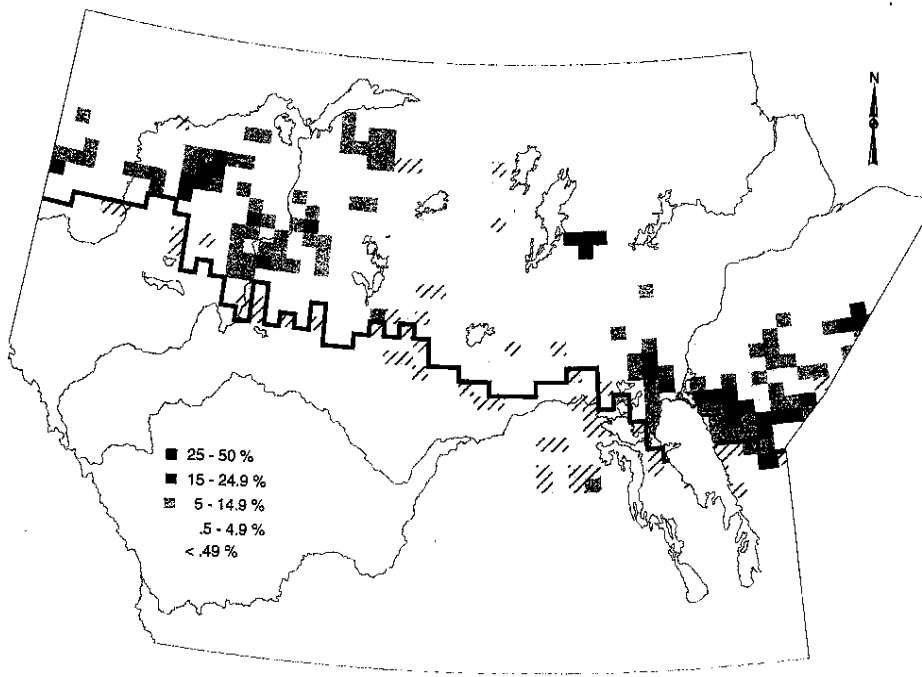


FIGURE 3. Cover of localized permafrost peatland expressed as percentage of total peatland area per gridcell. Hatched gridcells show localized permafrost peatlands with internal lawns only. The present southern limit of permafrost is shown by the heavy line.

out existing treed frost mounds). This complete permafrost degradation has occurred mainly in the south (Fig. 3), displacing the southern limit of permafrost north by an average of 39 km, though where internal lawns are found at higher elevations in boreal Saskatchewan and Manitoba, permafrost has moved more than 200 km north.

Discussion

LOCALIZED PERMAFROST PEATLAND DISTRIBUTION

The distribution of permafrost in Canada follows climatic gradients, evident in the broadly latitudinal zonation of permafrost zones at the continental scale (Heginbottom, 1995). In this way, Continuous and Discontinuous Zone boundaries closely parallel mean annual temperature isotherms. This pattern is also seen within the smaller region that is continental western Canada (Vitt et al., 1994), where exclusive peat plateau occurrence in the north is replaced by increasing localized permafrost peatland in the south (Fig. 2). Distribution of permafrost peatland type and abundance forms the basis of Zoltai's (1995) subclassification of discontinuous permafrost in peatlands. The total distribution of localized permafrost shown in Figure 2 spans his Spo-

radic and Localized Permafrost Zones. The region of localized permafrost peatland (Fig. 3) occurs as a broad band across continental western Canada. Cover is typically greatest in the middle of this band, and decreases towards the north and south, as a function of marginal climatic conditions in the south and replacement by peat plateau in the north. Though more localized permafrost occurs in fens than in bogs (Table 1), much more of the total bog area has localized permafrost than the total fen area. This affinity for permafrost occurrence in bogs is due to bog surfaces elevated above the water table, their dry peat reducing groundwater temperatures below that of neighboring fens (Vitt et al., 1995). However, relatively dry rich fens are also common, especially in Manitoba, that also have elevated brown moss dominated surfaces. These dry fens are also prone to localized permafrost development.

CLIMATE AND LANDSCAPE FACTORS

As a thermal condition of surface material, permafrost is closely related to climate. The limits of the Discontinuous Zone have been expressed in terms of mean annual temperature, occurring between about -8.3°C (Zoltai, 1995) and 0°C (Vitt et al., 1994) mean annual isotherms. Mean annual temperature is the most strongly correlated variable to canonical axis 1 (Table 2), that best separates the permafrost peatland classes (Fig. 4). This indicates that overall coldness strongly affects the occurrence of permafrost peatland types, and that climate (specifically temperature), is an underlying factor that determines permafrost peatland distribution at the regional scale. Thus, colder regions can develop extensive peat plateau, whereas warmer regions have a climatically imposed limit on landform development, and are conducive to aggradation of localized permafrost only. Seasonal precipitation also affects permafrost aggradation, maintenance and degradation. Wet peat has a thermal conductivity an order of magnitude greater than dry peat (Brown and Williams, 1972), and high summer precipitation and flooding has degraded small permafrost lenses in Finnish Lapland wetlands (Seppälä, 1994). Summer aridity was weakly but significantly correlated to canonical axis 1 (Table 2). This relationship likely has to do with the importance of aridity to permafrost maintenance at the

TABLE 2

Results of canonical discriminant analysis: Pearson correlation coefficients for climate/landscape characteristics and canonical axes 1 and 2.

FACTORS	AXIS 1	AXIS 2
Mean annual temperature	-0.83*	-0.36*
Summer aridity	-0.27*	-0.09*
Total peatland cover	0.27*	-0.19*
Bog proportion	0.62*	0.01
Maximum peat depth	-0.02	0.24*
Topography	-0.03	-0.04
Mineral soil texture	-0.34*	0.81*
Squared canonical correlation	0.32	0.03

* $P < 0.05$.

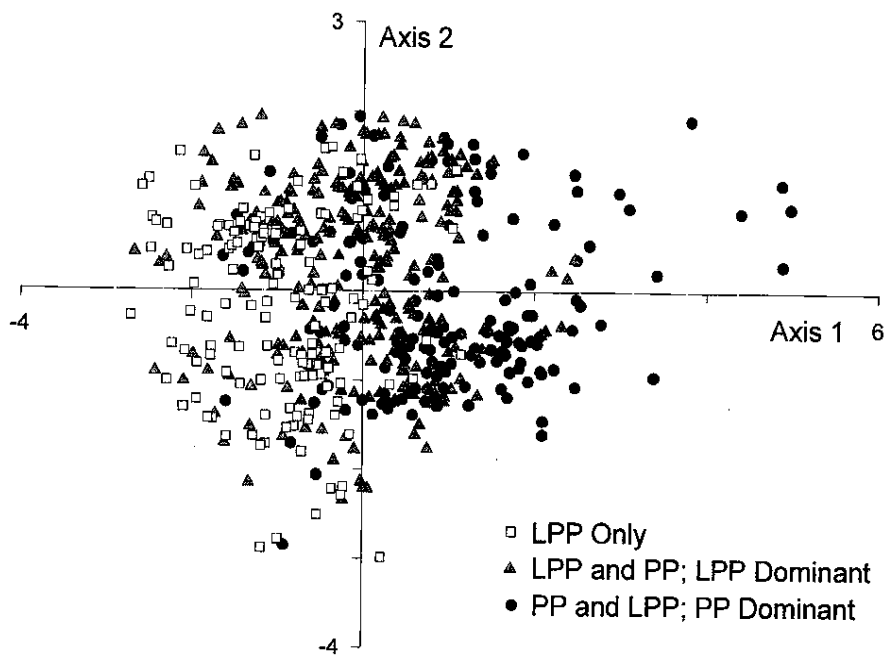


FIGURE 4. Results of canonical discriminant analysis of climate/landscape characteristics comparing permafrost peatland classes 1-3 (localized permafrost peatland). Canonical axes 1 and 2 are plotted.

southern limit of localized permafrost where aridity is highest, and promotes dry insulative peatland surfaces during the thaw season. Winter precipitation as snowfall, although not included in our analyses, also has an important effect on permafrost. The reduction of winter snowpack has been shown to be a limiting factor for permafrost aggradation in discontinuous zone wetlands (Seppälä, 1994). This can occur at the very local scale by wind scour of higher microrelief in hummocky terrain or redistribution of snow by wind in treeless wetlands. In treed wetlands dense tree cover has a similar effect, intercepting much snowfall within living forest canopies (Zoltai and Tarnocai, 1971).

Landscape factors that include peatland cover, peatland type (bog proportion of total cover), and mineral soil texture also show differences between permafrost peatland classes. Permafrost distribution is obviously related to peatland distribution, as permafrost is found most commonly in peatlands within the Discontinuous Zone and is restricted exclusively to peat in the south. The correlation of peatland cover variables to canonical axis 1 demonstrates that the landform gradient is also limited by the extent of peatland area, especially at the climatic limits of its occurrence. The amount of bog relative to total peatland cover in an area (gridcell) is more closely correlated to axis 1 than total peatland cover (Table 2), as ombrotrophic peatlands in the north of the provinces are almost exclusively peat plateau. Surface mineral soil texture shows hydraulic conductivity from low (clayey soils) to high (sandy soils). Increasing hydraulic conductivity has been associated with the occurrence of minerotrophic peatlands in Manitoba (Halsey et al., 1997) and Minnesota (Glaser, 1992). The negative correlation of soil texture to axis 1 reflects the high abundance of fen peatland in the south of the zone of localized permafrost peatland occurrence, where localized permafrost is dominant or exclusive. Farther north peat plateaus begin to dominate and ombrotrophic conditions become more common, seen in the positive correlation of proportion bog to axis 1 (Table 2).

The variation in cover of localized permafrost peatland is best explained by total peatland cover, and to a much lesser degree by mean annual temperature. The bog proportion of total peatland cover is less important than total peatland area in this case. The high cover values of fen peatland within the distri-

bution of exclusive or dominant localized permafrost peatland (class 1 and 2 gridcells) results in more localized permafrost fen than localized permafrost bog. Even though permafrost has a demonstrable affinity for bogs, localized permafrost aggradation is facilitated by dry microhabitats in fens. These include hummocky microrelief created by common peatland bryophytes such as *Sphagnum* spp. and *Tomenthypnum nitens* (Hedw.) Loeske, and dry ridges (strings) separating wet pools (flarks) in patterned fens. When regressed against coverage of localized permafrost landforms, climate is a poor explanatory variable. Part of this weak relationship is due to some nonlinear response of localized permafrost peatland area to climate, since cover decreases in colder areas when localized permafrost is replaced by peat plateau. However, the majority of data for localized permafrost peatland cover per gridcell is less than 5% and spans the range of mean annual temperatures for these gridcells, implying that most of the variability in cover is controlled by other factors (i.e., peatland cover). Altogether, this suggests that climate is an important factor in determining whether permafrost develops into expansive landforms or is limited to localized landforms. In areas where climate supports localized permafrost, cover is largely a function of available peatland area.

Although climate and landscape factors explain much of the presence/absence of permafrost landform types as well as the extent of localized permafrost at the regional scale, some variability remains unexplained. In continental western Canada, distribution of permafrost landform types and the extent of peatlands containing landforms at their climatic limits such as localized permafrost, reflect climatic patterns that existed during permafrost aggradation, i.e., during the Little Ice Age. While the Little Ice Age is expected to have been about 1°C colder than present mean annual temperatures in the region (Vitt et al., 1994), this cold period has been shown to have been asynchronous and of varying intensity worldwide (Bradley and Jones, 1992). It is also possible that the climatic conditions and weather patterns of the Little Ice Age could have been substantially different than modern climate, as has been implicated as the cause of past dramatic weather changes in Churchill, Manitoba (Scott et al., 1988). Thus, even though modern climate is an important variable explaining the presence/absence of peat plateaus and

localized permafrost in peatlands, some unexplained variability in our analyses may partially be due to climate data that inaccurately represent aggradation conditions. The inclusion of additional regional scale variables could likely explain more variation, however, factors that operate locally also have a strong effect on permafrost peatland type and coverage. Camill and Clark (1998) showed that maintenance of relict permafrost is controlled by complex local factors that operate on a landform-to-landform scale. The large region of peat plateau and localized permafrost peatland co-occurrence, and that only certain peatlands or parts of peatlands have permafrost supports the importance of local factors and processes. Though climate and landscape impose regional thresholds, local factors are influential in dictating the aggradation and degradation of permafrost at the southern limit of the Discontinuous Zone.

DEGRADATION

Permafrost has been dynamic in its distribution in continental western Canada through the climatic changes of the Holocene. Zoltai (1995) tentatively demonstrated that at 6000 yr BP permafrost zones were up to 500 km north of their current position. The Little Ice Age was the most extensive cold period since Late Wisconsinan deglaciation, evident in the most extensive glacial advances of the Holocene in the Canadian Rockies (Luckman, 1986; Grove, 1988), and tree ring records from Alberta (Case and MacDonald, 1995). It has been proposed that permafrost reached its maximum Holocene extent during this time, and account for much of the localized permafrost aggradation at the southern limit (Halsey et al., 1995). Dendrochronological dating of melt events show that degradation was initiated in the last 100 yr (Vitt et al., 1994), which is synchronous with the amelioration of climate since the Little Ice Age (Thie, 1974; Vitt et al., 1994). The spatial distribution of internal lawns shows that degradation has occurred throughout the zone of localized permafrost peatland occurrence (Vitt et al., 1994). This melting can be complete, with 40% of gridcells with only localized permafrost peatland (Class 4 on Fig. 2) having internal lawns only. The predominant distribution of completely degraded permafrost at the southern limit of permafrost demonstrates that climate warming is responsible for changes in permafrost distribution. The distribution of existing treed frost mounds has been highly dynamic over a relatively short period of time within the zone of localized permafrost peatland occurrence. Further study of localized permafrost landforms is important due to their utility as climate indicators, as well as to further understand the environmental consequences of ongoing permafrost melt in the boreal forest.

Conclusions

As a result of extensive inventory of peatland landforms and comparison to climate/landscape within continental western Canada, we demonstrate here that:

(1) Permafrost landform occurrence as either peat plateaus or localized permafrost peatland is distributed in latitudinally-oriented bands of occurrence with peat plateaus only in the north, typically localized permafrost only in the south, separated by extensive overlap or co-occurrence of landform types.

(2) Localized permafrost peatlands (peatlands with treed frost mounds and/or internal lawns) cover 17,505 km² in a zone of occurrence within the boreal forest of continental western Canada, concentrated in north-central and northeastern Alberta, northwestern Saskatchewan and central Manitoba. Localized

permafrost occurs in both fen and bog: localized permafrost fen covers 9868 km² in this zone, localized permafrost bog covers 7636 km².

(3) Climate and peatland area are the most important regional factors for the occurrence of permafrost landform types as well as the extent and distribution of localized permafrost peatlands. At the regional level, climate controls permafrost development into either extensive peat plateau or localized frost mounds. In climates where localized permafrost peatlands occur, their coverage is mostly a function of peatland area. Local factors are responsible for short-term temporal dynamics at the site level.

(4) Localized permafrost in peatlands is the most recently formed and the most climatically sensitive permafrost in the Discontinuous Zone. The continuing degradation of permafrost has moved the southern limit of permafrost north by an average of 39 km and by more than 200 km at some locations over the last century.

Acknowledgments

Support to D. W. Beilman from the Alberta Challenge Grants in Biodiversity Program funded by the Alberta Conservation Association, and from the Northern Science Training Program of the Canadian Circumpolar Institute is gratefully acknowledged. Thanks is extended to Tim Martin for GIS assistance. This project was also supported through a Climate System History and Dynamics NSERC Research Network Grant, a Network of Centres of Excellence in Sustainable Forest Management Grant, and a NSERC Operating Grant to D. H. Vitt.

References Cited

- Belland, R. J. and Vitt, D. H., 1995: Bryophyte vegetation patterns along environmental gradients in continental bogs. *Ecoscience*, 2: 395-407.
- Bradley, R. S. and Jones, P. D., 1992: *Climate since A.D. 1500*. New York: Routledge. 679 pp.
- Brown, G., 1980: Palsas and other permafrost features in the lower Rock Creek valley, west-central Alberta. *Arctic and Alpine Research*, 12: 31-40.
- Brown, R. J. E., 1968: Occurrence of permafrost in Canadian peatlands. *Proceedings of the Third International Peat Congress, Quebec*, 174-181.
- Brown, R. J. E. and Williams, G. P., 1972: *The Freezing of Peatlands. Technical Paper of the Division of Building Research*, 381. Ottawa: National Research Council of Canada. 24 pp.
- Camill, P. and Clark, J. S., 1998: Climate change disequilibrium of boreal permafrost peatlands caused by local processes. *The American Naturalist*, 151: 207-222.
- Case, R. A. and MacDonald, G. M., 1995: A dendroclimatic reconstruction of annual precipitation on the western Canadian prairies since A.D. 1505 from *Pinus flexilis* James. *Quaternary Research*, 44: 267-275.
- Gignac, L. D. and Vitt, D. H., 1994: Responses of northern peatlands to climate change: effects on bryophytes. *Journal of the Hattori Botanical Laboratory*, 75: 119-132.
- Glaser, P. H., 1992: Peat Landforms. In Wright, H. E., Coffin, B. A., and Aaseng, N. E. (eds.), *The Patterned Peatlands of Minnesota*. Minneapolis: The University of Minnesota Press, 3-14.
- Grove, J. M., 1988: *The Little Ice Age*. New York: Methuen. 498 pp.
- Halsey, L. A., Vitt, D. H., and Bauer, I. E., 1998: Peatland initiation during the Holocene in continental western Canada. *Climatic Change*, 40: 315-342.
- Halsey, L. A., Vitt, D. H., and Zoltai, S. C., 1995: Disequilib-

- rium response of permafrost in boreal continental western Canada to climate change. *Climatic Change*, 30: 57–73.
- Halsey, L. A., Vitt, D. H., and Zoltai, S. C., 1997: Climatic and physiographic controls on wetland type and distribution in Manitoba, Canada. *Wetlands*, 17: 243–262.
- Harris, S. A., French, H. M., Heginbottom, J. A., Johnston, G. H., Ladanyi, B., Segó, D. C., and van Everdingen, R. O., 1988: *Glossary of Permafrost and Related Ground-ice Terms*. Ottawa, Canada: National Research Council of Canada Technical Memorandum 142.
- Heginbottom, J. A., 1995: Canada—Permafrost, Plate 2.1, MCR 4177. In: *The National Atlas of Canada*. 5th ed. Ottawa: National Resources Canada.
- Kershaw, G. P. and Gill, D., 1979: Growth and decay of palsas and peat plateaus in the Macmillan Pass—Tsichu River area, Northwest Territories, Canada. *Canadian Journal of Earth Sciences*, 16: 1362–1374.
- Luckman, B. H., 1986: Reconstruction of Little Ice Age events in the Canadian Rocky Mountains. *Géographie physique et Quaternaire*, 40: 17–28.
- Muller, S. W., 1945: *Permafrost or Perennially Frozen Ground and Related Engineering Problems, Special Report. Strategic Engineering Study*, 62. 2nd ed. Washington: United States Geological Survey.
- Nelson, F. E., Hinkel, K. M., and Outcalt, S. I., 1991: Palsa-scale frost mounds. In Dixon, J. C. and Abrahams, A. D. (eds.), *Periglacial Geomorphology*. London: Wiley, 305–325.
- Oke, T. R., 1987: *Boundary Layer Climates*. London: Methuen. 435 pp.
- Pettapiece, W. W., 1995: *Land Suitability Rating System for Agricultural Crops: 1. Spring-seeded small grains. Technical Bulletin 1995–6E*. Ottawa, Canada: Centre for Land and Biological Resources Research, Agriculture and Agri-Food Canada.
- SAS, 1990: *SAS/STAT User's Guide, Version 6, Fourth Edition, Volume 2*. SAS Institute Inc. Cary, N.C., U.S.A.
- Scott, P. A., Fayle, D. C. F., Bentley, C. V., and Hansell, R. I. C., 1988: Large-scale changes in atmospheric circulation interpreted from patterns of tree growth at Churchill, Manitoba, Canada. *Arctic and Alpine Research*, 20: 199–211.
- Seppälä, M., 1988: Palsas and related forms. In Clarke, M. J. (ed.), *Advances in Periglacial Geomorphology*. Chichester: Wiley, 247–278.
- Seppälä, M., 1994: Snow depth controls palsa growth. *Permafrost and Periglacial Processes*, 5: 283–288.
- Sollid, J. L. and Sorbel, L., 1974: Palsa bogs at Haughtjornin, Dovrefjell, south Norway. *Norsk Geografisk Tidsskrift*, 28: 53–60.
- Sollid, J. L. and Sorbel, L., 1998: Palsa bogs as climate indicator—examples from Dovrefjell, south Norway. *Ambio*, 27: 287–291.
- Thie, J., 1974: Distribution and thawing of permafrost in the southern part of the discontinuous permafrost zone in Manitoba. *Arctic*, 27: 189–200.
- Vitt, D. H., Bayley, S. E., and Jin, T.-L., 1995: Seasonal variation in water chemistry over a bog-rich fen gradient in continental western Canada. *Canadian Journal of Fisheries and Aquatic Sciences*, 52: 587–606.
- Vitt, D. H., Halsey, L. A., and Zoltai, S. C., 1994: The bog landforms of continental western Canada in relation to climate and permafrost patterns. *Arctic and Alpine Research*, 26: 1–13.
- Vitt, D. H., Halsey, L. A., Bauer, I. E., and Campbell, C., 2000b: Spatial and temporal trends in carbon storage of peatlands of continental western Canada through the Holocene. *Canadian Journal of Earth Sciences*, 37: 683–693.
- Vitt, D. H., Halsey, L. A., and Zoltai, S. C., 2000a: The changing landscape of Canada's western boreal forest: the current dynamics of permafrost. *Canadian Journal of Forest Research*, 30: 283–287.
- Washburn, A. L., 1980: Permafrost features as evidence of climate change. *Earth-Science Reviews*, 15: 327–402.
- Washburn, A. L., 1983: What is a palsa? *Abhandlungen der Akademie der Wissenschaften in Göttingen, Mathematisch-Physikalische Klasse*, 35: 34–47.
- Zar, J. H., 1984: *Biostatistical Analysis*. Englewood Cliffs, New Jersey: Prentice Hall.
- Zoltai, S. C., 1971: Southern limit of permafrost features in peat landforms, Manitoba and Saskatchewan. *Geological Association of Canada, Special Paper*, 9: 305–310.
- Zoltai, S. C., 1972: Palsas and peat plateaus in central Manitoba and Saskatchewan. *Canadian Journal of Forest Research*, 2: 291–302.
- Zoltai, S. C., 1988: Wetland environments and classification. In Rubec, C.D.A. (coord.), *Wetlands of Canada*. Montreal: Polyscience Publications, 1–26.
- Zoltai, S. C., 1995: Permafrost distribution in peatlands of west-central Canada during the Holocene warm period 6000 years B.P. *Géographie physique et Quaternaire*, 49: 45–54.
- Zoltai, S. C. and Tarnocai, C., 1971: Properties of a wooded palsa in northern Manitoba. *Arctic and Alpine Research*, 3: 115–129.
- Zoltai, S. C. and Tarnocai, C., 1975: Perennially frozen peatlands in the western Arctic and Subarctic of Canada. *Canadian Journal of Earth Sciences*, 12: 28–43.

Ms submitted January 2000