University of Alberta

RATE OF PERMAFROST DEGRADATION IN PEATLANDS

by

© Peter G. C. Englefield

A thesis submitted to the Faculty of Graduate Studies and Research
in partial fulfillment of the requirements for the degree of Master of Science

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"'Ha-ha!' I cried, for now the ideas were beginning to come.

'What is the oldest living thing in the world?

What lives longer than anything else?'"

"A tree," said Charlie.

- Roald Dahl

Charlie and the Great Glass Elevator

University of Alberta

Faculty of Graduate Studies and Research

The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies and Research for acceptance, a thesis entitled Rate of Permafrost Degradation in Peatlands submitted by Peter G.C. Englefield in partial fulfillment of the requirements for the degree of Master of Science.

Dr. Ross W. Wein

Dr. Mark R.T. Dale

Dr. Richard L. Rothwell

DEDICATION

To my parents.

Thank you.

ABSTRACT

Due to the insulating properties of dry peat, permafrost at its southern limit occurs mainly in peatlands, where it is found in raised mounds or plateaus because of the expansion of freezing water. The dry peat on the surfaces of plateaus protects the permafrost from summer heat. However, because peat forms in wet conditions, peat plateaus are usually surrounded by wetlands, and often by standing water. The standing water acts as a heat conductor, causing the permafrost core to melt from the sides. Peat plateaus have been found to undergo cycles of aggradation and collapse. Fire is a major trigger for peat plateau collapse because it can consume the insulating peat.

The peat plateau surface provides a suitable habitat for tree growth. Trees on the subsiding plateau edges die when their roots drown in the wetland. The dead trees provide a record of the location of the plateau edge over time because their dates of death, determined by crossdating, indicate when they were deposited into the water.

Study sites were at Hotchkiss (57°10'N 118°11'W) and Lutose (59°26'N 117°16'W) in northern Alberta and at Sandy Lake (60°32'N 114°30'W) in the Northwest Territories. At each site, 16 transects were established across retreating plateau edges. Live and dead trees along the transects were sampled for crossdating and examination of compression wood. Dead trees were crossdated using frost rings as markers.

The tree ring record extended back to about 1950. Since that time, plateau edges retreated at 0.1 to 0.2m per year on average. The highest retreat rates occurred after 1975, probably due to changes in climatic factors such as temperature and precipitation which affect the soil thermal regime. Year-to-year variability in retreat rates was high, reflecting variability in climate and in tree resistance to drowning.

The collapse of peat plateaus brings about major changes in vegetation, decomposition, and carbon storage and release. Peatlands are a major carbon sink, drawing more carbon from the atmosphere by photosynthesis than they return to it by decomposition. Changes in fire frequency and severity triggered by climate change could reverse this imbalance. Fire itself releases large amounts of carbon dioxide, and the collapse of peat plateaus into wetlands increases anaerobic decomposition and methane release.

ACKNOWLEDGEMENTS

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Science Institute of the Northwest Territories provided accomodation and office space in Inuvik, as well as field equipment. Information on fires in the area was obtained from the Renewable Resources Fire Centre at Shell Lake. Transportation to and around Inuvik was provided by Dr. Simon M. Landhäusser. Air photos of the Dempster Highway were made available by the NWT Department of Transportation in Inuvik.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

INTRODUCTION

At the southern limit of the discontinuous permafrost zone, permafrost is most often found in peatlands (Brown 1970a, 1977, Lagarec 1982). Peatland areas containing permafrost are raised above the surrounding wetland because of the expansion of freezing water and formation of ice lenses (Sollid and Sorbel 1974, Zoltai and Tarnocai 1971) and possibly because of buoyancy (Salmi 1970, Zoltai 1972). These permafrost-cored mounds, ridges and plateaus are well described in the literature (Zoltai and Tarnocai 1975, Seppala 1988). This study deals with peat plateaus, but the melting and subsidence process is similar for all permafrost-dependent raised peatland forms (Brown 1968, Payette *et al.* 1976). Developed peat plateaus in the discontinuous permafrost zone are typically 1m in height and a few square meters to several square kilometers in area, and have an active layer 0.5m deep over a permafrost layer 2-3m thick (Zoltai 1972, Zoltai and Tarnocai 1975).

Because peat plateaus are higher than the rest of the peatland, their surfaces are well-drained. Dry peat is a very effective insulator, allowing the permafrost core to persist through the summer. In the fall, the peat becomes moist due to decreased evaporation, and then freezes. The thermal conductivity of frozen saturated peat is 25-30 times greater than that of dry peat (Brown 1966, Washburn 1979). As a result, heat energy is lost from the plateau during the winter more quickly than it is absorbed during the summer (Brown 1969).

This imbalance is enhanced by several factors, including snow and vegetation. Snow tends to blow off the plateau surface, depriving it of winter insulation and allowing heat to escape (Brown 1977, Seppala 1982). Plateau vegetation includes trees (mainly *Picea mariana*) which intercept snow in winter and provide shade in summer (Zoltai and Tarnocai 1971), and lichens (mainly *Cladonia* spp.) which have a high albedo.

Cyclic Growth and Subsidence of Peat Plateaus

As water migrates toward the ice core and freezes, the peat plateau grows higher (Seppala 1988). It cannot do so indefinitely, however. Cracks form in the plateau surface due to differential freezing and thawing (Salmi 1970) and possibly due to vertical expansion of the plateau (Svensson 1970), increasing heat flow into the permafrost core. The dry peat on the surface is susceptible to burning (Rowe and Scotter 1973), which can remove both the vegetation and the peat. Also, a moat of standing water often forms around the edge of the plateau (Brown 1969, Chatwin 1981). The moat may be the result of retreat of the plateau edges, subsidence due to the weight of the plateau (Svensson 1970), or fire (R.W. Wein per. comm.; fire is discussed below in more detail). The water in the moat acts as a conductor whereby heat energy is conducted laterally into the permafrost core (Sollid and Sorbel 1974) across a steep temperature gradient. For this reason, permafrost melting is mainly horizontal rather than vertical.

Pools of water can also form in depressions or cracks in the plateau surface (Salmi 1970), especially when the plateau is large enough that drainage near the center is impeded by the permafrost. These pools become deeper and larger as the water causes melting of the ice, and are called collapse scars, thaw ponds, or thermokarst pools (Viereck 1973, Seppala 1982). Peat plateaus may be several square kilometers in area (Zoltai and Tarnocai 1975) and contain many collapse scars. If a collapse scar dries out, the depression remains a local drainage point. When the permafrost underneath the collapse scar has melted, lateral permafrost meltout continues at the edges.

Measurements of Permafrost Degradation Rates using Air Photos

The rate of plateau edge retreat can be measured by examining air photos of peatlands taken at different times (see Table 1). Using this method, Thie (1974) measured retreat (peripheral collapse) rates of 0 (inactive) to 1.0m per year between 1947 and 1967 near Lake Winnipeg, Manitoba. Many plateaus less than 50m in diameter disappeared completely during the 20-year period. Internal collapse (advance of collapse scar edges) was slower, averaging less than 0.25m per year. No measurable aggradation took place between 1926 and 1967. The permafrost in the study area was estimated to be between 200 and 600 years old, and by 1967 three quarters of this originally occurring permafrost had melted.

Chatwin (1981) measured peripheral retreat rates of up to 1.5m per year from air photos taken in 1948 and 1976 near Fort Simpson, NWT. Plateaus less than 50m in diameter disappeared completely. Some edges were advancing, but the retreat rates exceeded the advance rates between 1948 and 1976. No measurable internal retreat was observed, although collapse scars were present. Also using air photos, Reid (1977) found considerable thawing (20-80% of the original permafrost) and no measurable aggradation between 1955 and 1973 in northwestern Alberta. Peripheral retreat rates were up to 2.8m per year, and most plateaus less than 50m in diameter disappeared completely. Internal collapse rates were much slower, averaging 0.2m per year. Based on carbon-14 dates and vegetation patterns, it was estimated that permafrost degradation had exceeded aggradation for 80-110 years.

Measurement of Permafrost Degradation Rates using Tree Rings

A tree on the retreating plateau edge tends to lean toward the collapse scar, and forms compression wood in response. The onset of compression wood formation indicates the time that the plateau edge reached the location of the tree (Laprise and Payette 1988). As melting continues, the tree subsides into the collapse scar and drowns. In many cases, the bole remains standing, often severely tilted, and the submerged portion is preserved in anaerobic and acidic (bog) conditions (Zoltai and Tarnocai 1975, Chatwin 1981). The distance between the dead tree and the current plateau edge is the distance that the plateau edge has receded since the tree died. The date of death can be determined by crossdating. The number of years of compression wood formation may be an indication of how much time the tree spent on the plateau edge before reaching the collapse scar.

Table 1. Summary of results from previous studies, in which air photos were used to measure plateau edge retreat and percentage decrease in peatland area underlain by permafrost.

Reference	Study location	Time period	Mean annual decrease in permafrost area	Mean annual peripheral retreat rate	Mean annual internal retreat rate
Tarnocai (1972)	Central Manitoba	1946-1971	1.0%		
Thie (1974)	Central Manitoba	1947-1967		0-1.5m/yr	<0.25m/yr
Reid (1977)	Hay Lake, Alberta	1955-1973	1.1-4.4%	0-2.8m/yr	<0.2m/yr
Kershaw & Gill (1979)	Selwyn Mts., NWT	1944-1974	1.1%		
Chatwin (1981)	Fort Simpson, NWT	1948-1976	0.9%	0.3-1.5m/yr	~0
Laprise & Payette (1988)	Northern Quebec	1957-1983	1.9%		

The tree-ring method for measuring plateau edge retreat rate has several advantages over the air photo method. It yields many short-term rates, rather than one average rate, allowing for measurement of acceleration and variability, and it is not limited to times and places of air photo availability. However, it is limited by the rate of decomposition of dead trees and can only be used in forested peatlands. Furthermore, at rates as high as those mentioned above (up to 2.8m per year), a tree would not have time to straighten out and would be more likely to fall over as it is deposited into the collapse scar. Once it has fallen over, it is in the zone where moisture fluctuates from season to season, and is soon too decomposed to be crossdated; at the same time, peat development continues, enveloping the tree.

Laprise and Payette (1988) used frequency of compression wood occurrence to estimate permafrost degradation rates in a peatland on the eastern coast of Hudson Bay. Dead trees from the peatland were crossdated to extend the tree ring record. The peak degradation period was between 1930 and 1965, and the time of subsidence of some of the peat plateaus was determined from tree death dates. The results of the tree ring study confirmed that permafrost degradation rates were higher before 1973 than presently, as was determined with air photos and maps of the peatland (see Table 1). However, no areal or lateral rates of degradation were calculated using tree rings.

Factors Affecting Plateau Edge Retreat Rate

Plateau edge retreat rates are influenced by vegetation, snow cover, standing water, rainfall, drainage, temperature, soil nutrient status, aspect, and fire. Vegetation, snow cover and standing water have been discussed already.

Rainfall. Moisture decreases the effectiveness of the peat in insulating the permafrost, allowing more heat to penetrate the plateau. The thermal conductivity of dry unfrozen peat is about 0.08 W/m/°C, while that of saturated unfrozen peat is almost 6 times higher, 0.46 W/m/°C, although not as high as that of frozen saturated peat (2.3W/m/°C) (Washburn 1979).

Drainage. Poor drainage and a moisture surplus are necessary for peat formation, but permafrost development is inhibited beneath standing or flowing surface water (Brown 1977). Therefore water plays a part in both the formation and degradation of permafrost. Peat impedes drainage, and permafrost is impermeable to water (Brown 1970b). As a result, paludification is somewhat self-perpetuating.

Temperature. Hot summers have the potential to cause faster permafrost degradation, but may also result in drier, better-insulating peat and less standing water. Therefore climatic warming can be expected to cause a northward shift in peatland permafrost distribution only after a substantial lag period, unless the surface peat is disturbed in some way. The southern limit of permafrost currently coincides roughly with the -1°C mean annual (air) isotherm (Brown 1971). Scattered permafrost bodies can be found south of this limit, but are generally relicts, possibly formed during the Little Ice Age (Vitt *et al.* 1994).

Soil nutrients. Permafrost usually forms in ombrotrophic wetlands (bogs), which cannot form on nutrient-rich mineral soil (Ruuhijarvi 1970). The variation in nutrient status within permafrost peatlands is mainly due to drainage patterns and rates. Soil and water nutrients in turn affect vegetation growth rates and recovery after fire.

Aspect. Aspect is of minor importance. Peatlands are generally flat and the plateaus provide only low relief (1-2m). Because of the insulating qualities of dry peat, heat moves into the plateaus almost exclusively through standing water, which distributes heat uniformly throughout the wet area.

Fire. Most fires kill only surface vegetation (Jasieniuk and Johnson 1982), leaving the peat unaffected. However, a fire that only kills the trees may result in a lowering of the permafrost table (Brown 1970b) because of decreased shade and blackening of the soil surface. Zoltai (1972) observed melting of permafrost beneath a clearcut. When a severe fire occurs, layers of peat are burned away, especially from the drier and better-drained shoulders of the plateau. Thus fire removes peat from the areas where the permafrost core is most vulnerable. The removal of peat at the plateau edges may result in a water-filled moat when the plateau edge subsides.

Studies in peatlands and other soil types indicate that the depth of the active layer typically increases by over 100% within 5 years after a severe fire, and permafrost meltback continues for 10 to 50 years (Viereck 1973, Mackay 1977, Viereck and Dyrness 1979, Heinselman 1981, Van Cleve and Viereck 1983). Fire-induced permafrost degradation in peatlands has been documented by Viereck (1973), Thie (1974), Reid (1977), Couillard and Payette (1985), Zoltai (1993) and others.

However, stands of trees of fire origin growing on peat plateaus indicate that plateaus can persist even long after stand-replacing fires (Zoltai 1975b, Reid 1977). Zoltai (1993) used peat cores to show that while periods of rapid melting and subsidence are triggered by fire, not all fires have this effect. The determining factors are depth of burn and peat plateau maturity. For example, a spring fire may kill all the trees, but burn little of the peat (Brown 1969, Heinselman 1981). Thie (1974) found no difference in peat plateau collapse rates in a burned vs. unburned peatland area in Manitoba. Similarly, compression wood evidence indicated that fires did not cause an increase in soil movement near Inuvik and Norman Wells, NWT (Zoltai 1975a).

OBJECTIVE

The objective of this study was to measure the rate of peat plateau edge retreat in three peatland areas in the discontinuous permafrost zone by examining live and dead trees near plateau edges.

METHODS

Study sites were located in three peatland areas in the discontinuous permafrost zone (Figure 1). All were characterized by 1-2m high peat plateaus (using the terminology of Zoltai and Tarnocai 1975) or peat complexes (Seppala 1988) dominated by black spruce and lichens, and collapse scars dominated by *Sphagnum* spp. (see Figure 2). All the plateaus were classified as overmature according to Zoltai (1972). Vegetation on the plateaus and in the collapse scars was similar to that described in Zoltai (1993). At some transects there was open water between the plateau edge and the *Sphagnum*. All sites involved extensive peat plateaus containing multiple collapse scars.

Characteristics of the collapse scars differed between sites (Table 2). At Hotchkiss, collapse scars were smaller than at the other two sites, and within 20m of each other. Several were conglomerations of two or more originally separate collapse scars. At Lutose, the collapse scars were larger, but irregularly shaped, indicating different rates of retreat along the edges, and were usually more than 100m apart. At Sandy Lake, individual collapse scars were 10-20m across, but most of the collapse scars were made up of two or more originally distinct scars. At some transects, the collapse scar area exceeded the remaining plateau area, and the plateau was no longer contiguous. Sandy Lake collapse scars were also deeper than those at the other two sites.

At each site, 16 plateau edges were selected that had trees on the plateau and in the collapse scar. Subsided "peninsulas" and "islands", indicated by rows or clumps of dead trees, were avoided. For each plateau edge, a transect was established from the top of the plateau across the retreating edge and into the collapse scar. The transect distance at which the lichens on the plateau met the moss in the collapse scar was recorded to within 0.1m, as a biological approximation of the plateau edge. For transects where the lichen and moss did not meet due to open water, the limit of the lichens was considered the plateau edge. Disks were taken from just above the root collars of trees along the transects. The number of trees sampled depended on availability, and varied between 3 and 10. With a few exceptions, sampled trees were within 2m of the transects. Each tree's distance along the transect was recorded to the nearest 0.1m. The condition of dead trees was noted, in particular the presence of bark, cones, twigs and branches. Plateau height was measured with a clinometer as a possible indication of plateau maturity (Seppala 1982). To establish fire histories for each site, a fire-scarred tree was sampled in the vicinity (within 100m) of each transect whenever possible. An old unscarred tree was also sampled near each transect to make a master chronology.

Disks were sanded with a belt sander to 120 grit, then with an orbital sander to 400 grit. Ring widths were measured by scanning the disks with an optical scanner at 600dpi and analyzing the image with *Dendroscan* (Campbell and Varem-Sanders 1994). However, crossdating of the dead trees with live trees using ring widths was unsuccessful because of low year-to-year ring width variability (i.e., complacency) and lack of similarity in ring width patterns among trees, even live trees growing next to each other. Instead, frost rings were used as crossdating markers. The most reliably-

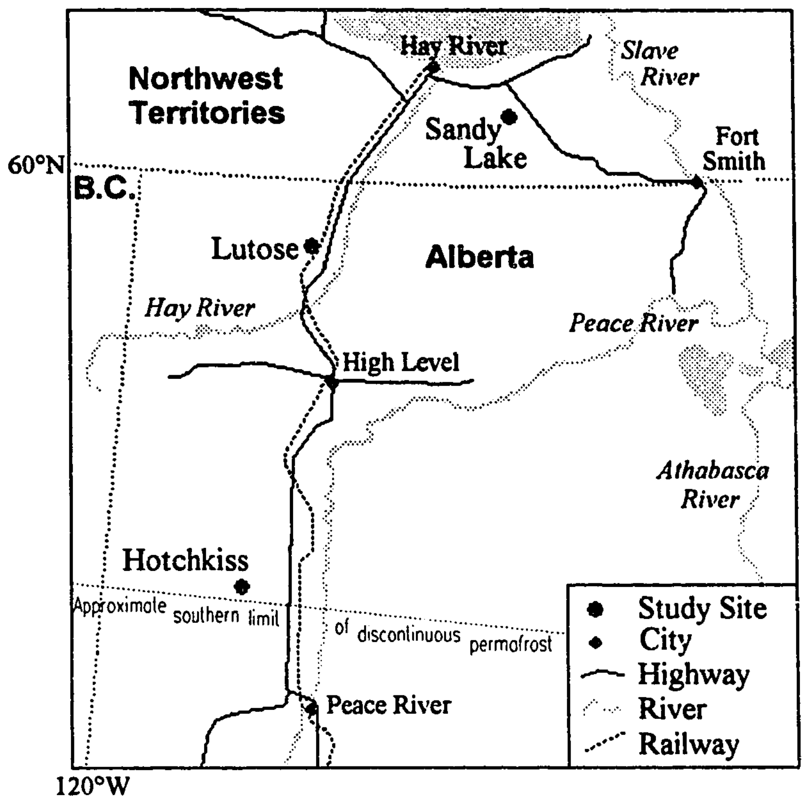

Figure 1. Map of Study Site Locations.

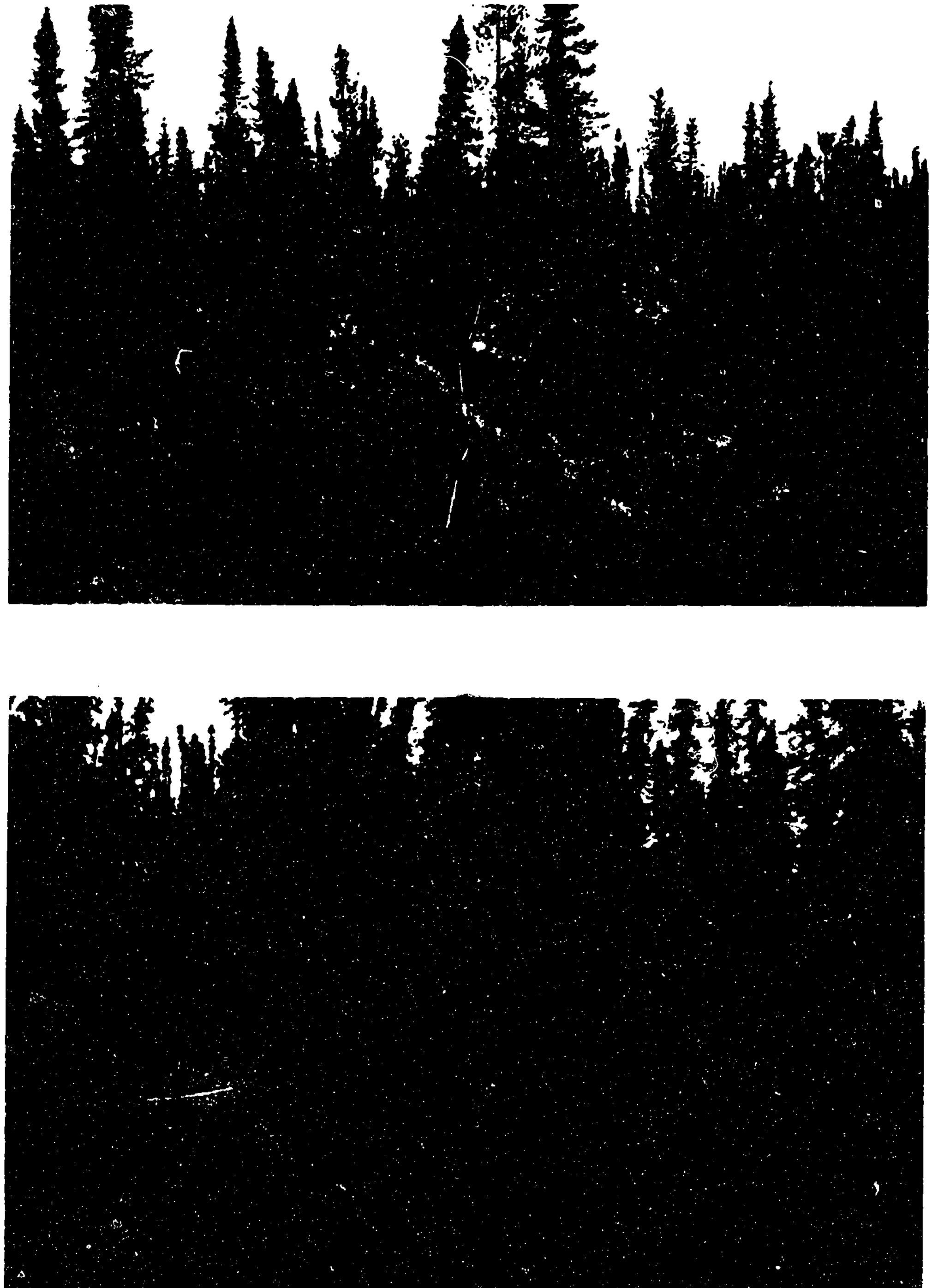

Figure 2. (a) Peat plateau edge at the Sandy Lake study site. The collapse scar is in the foreground; the plateau surface is about 2m above the collapse scar surface. (b) Peat plateau edge at Hotchkiss. The plateau is about 1m high. Note the dead trees in the collapse scar and the leaning trees on the plateau edge.

Table 2. Study site locations, climate and characteristics.

	Study Site Hotchkiss	Lutose	Sandy Lake
Location	57°10'N 118°11'W	59°26'N 117°16'W	60°32'N 114°34'W
Peatland area sampled	0.2km²	11km²	1km²
Normal air temperature*			
Annual	-0.8°C	-2.0°C	-3.8°C
January	-20.5°C	-21.4°C	-25.7°C
July	15.7°C	16.2°C	16.0°C
Normal annual precipitation			
Rainfall	262.5mm	257.9mm	209.6mm
Snowfall (water equivalent)	141.6mm	128.8mm	149.3mm
Normal annual degree-days above 0°C	2134.8	2061.4	1916.9
Weather station location	57°01'N 117°34'W	58°37'N 117°10'W	60°39'N 116°00'W
Distance between study site and weather station	40km	90km	82km
Mean collapse scar depth	1.0m	1.0m	1.4m
Collapse scar diameter	5-15m	10-20m	>10m

*Climate normals are from 1951-80 (Environment Canada 1982).

occurring frost rings in live trees from each study site were used to construct a "frost skeleton plot" master chronology not unlike conventional thin-ring skeleton plots (Glock 1937). Instead of ring width, the quantity plotted was the frost ring's fractional radial position within the growth ring, a quantity which was consistent among trees, being a measure of the time that the frost occurred within the growth season. Individual plots for the dead trees were then constructed and compared with the master plots to determine the each tree's date of death (Figure 3). Stand age, fire scars and tree condition were also used in crossdating, but many trees could not be dated with certainty, especially comparatively old trees and those with very thin rings. Only those trees crossdated with certainty were used in the analysis.

Plateau edge retreat rates were calculated for each transect according to

$$R_{12} = (d_2 - d_1) / (t_1 - t_2)$$

where R_{12} is the mean retreat rate during the time period between the deaths of trees 1 and 2, d_x is the transect distance of tree x, and t_x is the year of death of tree x. The retreat rate between the year the first tree died and the sampling date was calculated for each transect according to

$$R_{01} = (d_1) / (t_0 - t_1)$$

where R_{01} is the mean retreat rate during the time period between the death of tree 1 and the sampling date, d_1 is the transect distance of tree 1 (the lichen/moss boundary has a transect distance of 0), t_0 is the sampling year, and t_1 is the year of death of tree 1. While the lichen/moss boundary was not a precise indication of the boundary between live and dead trees, it was the only distinct visible boundary available, being typically less than 0.1m wide.

Overall rates were also estimated by a linear regression of transect distance on year of death using all the dead trees from each site. The slope of the linear regression of distance on time gives an average rate of retreat over the study period. Because all the transects involved collapse scars within extensive peat plateau areas, the retreat rates measured were of internal rather than peripheral collapse (see Table 1).

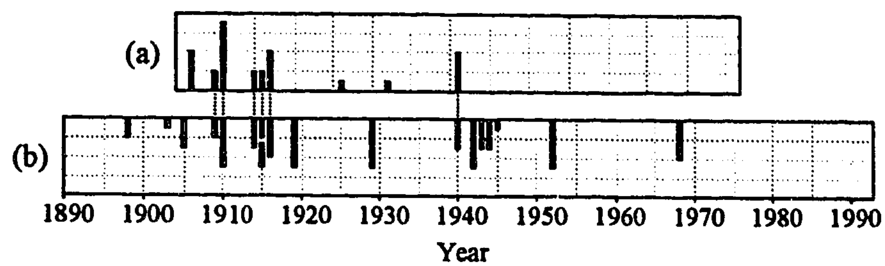

Figure 3. Crossdating with frost skeleton plots. The lengths of the line segments indicate how far through the growth ring the frost ring was found. Broken line segments indicate years with more than one frost ring. Hollow segments indicate that the frost ring was not dated with certainty. (a) Example of a frost skeleton plot for a dead tree. (b) Master frost skeleton plot for the Sandy Lake study site, with reliable frost ring dates determined from live trees. Based on matching frost ring years, it can be determined that the dead tree lived from 1904 to 1976.

RESULTS

The condition of the dead trees at the Hotchkiss study site (Figure 4) indicates that the longest-dead trees that still had standing boles died about 50 years ago; trees at the other sites were similar. This dictated the time limit over which retreat rates could be calculated. There may have been stumps in the peat in good condition from trees that died earlier, but their locations could not be determined without digging up the entire transect.

Figure 5 gives the results from a single transect. The results from all 16 transects from each study site are given in Figure 6. Although there is wide variability among transects, the highest retreat rates from all three sites occur after 1975, suggesting that permafrost degradation is accelerating. Negative rates arise when trees do not die "in order", probably due to variation in trees' resistance to drowning. The methodology clearly does not allow for measurement of true negative rates (permafrost aggradation). There are also two undefined (infinite) rates, which resulted from trees at different distances on the same transect dying in the same year. Two trees 0.4m apart both died in 1992, and two trees 1.5m apart died in 1956. This may indicate retreat of more than 0.4 or 1.5m per year respectively in those years, or could be caused by other factors as discussed later.

Retreat rates also vary from year to year. The rates in Figure 6 all represent averages over several years. The highest calculated rates are sustained for only a short period of time, while averages over long periods are rarely extreme because they include years of little or no activity. The long-term rates could also be expected to be lower because fewer trees die during periods of slow retreat. However, short-term averages are also more sensitive to variation in the ability of trees to survive in the collapse scar.

At Hotchkiss, almost 90% of the trees sampled were established between 1902 and 1909, presumably after a major fire in about 1901 (Figure 7). No scars from this fire were found, indicating that most or all of the trees were killed. There were fire scars from several spot fires, but none was widespread or followed by recruitment. At Lutose, most of the trees were of fire origin, but many of them were from small fires which burned at one or two transects. Widespread fires occurred in 1912 and 1943, but both were patchy and generally not stand-replacing. As at Hotchkiss, the highest retreat rates (Figure 6) occur after 1975. At Sandy Lake transects, 13 were within the perimeter of a 1936 burn, but only 7 were dominated by trees that were established between 1936 and 1946. There were three transects within the perimeter of a 1946 burn, but no postfire recruitment was found.

Table 3 summarizes the results from each site. The "overall" retreat rate is a weighted mean of the rates in Figure 6, each rate weighted according to the number of years over which it was calculated. The "dead trees only" rate was calculated in the same way, using only rates measured between dead trees and excluding those based on the lichen/moss boundary. The "regression slope" is the slope of the linear regressions in Figure 8. Retreat rates are similar to internal retreat rates in previous studies (Table 1). The retreat rates are lowest at Hotchkiss and highest at Sandy Lake, regardless of calculation method. At Sandy Lake, the retreat of the edges of plateau remnants

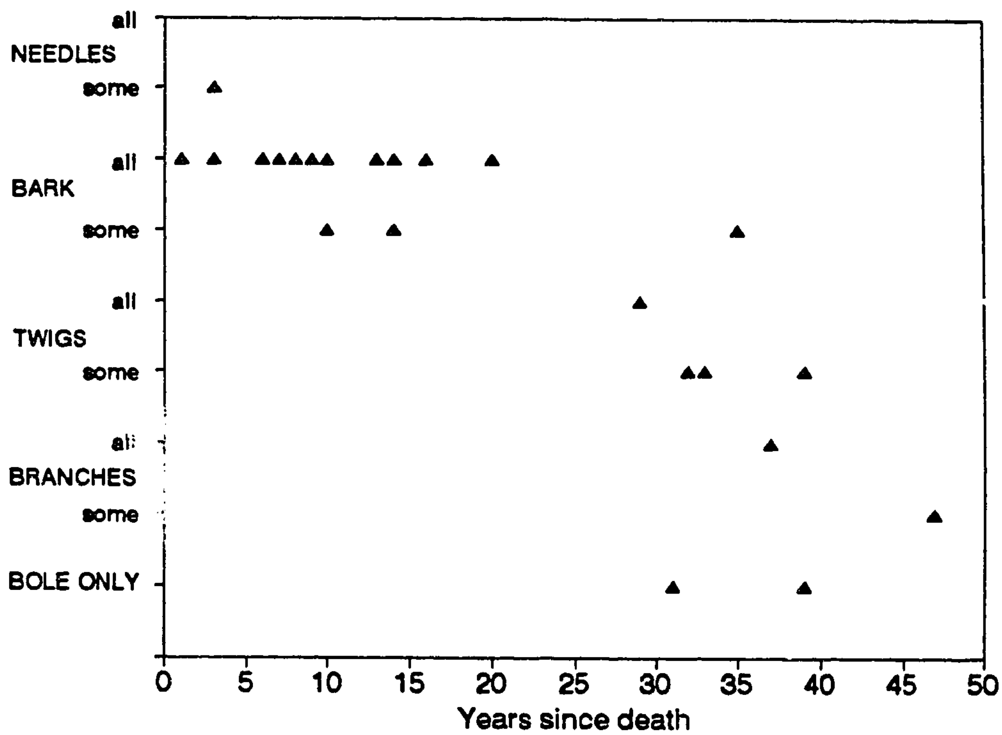

Figure 4. Estimated state of decomposition of successfully crossdated dead black spruce trees from the Hotchkiss study site.

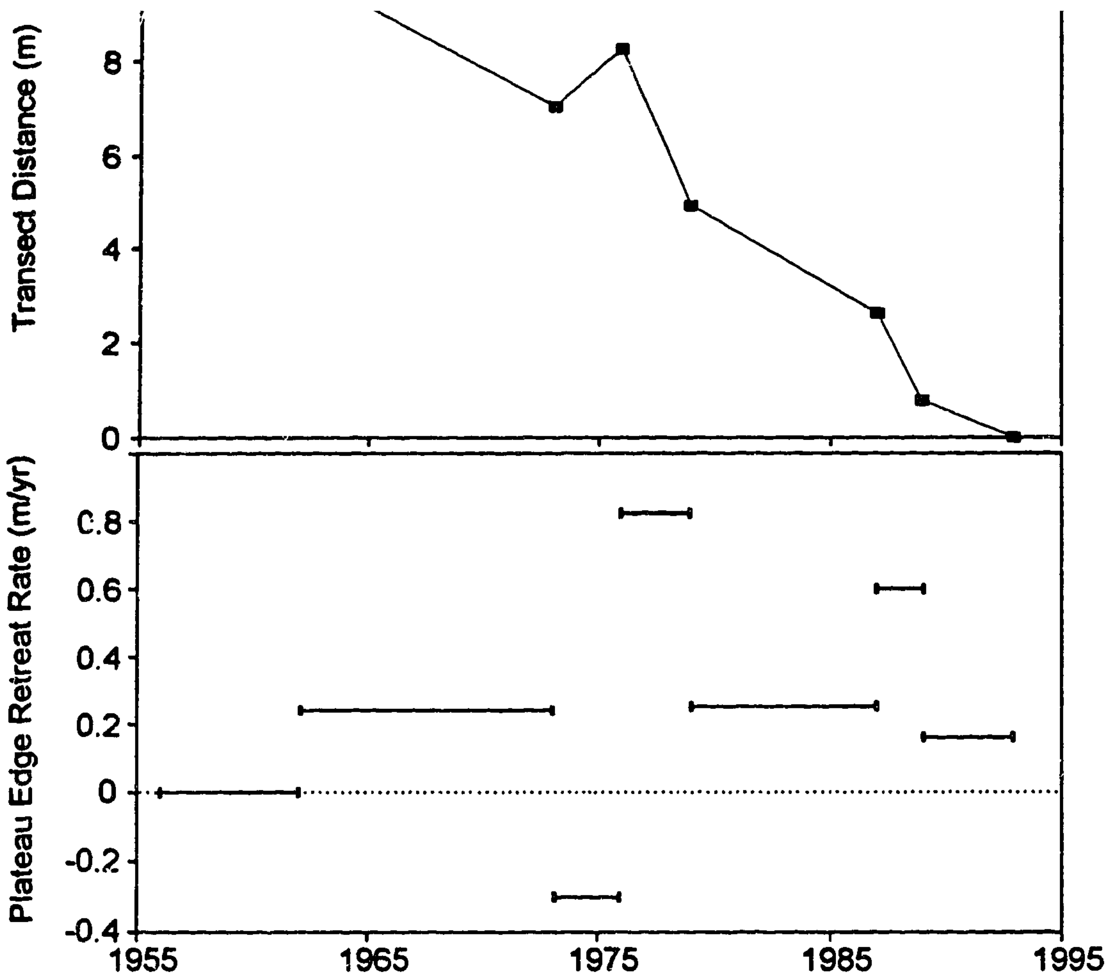

Figure 5. (a) Transect locations and dates of death of trees from a single transect. Positive distances refer to locations in the collapse scar; negative distances refer to locations on the plateau. The slopes of the line segments give the rate of plateau edge retreat for that time period. The y-intersect is the present (1993) lichen/moss boundary. (b) Plateau edge retreat rates calculated from the tree death dates in (a).

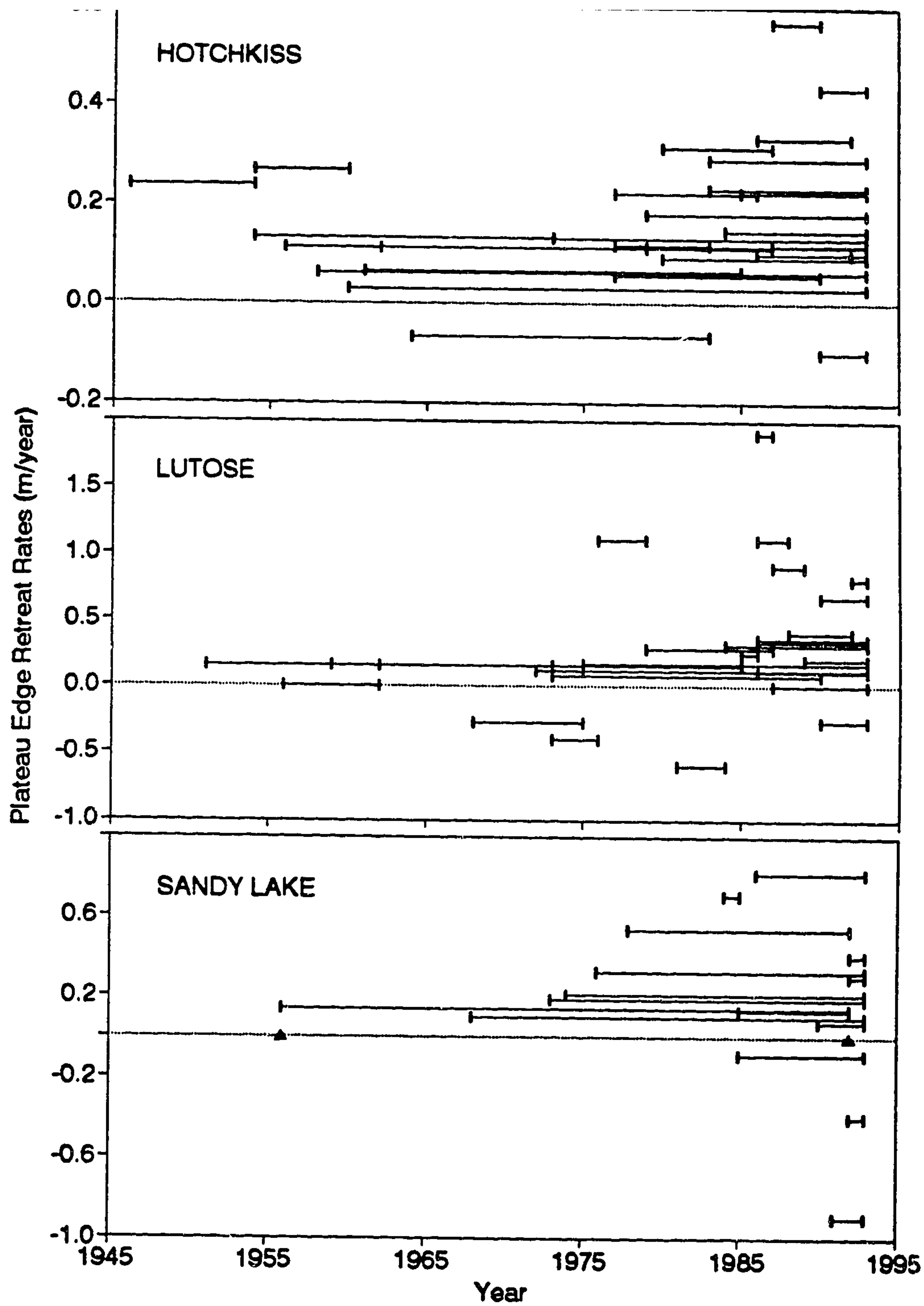

Figure 6. Plateau edge retreat rates from all transects calculated from tree death dates. Note the differences in scale along the vertical axes. Triangles indicate that two trees from the same transect died in the same year, yielding a calculated rate of infinity.

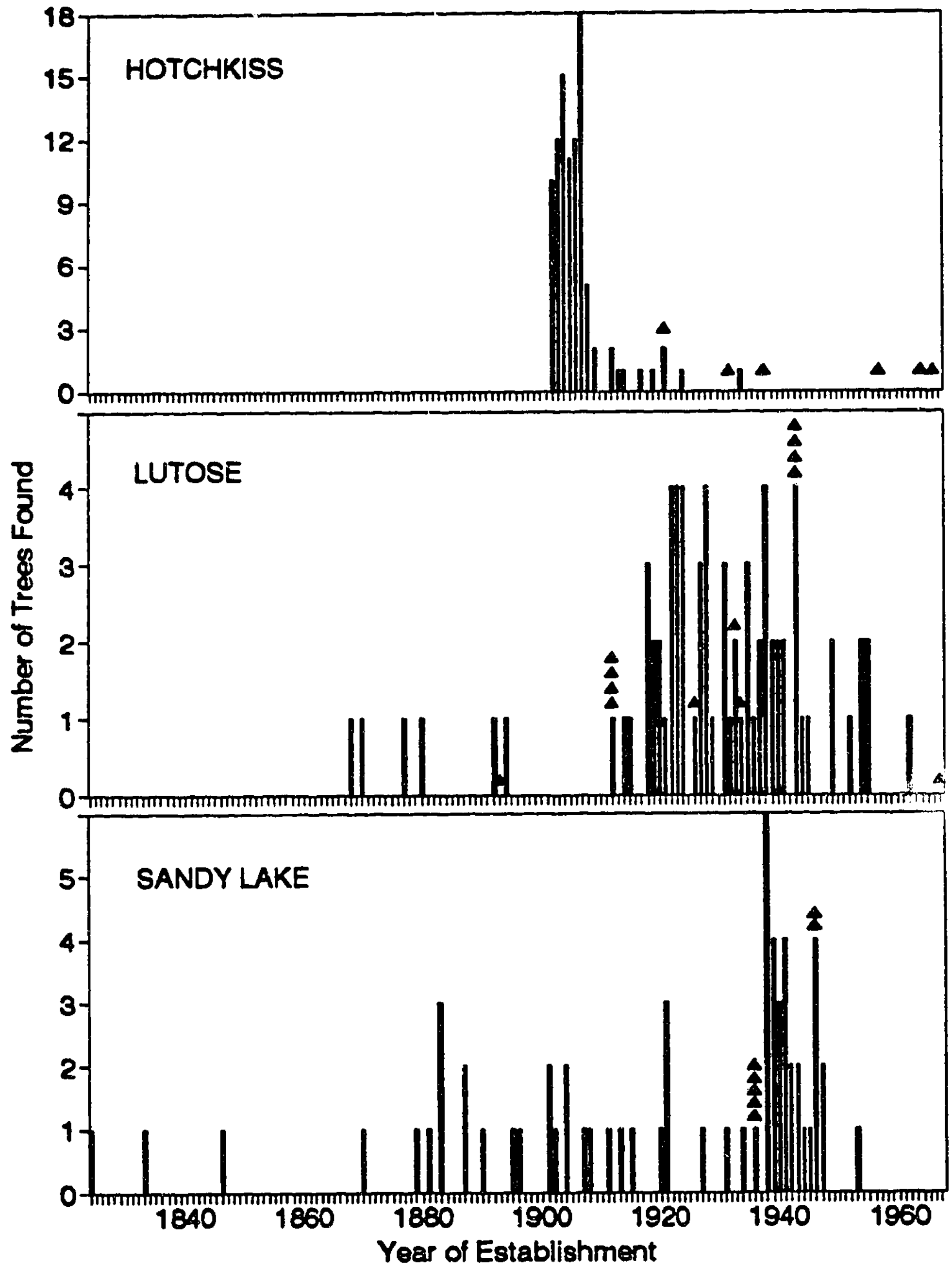

Figure 7. Tree establishment and fire scar dates from the three sites. Triangles indicate transects at which fire scars from that year were found. Note the differences in scale along the vertical axes.

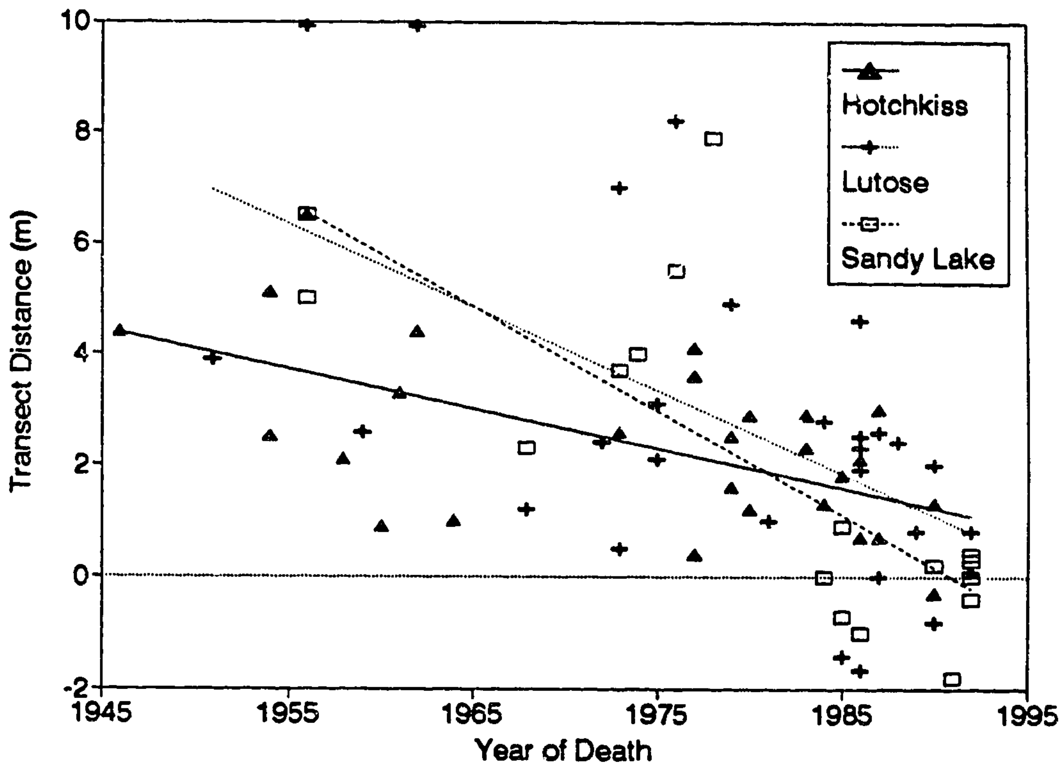

Figure 8. Locations and death dates of successfully crossdated dead trees from the three sites. Positive distances refer to locations in the collapse scar; negative distances refer to locations on the plateau. The slope of each linear regression gives an overall mean retreat rate for that site (see Table 3).

increasingly isolated by expanding collapse scars could be regarded as peripheral retreat, which is typically faster than internal retreat.

The increase in rates after 1975 suggested in Figure 6 may be partly due to the use of the lichen/moss boundary as an approximation for the live/dead tree boundary. Most trees do not drown immediately upon reaching the lichen/moss boundary, but spend some time in the collapse scar before dying. Mean transect distances for the last live tree on the transect (i.e., the live tree nearest to or farthest into the collapse scar) and for the first dead tree are given in Table 3. Many of the dead trees had very thin outer rings, indicating that they did not die suddenly. Where there were live trees in the collapse scars, they were bypassed in calculating retreat rates, possibly artificially increasing those rates, while dead trees on the plateau had the opposite effect.

For Lutose, the "dead trees only" mean is lower than the overall mean, suggesting that the use of the lichen/moss boundary increased the mean retreat rate slightly (Table 3); for Hotchkiss the two means are the same. This method of comparison is unfortunate in that the overall mean is for the whole time period, but the dead tree mean excludes recent rates. For Sandy Lake, the rates calculated using the lichen/moss boundary may be underestimated. The average location of the last live tree on the Sandy Lake transects was 0.75m up the plateau bank, and only one transect had a live tree in the collapse scar. Because more trees died in the lichens on the plateau than at the other two sites, more negative rates were generated by the lichen/moss boundary calculation method. These trees were typically at the bottom of the plateau edge, where the water table was at or near the surface; they can still be assumed to have died by drowning. There appears to be a lag time between plateau edge retreat and Spagnum moss advance; this affects the position of the lichen/moss boundary, especially when the retreat rate is high. Conversely, live trees were frequently found in the collapse scars, especially at Hotchkiss, where the last live tree was 0.23m into the collapse scar on average (Table 3). At a retreat rate of 0.12m/yr, this implies that the trees had survived in the collapse scar for about 2 years.

In the linear regressions (Figure 8), each tree is considered one observation and the lichen/moss boundary is not a factor. Quadratic regressions indicated that retreat rates at all three study sites were increasing, but in each case R^2 was not significantly higher than for the linear regression (Table 4).

Table 3. Mean plateau edge retreat rates and characteristics of each study site.

	Study Site		
	Hotchkiss	Lutose	Sandy Lake
Mean retreat rate			
Overall[1]	0.12m/yr	0.17m/yr	0.21m/yr
Dead trees only[2]	0.12m/yr	0.16m/yr	0.28m/yr
Regression slope	0.07m/yr	0.15m/yr	0.19m/yr
Mean transect distance[3]			
Last live tree	0.23m	0.13m	-0.75m
First dead tree	1.41m	1.64m	1.41m
Mean distance between trees on transect	1.0m	1.3m	2.2m
Last widespread fire	c1901	1943	1936

[1]Undefined (infinite) rates were excluded from the calculation.

[2]Mean calculated without rates based on the lichen/moss boundary.

[3]The lichen/moss boundary was at distance 0. Positive values indicate locations in the collapse scar; negative values indicate locations on the plateau.

Table 4. Analysis of variance for linear and quadratic regressions of transect distance (d) on year of death (y) for successfully crossdated dead trees from the three study sites.

Linear Regression
Model: $d = A + By$

Site	Source	df	SS	MS	F	p	R^2
Hotchkiss	Model	1	24.3	24.3	13.9	0.0009	0.35
	Error	26	45.3	1.7			
	Total	27	69.6				
Lutose	Model	1	74.8	74.8	11.6	0.0023	0.32
	Error	25	161.8	6.5			
	Total	26	236.6				
Sandy Lake	Model	1	80.5	80.5	21.2	0.0003	0.59
	Error	15	57.1	3.8			
	Total	16	137.6				

Quadratic Regression
Model: $d = A + By + Cy^2$

Site	Source	df	SS	MS	F	p	R^2
Hotchkiss	Model	2	24.5	12.3	6.8	0.0044	0.35
	Error	25	45.1	1.8			
	Total	27	69.6				
Lutose	Model	2	76.9	38.5	5.8	0.0089	0.33
	Error	24	159.7	6.7			
	Total	26	236.6				
Sandy Lake	Model	2	86.2	43.1	11.7	0.0010	0.63
	Error	14	51.4	3.7			
	Total	16	137.6				

DISCUSSION

Tree rings and climate

Ring width indices of black spruce from peatlands have been found to be significantly correlated with precipitation and temperature (Dang and Lieffers 1989a). Trees growing on the dry surfaces of peat plateaus depend on precipitation for water (Aaby 1976, Seppala 1988), so dry years could be expected to induce thin marker rings. Analyses of ring width in relation to climate were not done for the present study, but it was hoped that the dependence of ring width on climate would result in highly correlated ring-width sequences among trees from each site, facilitating crossdating. The lack of correlation among trees, even those growing within a few meters of each other, may be due to variability in soil water availability (Dang and Lieffers 1989b). A dry summer may yield release rings in a tree with its roots submerged in a collapse scar, while at the same time adversely affecting a tree a few meters away on top of the dry plateau.

While straight, healthy trees could be selected for making the master chronologies, dead trees on the transects had to be taken as they were. Most of them had several compression wood episodes, which severely altered ring-width patterns. Filion *et al.* (1986) crossdated black spruce from near the arctic treeline using rings with little or no latewood (light rings) which result from cold autumns. Light rings were not used for this study because they were present in only a few trees. However, frost rings proved to be reliable datable features, and may be a valuable tool for crossdating in general, especially for trees growing in low-lying areas. Frost rings result from frost injury to the cambium during the growth season and are made up of cells killed by the frost, and abnormal tracheids and traumatic parenchyma cells produced subsequently (Kramer and Koslowski 1979, Panshin and de Zeeuw 1980). Because of cold air drainage, summer frost is more frequent in peatlands than in the surrounding uplands (Rothwell and Lieffers 1988), resulting in a large number of frost rings in the trees (see Figure 9).

Most frost rings crossdated well only locally, and the three study sites have few frost rings in common. For example, the most reliable frost ring from Hotchkiss was in 1910, and occurred in over 90% of the sampled trees that were alive at the time. This ring was found in a few Sandy Lake trees, and none of the Lutose trees. Weather records from Hay River, Fort Smith and Fort Vermilion were examined for low temperatures in the summer months, but no definite links to the frost master chronologies were found. Weather stations nearer to the study sites did not have records extending back far enough to be useful; in addition, night temperatures at the ground surface can be significantly lower than those at screen height (1.4m above ground).

One disadvantage of using frost rings for marker years had to do with their dependence on tree height. Stems are much more susceptible to frost damage when they are small (Reich and van der Kamp 1993). Sampling height was just above the root collar, and most of the frost rings were found in the inner rings, so trees that were established at different times often did not have matching frost rings. Crossdating was

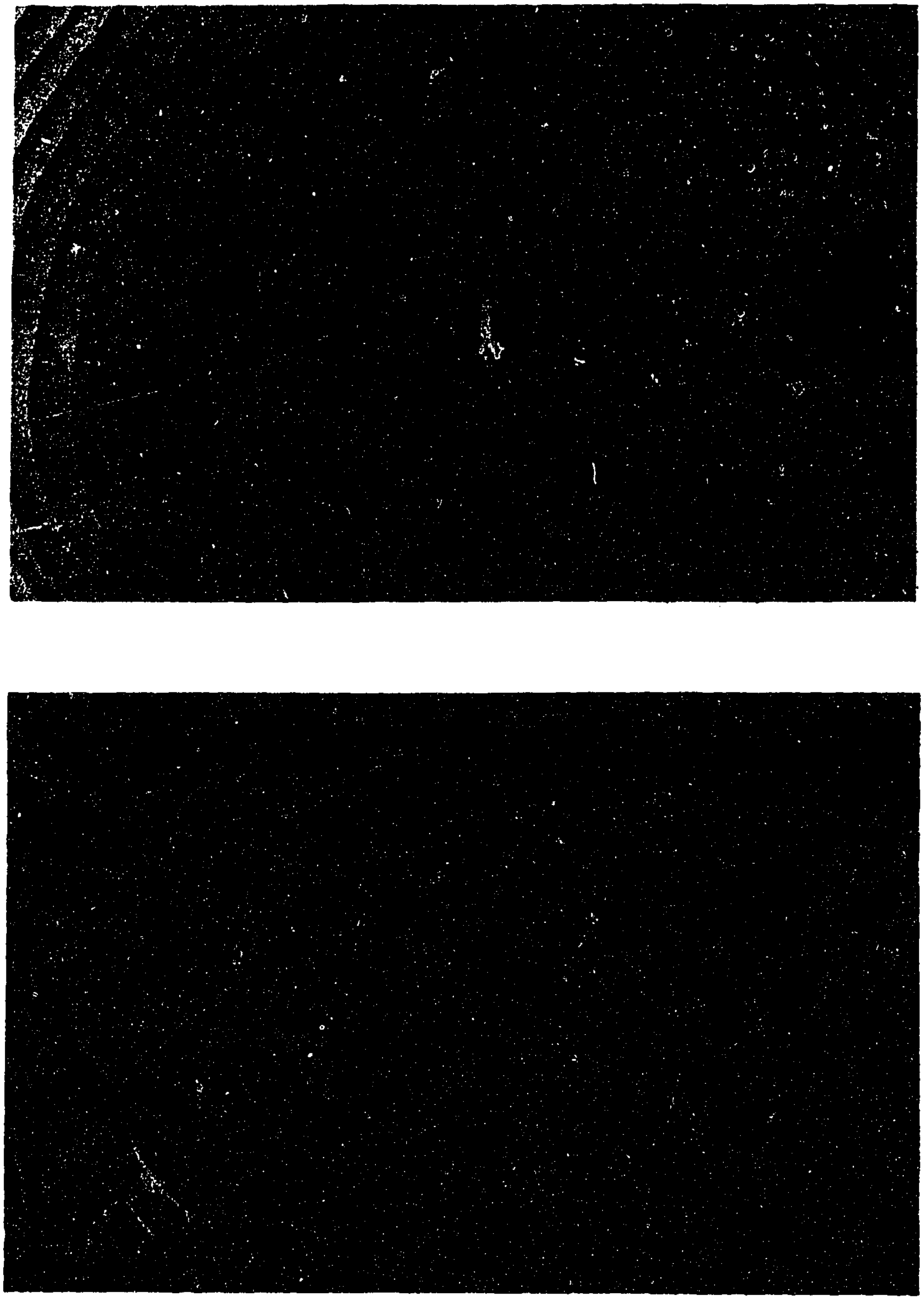

Figure 9. (a) Growth rings in a tree from the Sandy Lake study site. The frost ring indicated by the arrow was a formed in 1940. The tree also shows release rings after the 1936 fire. 4x magnification. (b) A tree from the Hotchkiss site. The frost rings are not evident, but the cracks indicated by the arrows formed along the 1910 and 1932 frost rings. 7x magnification.

most successful at Hotchkiss, where almost all the trees were established after one fire, and least successful at Sandy Lake, where trees were of widely varying ages. Also, rings were generally narrower at Sandy Lake than at the more southerly sites, many of them one or a few cells wide; frost damage in such rings was rarely found, either because it was absent or because it was indiscernible.

Retreat rates and climate

Year-to-year variation in plateau edge retreat rates is mainly due to year-to-year variation in temperature and precipitation. A plateau edge can retreat a meter or more during a warm, wet summer, and be stable the next summer. Standing water is particularly important, and water levels can fluctuate considerably from year to year. A year of above average water levels could yield the "infinite" results calculated for Sandy Lake (Figure 6). Other studies (see Table 1) have similarly found widely differing rates among plateau edges, including edges that are inactive (stable).

However, some of the variability in the rates in Figure 6 is due to differences in trees' resistance to drowning. Trees survive longer in the collapse scar if their roots extend up into the plateau, although these roots may snap during periods of rapid retreat. Trees may also survive longer when they are on blocks of peat that break off the shoulders of the plateau intact. Collapse scars where evidence of this was observed were avoided during transect selection, but such evidence may have been buried under moss or peat on some transects. The surfaces of the plateaus were not flat but had many hollows and undulations reflecting variations in peat thickness and underlying variations in permafrost thickness. As these undulations subside into the collapse scar, trees in the hollows may die before those on the ridges or hillocks. For example, in Figure 5 two trees at the same distance from the plateau edge died 6 years apart. Because of this variability, there is considerable uncertainty in rates like the 1.9m/yr calculated for 1986-87 at one Lutose transect (Figure 6), and rates for individual years do not necessarily correspond to the weather of that year.

Variation in retreat rates between collapse scars also depends on collapse scar depth and the thickness of the permafrost layer. Comparatively deep collapse scars will contain water more often and for longer periods. Although rainfall at Sandy Lake was slightly lower than at the other sites (Table 2), retreat rates are higher possibly because the collapse scars are wider (Table 3), presenting a greater area for solar radiation absorption, and also deeper, indicating deeper permafrost meltout or greater plateau maturity. The latter could result in a thinner peat cover over the sides of the permafrost core. It is possible that the smaller collapse scars at Hotchkiss were still underlain by permafrost (Zoltai per. comm.), which may not have been the case at Lutose. Reid (1977) suggested that permafrost could be found beneath collapse scars less than 10m in diameter. This would apply to most of the collapse scars at Hotchkiss, but only to a few at Lutose and Sandy Lake.

The influence of climate is also evident in the compression wood formed by trees on the plateaus. Compression wood was not a reliable indicator of the time a tree spent on the plateau edge because often several trees on a transect would begin forming compression wood in the same year, indicating differential vertical melting of the permafrost core in response to climatic factors in that year. Because of the unstable plateau surfaces, many of the trees had 30-40 years of compression wood from several leaning episodes in different directions, including trees still on the plateaus, as was found by Zoltai (1975a) in the continuous permafrost zone.

Permafrost at Hotchkiss was expected to be degrading more quickly than at the other sites. Hotchkiss is 300 km south of Lutose, and is even south of the -1°C mean annual air isotherm which approximates the southern limit of discontinuous permafrost. Meanwhile precipitation is similar to or higher than that of the other sites, as are degree-days above 0°C (Table 2). However, the Hotchkiss peatland is characterized by dense, continuous black spruce cover which largely shades the ground, including the collapse scars, while Lutose and Sandy Lake are more open with many untreed patches. The differences in tree density at the three sites are much greater than is suggested by the mean distance between trees on the transects (Table 3).

Vitt *et al.* (1994) found that in areas with mean annual temperature between -1 and 0°C (e.g. Hotchkiss), most of the permafrost in peatlands is now degraded. Retreat rates at Hotchkiss were comparatively slow, but because the collapse scars at Hotchkiss were closer together than at the other two sites, the total area of permafrost meltout over time would be higher. The high density of collapse scars also infers a faster rate of new collapse scar formation.

Temperature and precipitation are the major climatic factors in bog (and therefore permafrost) development and persistence (Vitt *et al.* 1994), and are the most likely causes of the continuing and possibly accelerating permafrost degradation. Similar trends in permafrost degradation rates can therefore be expected in permafrost peatlands throughout the discontinuous permafrost zone.

Implications of Climate Change

The subsidence of peat plateaus is part of their normal "life cycle" (Seppala 1988, Zoltai 1993), but this cycle could be altered with climatic warming. Climatic warming is expected to increase permafrost melting rates, although the processes involved are not staightforward. Higher air temperatures normally lead to higher soil temperatures, but may also contribute to drier peat and lower water levels in collapse scars. The increase in climate variability predicted by Rind *et al.* (1989) and others would tend to favour permafrost degradation because in unusually warm, wet years melting would proceed much more quickly than permafrost development in unusually cold, dry years. Furthermore, increases in drought frequency are expected to bring about increases in fire frequency and severity (Singh and Higginbotham 1988, Flannigan and Van Wagner 1991).

In the present study, no fires occurred within the time period over which plateau edge retreat rates could be calculated, so it was not possible to compare prefire and postfire rates, or even to measure retreat rates shortly after fire. Such measurements could be made with the same methodology in more recently-burned peatlands, using trees that survived the fire or were established after the fire. However, it is evident that plateau edge retreat is continuing and possibly accelerating in the absence of fire. This suggests that the observed degradation is driven by climate. At Hotchkiss, the permafrost persisted after a major fire in 1901, inferring that the climate after the fire was not conducive to permafrost meltout. In contrast, the current climate could support a complete and permanent loss of permafrost after a severe fire.

In many areas, the current climate allows the degradation and aggradation of permafrost to occur simultaneously in the same peatland (Zoltai and Tarnocai 1971, Zoltai 1972) or even on the same plateau. Therefore collapsing plateaus do not necessarily indicate climatic warming (Svensson 1970, Seppala 1982). However, permafrost buildup in peatlands is generally a much slower process than degradation (Zoltai 1993). A peatland in "permafrost equilibrium" would be dominated by aggrading plateaus. A predominance of degrading plateaus probably indicates a net loss of permafrost, as has already been observed (Table 1).

The implications of permafrost degradation and loss are greater than just the movement of the southern limit of permafrost. Changes in vegetation and wildlife, including loss of forest cover associated with peat plateaus, take place as a peat plateau's aerobic nutrient system is changed to the anaerobic wetland system (Auclair 1983). The major byproduct of decomposition in a plateau is carbon dioxide; in a wetland, it is methane. A molecule of methane absorbs 10-20 times more heat than a molecule of carbon dioxide, either directly or through other greenhouse gases produced in chemical reactions with methane (Mooney *et al.* 1987, Rodhe 1990). The global warming potential (Shine *et al.* 1990) of methane over 100 years is 21 times that of carbon dioxide by weight, although there is considerable uncertainty in this figure (Isaksen *et al.* 1992). Although methane release is typically much slower than carbon dioxide release, an increase in methane release as a result of permafrost melting may represent a positive feedback mechanism contributing to climatic warming.

However, climatic warming and more frequent drought, along with drainage caused by melting of permafrost (Chatwin 1981) would lower the water table, reducing the amount of methane produced (Harriss *et al.* 1982). Also, climatic warming could increase the rate of peat formation in far northern peatlands (Gorham 1988), although not necessarily their net carbon drawdown rate (Billings *et al.* 1982). The extent of permafrost degradation and carbon release is expected to increase with an increase in fire frequency or severity (Kurz *et al.* 1992). Large amounts of carbon dioxide are released by fire, but peat accumulation continues after plateau subsidence and may even be facilitated. Postfire carbon release is largely determined by decomposable matter availibility and factors such as climate and soil water (Moore and Knowles 1989, Anderson 1991) which also determine vegetation recovery.

Measurements of methane and carbon dioxide release from peatlands have been carried out by Moore and Knowles (1987), Hogg *et al.* (1992), Hogg (1993) and others. Data such as this could be used to construct a "carbon budget" for peatlands under possible future fire scenarios. However, additional information would be necessary, such as the amount of carbon released during fire and the response of live plants in an altered climate.

Peatlands represent a major carbon sink (Tarnocai 1984, Armentano and Menges 1986). The net carbon drawdown by global peatlands is about $3x10^{13}$ g/yr (Gorham 1991), or about 1% of the annual global atmospheric carbon increase (Kurz *et al.* 1992). Global peatlands are estimated to contain a total of 4.55×10^{17} g of carbon (Gorham 1991), which is 150 times the annual atmospheric increase. If peatlands were to become a source of carbon rather than a sink, they could make a significant contribution to rising atmospheric carbon dioxide and methane levels.

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APPENDIX 1: POSTFIRE PEAT PLATEAU COLLAPSE IN THE CONTINUOUS PERMAFROST ZONE NEAR INUVIK, NWT

Mean annual temperature at Inuvik (68°18'N 133°29'W) is -9.8°C. Normal mean temperature in January is -29.6°C; in July, it is 13.6°C. Normal annual precipitation is 266.1mm, of which 151.5mm falls as snow (Environment Canada 1982).

Arctic Red River - Fort McPherson

Fourteen peatland areas were examined near the Dempster Highway between Arctic Red River and Fort McPherson. None had burned within at least 50 years. The areas observed fell into two general categories:

1. Flat peat surface with almost continuous lichen cover. The predominant tree species was black spruce. There were no collapse scars or standing water.
2. Undulating surface with sporadic lichen cover. Plateau areas were indistinct and rarely more than 0.5m high. Wetter areas were dominated by sedges. The predominant tree species were black spruce and tamarack. There was no standing water, possibly because of the unusually dry summer. Some of the wetter areas may have been collapse scars, but the majority of them were drainage ways to nearby lakes.

Air photos along the Dempster Highway route at a scale of 1:40,000 indicated that the peatlands observed included all types present. These were peat plateaus or palsa plateaus and polygonal peat plateaus (Zoltai and Tarnocai 1975, Seppala 1988). Air photos of peatlands containing collapse scars have a characteristic pockmarked appearance. This was not seen on the Dempster Highway photos.

Inuvik - Arctic Red River

Seven peatland areas were examined near the Dempster Highway between Inuvik and Arctic Red River. Some were burned in 1968 and some in 1954; the remainder had not burned for at least 50 years. Small wet depressions of a few square meters were found which may have been collapse scars. These were found in unburned as well as burned peatlands. Again, air photos of the highway at a scale of 1:5000 showed no evidence of the permafrost degradation observed in the discontinuous permafrost zone.

All the peatlands examined had few or no trees. As a result, the present study could not be conducted, nor was there an alternative method of measuring the past retreat rate of peat plateau edges. It was evident from the appearance of the peatlands that the processes observed further south were either not occurring or were occurring on a very different time scale. The permafrost table was found to be lower in wetter areas, but at these latitudes the permafrost is continuous and hundreds of meters thick (Brown 1970a, Price 1972) and as cold as -7°C. A different ground thermal regime was to be expected, although widespread collapse scars have been observed as far north as Norman Wells (65°N) (Zoltai and Tarnocai 1975).

Extensive permafrost melting after the 1968 Inuvik fires is well documented (Heginbottom 1971, Mackay 1970, 1977). It is likely that stabilization of the permafrost occurs much more quickly than at more southerly sites and that the 1968 fire was too long ago for permafrost degradation to be continuing today. If this is the case, more recent fires would be the key to studying postfire permafrost degradation in Inuvik area peatlands. Such fires are documented but are not practicably accessible except by helicopter or float plane.

APPENDIX 2: MAP AND AIR PHOTO REFERENCES

Hotchkiss

Air photo:	AS4299:157 (1992) 1:40,000
NTS Map sheet:	84E (Chinchaga River)

Lutose

Air photos:	AS3055:288 (1984) 1:60,000
	AS3871:201 (1989) 1:20,000
	AS3871:203 (1989) 1:20,000
NTS Map sheet:	84N (Steen River)

Sandy Lake

NTS Map sheet:	85B (Buffalo Lake)

Dempster Highway

Air photos from 1990 (1:5000) were examined at the GNWT Department of Transportation in Inuvik. Air photos from 1954 (1:40,000) were borrowed from S.C. Zoltai (Northern Forestry Centre, Edmonton).

NTS Map sheets:	107B (Aklavik)
	106M (Fort McPherson)
	106N (Arctic Red River)