DISEQUILIBRIUM RESPONSE OF PERMAFROST IN BOREAL CONTINENTAL WESTERN CANADA TO CLIMATE CHANGE

LINDA A. HALSEY and DALE H. VITT
Devonian Botanic Garden and Department of Biological Sciences, University of Alberta, Edmonton, Alberta, T6G 2E1, Canada

and

STEPHEN C. ZOLTAI
Canadian Forest Service, Northern Forestry Centre, Edmonton, Alberta, T6H 3S5, Canada

Abstract. In the boreal forest of continental western Canada, permafrost is restricted to *Sphagnum*-dominated peatlands on which air photo interpretation reveals the occurrence of five types of surface physiography. Concentrated in the northern part of the boreal forest, permafrost is present in peat plateaus with and without collapse scars. In the southern part of the boreal forest, continental bogs dominate, representing ombrotrophic peatlands that have never contained permafrost. In the mid-boreal zone, internal lawns are present in bogs and in fens. These internal lawns do not presently contain permafrost but did in the recent past, representing degradation of permafrost since the Little Ice Age. Evaluation of the distribution of these peat landforms indicates that today 30% of bogs contain permafrost at the –0.4 °C isotherm and 50% of bogs contain permafrost at the –1.2 °C isotherm, whereas in the past, 30% of bogs contained permafrost at the –1.4 °C isotherm and 50% of bogs contained permafrost at the –2.3 °C isotherm. Although spatial degradation has occurred with a shifting of permafrost northwards in response to warming since the Little Ice Age, permafrost cover has increased in any given area where present-day temperatures are between 0.5 and –3.5 °C.

1. Introduction

In the discontinuous permafrost zone of the boreal forest, permafrost is present in *Sphagnum*-dominated peatlands, almost all of which are ombrotrophic (Vitt *et al.*, 1994a). Ombrotrophic peatlands receive water and nutrients solely from precipitation, sequestering carbon through peat accumulation due to reduced rates of decomposition (Zoltai *et al.*, 1988). These nutrient poor ecosystems support a unique flora that is dominated by species of *Sphagnum* in the southern boreal forest. Under permafrost conditions, lichens dominate, particularly species of *Cladina* (Vitt *et al.*, 1994a). Together with the insulative properties of the accumulated *Sphagnum* peat and the high reflectance of the lichen mat, permafrost will exist under climatic conditions that do not support permafrost in other soils (Tyrtikov, 1964).

Changes in the distribution of permafrost are known to have occurred in the past, responding to changes in climate (Thie, 1974; Mackay, 1975; Lagarec, 1982; Burn *et al.*, 1986, Vitt *et al.*, 1994a). At present, permafrost exists in bogs south of the 0 °C isotherm, occurring as relict features from the Little Ice Age (Dionne and Seguin, 1992; Vitt *et al.*, 1994a). The presence of these relict permafrost

Climatic Change **30:** 57–73, 1995.

features indicates that the current southern limit of discontinuous permafrost is not in equilibrium with contemporary climate. Other forest ecosystems are known to have responded in disequilibrium to climate change (Campbell and McAndrews, 1994).

Permafrost degradation models generated from climate warming scenarios use an equilibrium paradigm. Northerly shifts of up to 1,000 km have been predicted for the southern limit of discontinuous permafrost following a 4–5 °C increase in mean annual temperature (Woo *et al.*, 1992). The effect that permafrost melting will have on the land surface through thermokarst and mass wasting, coupled with changes in hydraulic regime and carbon storage could be dramatic (Gorham, 1991; Woo *et al.*, 1992). If the southern limit of discontinuous permafrost is not in equilibrium with climate today, permafrost degradation models that are constructed using equilibrium paradigms are flawed and the results may be suspect, though highly necessary given the potential ecological and financial impacts.

Recently, reliable maps of present and past permafrost distribution have become available for the southern part of the discontinuous permafrost zone of western continental Canada from the interpretation of bog landforms (Vitt *et al.*, 1994a). Comparisons between present and past permafrost distribution in relation to climate permits an evaluation of permafrost degradation models. Similar studies have been conducted to test predicted general-circulation-model climate simulations using fossil pollen (e.g. Schweger and Hickman, 1989; Budyko *et al.*, 1990).

The objectives of this paper are to examine the distribution of permafrost today and during the Little Ice Age on a regional scale and to relate permafrost distribution to the regional climatic variable of mean annual temperature. The response of permafrost to climate warming since the Little Ice Age is examined by generating regressions between mean annual temperatures and bog landform distribution for today and in the past.

2. Study Area

The study area is the southern part of the discontinuous permafrost zone of Alberta, Saskatchewan and Manitoba, excluding the Western Cordillera, here termed continental western Canada (Figure 1). Peatlands occupy 3.4×10^7 ha (or 21%) of continental western Canada west of 95° W longitude, with bogs covering 1.3×10^7 ha or 8% of the land surface (based on Zoltai *et al.*, 1988; Vitt, 1992; Vitt and Halsey, unpublished data). Today, permafrost is present in approximately half of these bogs (Vitt and Halsey, unpublished data).

3. Permafrost Landforms

In the southern part of the discontinuous permafrost zone, permafrost is restricted to *Sphagnum*-dominated peatlands (Vitt *et al.*, 1994a). The influence of permafrost

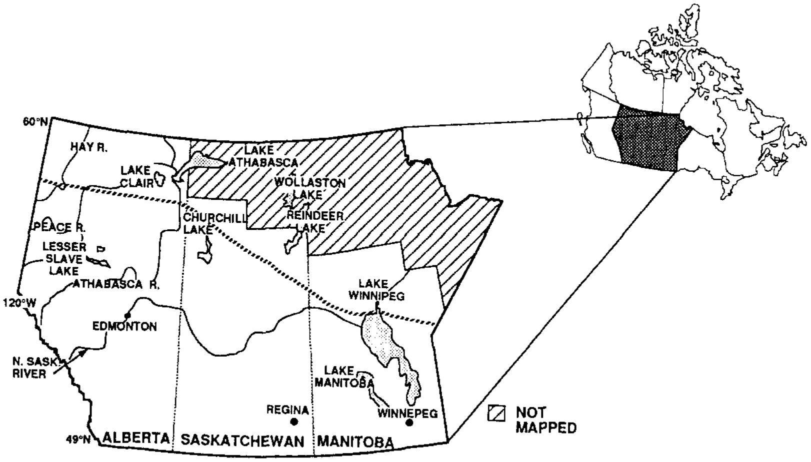


Fig. 1. Location of study area showing area mapped for bog landforms. The hatched line represents the limit of discontinuous permafrost following Brown (1967).

on peatland surface morphology has long been known (Hopkins, 1959; Tedrow and Harris, 1960; Zoltai, 1971), and permafrost degradation at the limit of discontinuous permafrost has been reported (Sjörs, 1959; Mollard and Janes, 1984) and was quantified over small areas of central Manitoba as early as the 1970's (Tarnocai, 1972; Thie, 1974).

In the southern- to mid-boreal forest region of western Canada, ombrotrophic peatlands consist mainly of continental bogs that are elevated 50–100 cm and do not contain permafrost (Zoltai *et al.*, 1988). These bogs usually occur as islands or peninsulas in large, complex fens (Nicholson and Vitt, 1990). In the prairie provinces, continental bogs almost always are wooded, with a uniform cover of *Picea mariana*, excluding areas that have been burned. The surface morphology of continental bogs has a microrelief consisting of relatively dry hummocks and wet hollows. Standing pools of water are almost unknown. Ground cover is dominated by ericaceous shrubs and oligotrophic species of *Sphagnum*.

In the mid- to high-boreal forest region, bog landforms are dominated by peat plateaus containing permafrost with collapse scars. Peat plateaus with collapse scars are elevated 100–200 cm above the surrounding surface. They can cover extensive tracts of land in areas of low relief such as the Hudson Bay Lowlands, or occur as small irregularly shaped islands generally along the edges of fens (Figure 2). Peat plateaus with collapse scars are forested (> 70% tree cover) to wooded (30–70% tree cover) with a uniform cover of *Picea mariana*. A microrelief of hummocks and hollows is present on the surface of the peat plateaus and the ground cover is dominated by feather mosses (*Hylocomium* and *Pleurozium*), ericaceous shrubs (*Ledum* and *Chamaedaphne*) and lichens (*Cladina*, *Cladonia* and *Cetraria*). Collapse scars develop in peat plateaus due to local permafrost degradation (Zoltai,

Fig. 2. Aerial photograph of the mid boreal region (56°03′ N, 112°57′ W) showing ombrotrophic peatlands that are present as bog islands (b) in large fens (f). Isolated peat plateaus with collapse scars have developed on some of the bog islands (p). Since the Little Ice Age, collapse of permafrost caused the formation of internal lawns (i).

1972, 1993). They are typically 100 cm lower than the surrounding bog and have a mesotrophic ground cover dominated by *Carex* and *Sphagnum*.

In the high-boreal region, peat plateaus without collapse scars are also found. Peat plateaus without collapse scars are elevated above the surrounding surface by approximately 100 cm and also contain a microrelief developed from the presence of hummocks and hollows. Again, these ombrotrophic wetlands are forested to wooded with *Picea mariana* and have a ground cover of feather mosses, ericaceous shrubs, and lichens. They do not contain distinct collapse scars, though indistinct (old) scars may be present that have regenerated permafrost (Vitt and Belland, unpublished data).

Continental bogs that contain internal lawns (Figure 2) are found in the mid- to high-boreal forest region. Internal lawns are characteristically less than 50 cm lower than the surrounding bog and contain dead stands of *Picea mariana* and a *Sphagnum* ground cover. Internal lawns form due to melting of an area in the bog that contained permafrost. Melting of permafrost results in a drop in surface elevation from the initially elevated permafrost area to slightly below the non-permafrost portion of the bog. The change in surface elevation relative to the location of the water table results in conditions suitable for *Sphagnum* to be established (Vitt *et al.*, 1994a). In some cases, entire bog islands (peat plateaus) can collapse into the surrounding fen (Figure 2). Internal lawns are also found in wooded fens. These internal lawns contain a mesotrophic ground cover, but instead of being surrounded by oligotrophic species as in the case of the continental bogs, they are surrounded by drier mesotrophic vegetation. In this paper ‘bogs’ and ‘ombrotrophic peatlands’ refers to these five types of landforms excluding the fens with internal lawns which represent ‘paleobogs’.

4. Methods

4.1. CLIMATE VARIABLES

Mean annual temperature data are sporadic in the boreal forest of western continental Canada. In northern Alberta, where uplands are frequent, the majority of climate stations only collect data during the ice-free season. The lack of yearly data makes it difficult to estimate the distribution of mean annual temperatures in Alberta, especially in areas where elevational differences are present. For this reason, a model of mean annual temperature was generated that utilized elevation, summer only stations, and yearly stations. This model was established by regressing monthly mean temperatures for summer only stations against monthly mean temperatures from the closest yearly station for the 1951–1980 time period. Using these regressions, mean annual temperatures for summer stations were generated. A linear model was then established using station elevation and location to predict these generated mean annual temperatures for summer only stations coupled with mean annual temperatures from yearly stations in blocks of 4° latitude and 8° longitude for western Canada. Each model block was overlapped by 1° latitude and/or 2°longitude north of 53° N. South of 53° N, no overlap was needed due to the abundant number of annual climate stations. Grid nodes were established in the center of a 15′ latitudinal and 30′ longitudinal grid (a 1 : 50,000 map sheet). Elevation for each grid node was then determined. Using these elevations, mean annual temperatures were generated with the linear elevation model. A standard error budget (cumulative errors from all temperature models) for the study area was determined spatially and was contoured at 0.1 intervals by MacGridzo (Rockware Inc., 1991), a grid-generated contour program. Due to the inherent autocorrelation of the error sources, the spatial error budget represents the maximum potential error. Standard error contour values ranged from 0.4 to 1.0 increasing to the northwest of the study area where the majority of the seasonal climate stations are (Figure 3a). Modern mean annual temperatures, corrected for elevation, were modified from Vitt *et al.* (1994a) by increasing the number of significant digits used in the elevation models from one to two.

During the Holocene, the maximum extent of neoglacial moraines in the Rocky Mountains of western Canada has been associated with the Little Ice Age (Luckman *et al.*, 1993). As the Little Ice Age represents the maximum extent of neoglacial moraines in western Canada, it probably represents the coldest extended time interval throughout the Holocene. Little Ice Age temperatures in northern Canada were approximately –1 °C colder than today (Cermack, 1973; Jacoby and D'Arrigo, 1992). As internal lawn development represents collapse since the Little Ice Age (Vitt *et al.*, 1994a), it is assumed that past maximum permafrost distribution determined from bog landforms was related to Little Ice Age temperatures.

Little Ice Age mean annual temperature departures were not uniform throughout western continental Canada, being slightly colder in central Canada than in western Canada (Schweingruber *et al.*, 1991; Lough, 1992). Departures from 1901–1970 means were taken from Lough (1992, Figure 6i) for western North America, with temperature departure isotherms being extrapolated parallel to the Alberta foothills. A map of Little Ice Age isotherms was constructed by subtracting these temperature departures from present day values.

4.2. BOG LANDFORM DISTRIBUTION

Aerial photographs taken from 1949 to 1952 at a 1 : 40,000 scale were examined for the study area following the methods of Vitt *et al.* (1994a). The occurrence and type of bog landforms (peat plateaus with and without collapse scars and continental bogs with and without internal lawns) were identified, as well as the occurrence of wooded fens with internal lawns. These occurrences were plotted on 1 : 1,000,000 scale maps.

Bogs presently containing permafrost were considered to be peat plateaus with and without collapse scars while bogs and fens with internal lawns and continental bogs without internal lawns where considered to contain no permafrost currently. Past permafrost distribution was calculated by assuming that peat plateaus with and without collapse scars that contain permafrost today also contained permafrost in the past. Bogs and fens with internal lawns were assumed to contain permafrost in the past as shown by Vitt *et al.* (1994a), while continental bogs without internal lawns never had permafrost. Using these bog landform criteria, percentage of

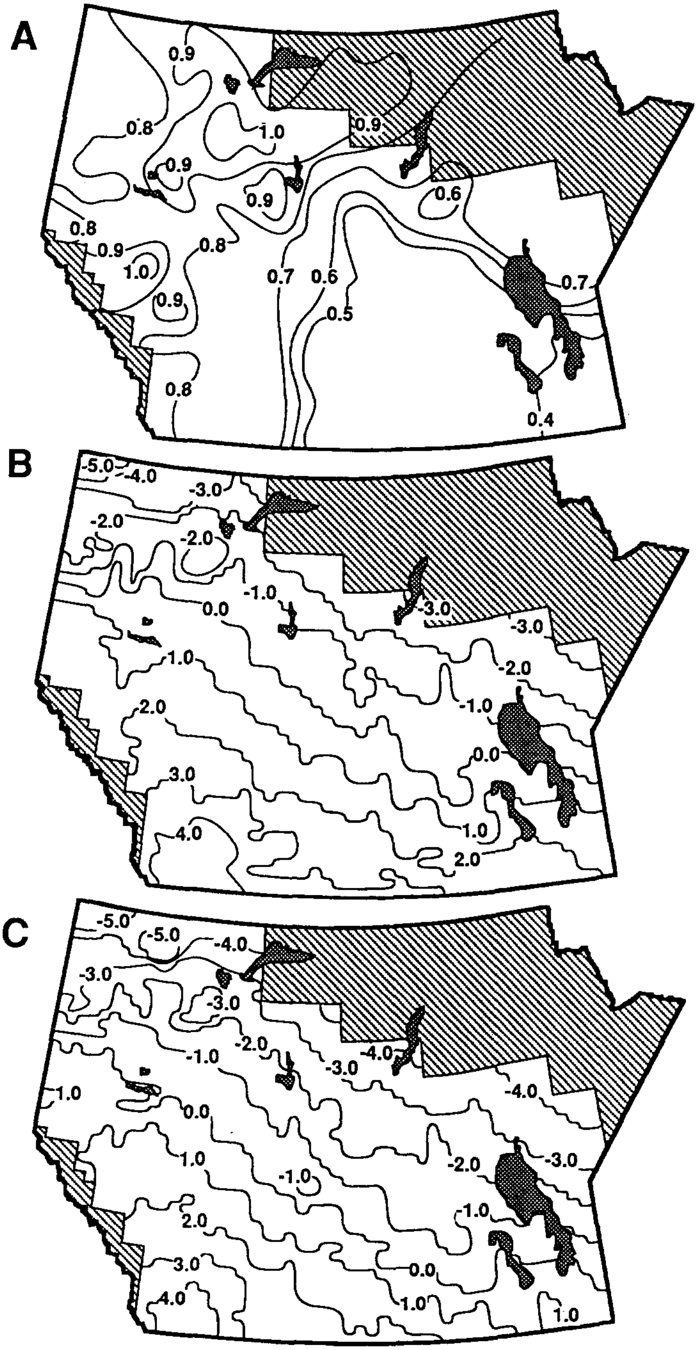


Fig. 3. Mean annual temperature (°C) corrected for elevation calculated to the nearest 0.1 °C. Hatched areas were not mapped. (A) Standard error budget of modern temperature isotherms; (B) Modern temperature isotherms (modified from Vitt *et al.*, 1994a); (C) Past temperature isotherms.

present and past permafrost cover in ombrotrophic peatlands was determined for 1 : 50,000 map sheets.

A regression was developed between mean annual temperatures and percentage of bog landform distribution in relation to total bog coverage for the present and for the past. Mean annual temperature increments of 0.1 °C were used and the percentage of the five bog landform types relative to the total number of bogs was calculated for each of the temperature increments. Regressions were checked for non-linearity and residuals were examined for trends to verify if the regressions were correctly specified.

5. Results and Discussion

The modern distribution of permafrost in ombrotrophic peatlands is shown in Figure 4a. In areas where the regional mean annual temperature is less than –3 °C, almost all bogs contain some permafrost (Figures 3b and 4a). Peat plateaus with and without collapse scars are found in areas where the mean annual temperature is between –3 and 0 °C, however their distribution decreases substantially as temperature increases. Bogs with no evidence of permafrost today are almost exclusive to areas where the mean annual temperature is above 0 °C (Figures 3b and 4a). Bogs without permafrost can also be found between 0 °C and –3 °C, but their distribution decreases as mean annual temperature decreases (Figure 3b and Figure 4a). Thus, the overlap between areas with bogs exclusively with permafrost and bogs without, represents a temperature range of approximately 3 °C. This extensive overlap can be attributed to the complex nature of the permafrost system, that is:

1. The permafrost environment is not in equilibrium with the present regional climate. Peat plateaus and palsas exist as relict features near their southern limit (Dionne and Seguin, 1992). These relict features can be attributed to the insulating properties of *Sphagnum*, particularly *Sphagnum fuscum* (Tyrtikov, 1964; Brown, 1966). Bog surface waters dominated by *Sphagnum fuscum* are typically 3 °C to 4° C colder than surface water of other local peatlands (Vitt *et al.*, 1994b). As *Sphagnum* acts as an insulator, bogs with *Sphagnum* peat are colder than peatlands without *Sphagnum* in areas where the mean annual temperatures are equivalent. As a result, external factors such as climate warming or fire are required to initiate permafrost degradation where *Sphagnum* layers are present.
2. Local mean annual temperatures can be different from regional mean annual temperatures. Water bodies, which are often associated with bogs because of developmental histories, are known heat sources (Woo *et al.*, 1992), causing local areas around water bodies to be warmer. Water bodies are frequently associated with bogs that do not contain permafrost, while bogs that do contain

permafrost are not often associated with water bodies in the mid boreal forest (Vitt, unpublished data).

3. Regional mean annual temperature is not the only climatic factor controlling permafrost distribution. Snow cover, for example, is also important (Nicholson, 1978), as is aspect (Brown, 1969; French, 1970), shade (Viereck, 1973), and rock and soil types (Brown, 1966).

Although local climatic factors play an important role in local permafrost distribution, regional scale distribution of permafrost is largely related to variables and processes which act on a regional scale such as mean annual temperature. For this reason, much effort has been channeled into permafrost research in the last forty years in order to determine the relationships between regional climatic factors and permafrost distribution (i.e. Brown, 1967; Péwé, 1983; Heginbottom, 1984; Nelson, 1986; Anisimov, 1989). The southern limit of discontinuous permafrost has in some areas been moved by various authors by as much as 100 km (reviewed by Nelson, 1989). For example, Brown (1967) placed the southern boundary of discontinuous permafrost at the –1.1 °C isotherm, while other workers have placed it at the 0 °C isotherm (Johnston, 1981). This discrepancy is largely due to an attempt to relate climate to regional permafrost distribution, rather than regional permafrost distribution to climate, and to the definition of what constitutes discontinuous permafrost (Nelson, 1989). The paucity of long-term climate stations in northern Canada, coupled with no clear definition of what constitutes discontinuous permafrost has made the development of regional permafrost maps difficult (Nelson, 1989).

Recent workers have begun to use permafrost cover to evaluate zonal permafrost boundaries (Kudryavtsev *et al.*, 1980; Harris, 1986; Allard and Seguin, 1987). Harris (1986) suggested that the boundary of discontinuous permafrost be placed at 30% cover following Kudryavtsev *et al.* (1980). In the southern part of the discontinuous permafrost zone, permafrost is restricted to bogs, and thus permafrost is dependent on bog occurrence. In areas of little relief and poor drainage, bog cover may be nearly continuous, resulting in nearly continuous permafrost distribution (e.g. Birch Mountains, Alberta) (Halsey *et al.*, 1993). However, in areas with similar mean annual temperatures, permafrost distribution is sporadic, as bog coverage is sporadic (e.g. Clear Hills, Alberta) (Halsey *et al.*, 1993). For this reason, percentage cover of permafrost at the southern limit of discontinuous permafrost must be related to bog cover, not total land cover.

Correct identification of peatland type is crucial in determining permafrost distribution as treed fens (peatlands forested with black spruce and tamarack) do not contain permafrost in the boreal forest. As peat plateaus can occur as small, irregularly shaped islands within fens, they, and thus permafrost occurrence, are often missed during field reconnaissance. Surveys of permafrost distribution done without rigorous floristic examination can potentially result in erroneous conclusions of local and regional permafrost occurrence (e.g. Kwong and Gan, 1994).

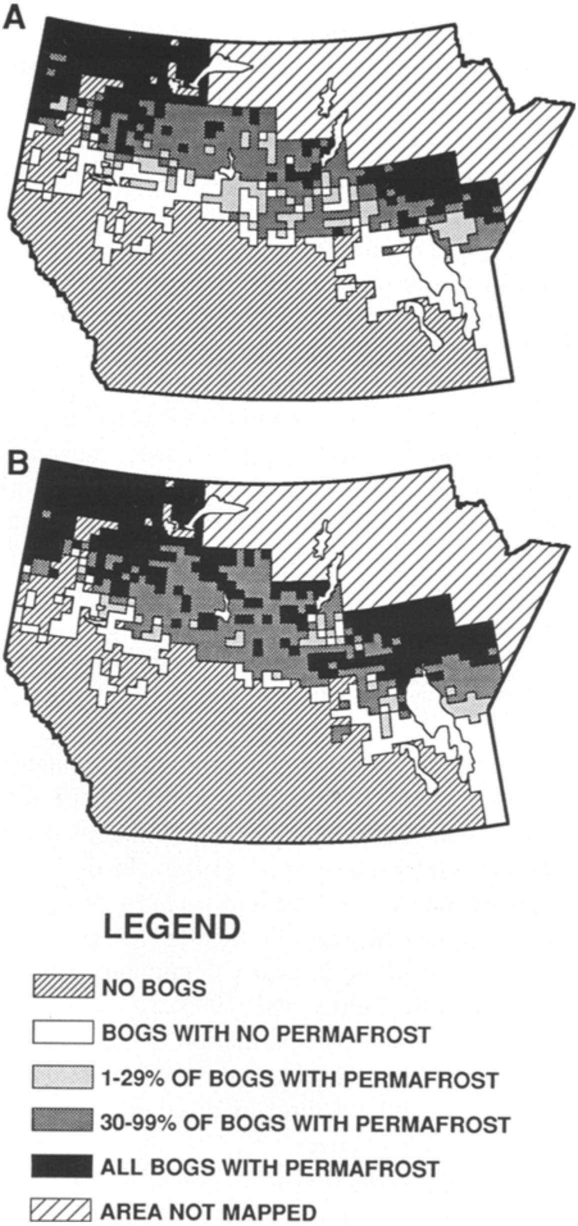


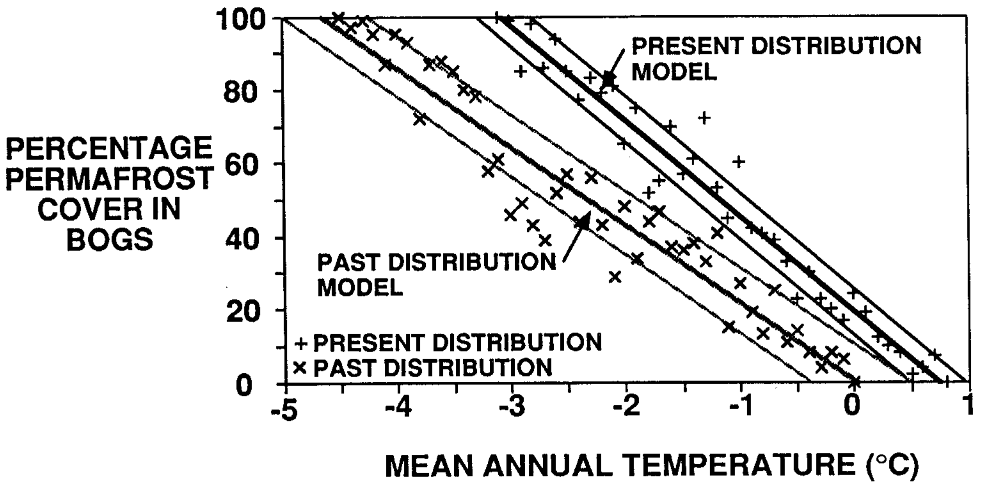
Fig. 4. Percentage distribution of ombrotrophic peatlands containing permafrost in 15′ latitude × 30′ longitude grids (1 : 50,000 map sheets); (A) Modern percentage distribution; (B) Past percentage distribution.

The distribution of discontinous permafrost has been much more extensive in the past, having retreated northwards (Figure 4a and 4b) within the past 100 to 150 years based on dendrochronological data (Vitt *et al.*, 1994a). Individuals of *Picea mariana* grow upright on stable permafrost peat, but when the permafrost thaws the ground subsides differentially, and the trees suddenly become tilted. The leaning trees that remain alive develop abnormal compression wood, marking the time of permafrost collapse at that location and a minimum date of general subsidence. Such data show that subsidence was occurring by the 1890's, forming internal lawns, and has continued since then. This time period is compatible with the ending of the Little Ice Age, at about 1850 (Grove, 1988). The thin hydrophytic (30 to 40 cm) peat development in internal lawns (Vitt *et al.*, 1994a) also implies a brief time period (100 to 150 years) since the degradation of permafrost. Evidence for paleopermafrost from internal lawns is concentrated where modern mean annual temperatures are in the –1 °C to 0 °C range (Vitt *et al.*, 1994a).

The relationship between mean annual temperature and present and past permafrost distribution was quantified by establishing separate linear regressions using mean annual temperature as the explanatory variable (Figure 5). The regression between mean annual temperature and present distribution of percentage permafrost cover in bogs resulted in the model $y_i = -26.2x_i + 19.5$ with a coefficient of determination $r^2 = 0.96$ (Figure 5). Examination of the cross correlations between the residuals of this model and the independent variable (temperature) reveals no significant correlation (Table I). This implies that the model has been correctly specified and is indeed linear (Orlóci and Kenkel, 1985). Comparison of mean annual temperature to modern percent permafrost cover predicts that in western continental Canada 30% of bogs presently contain permafrost at –0.4 °C (Figure 5).

A linear regression was also established between mean annual temperature and the past percentage of permafrost cover in bogs (Figure 5). This regression resulted in the model $y_i = -21.4x_i + 0.6$ with a coefficient of determination of $r^2 = 0.92$ (Figure 5). Cross correlations between the residuals of this model and the independent variable temperature reveal significant correlation between the twelfth to sixteenth order (Table I). This suggests that the model has not been correctly specified, as a trend exists in the residuals (Orlóci and Kenkel, 1985).

As mean annual temperature is perfectly linear (matrix was established in 0.1 °C increments) using other orders of the independent variable (e.g. x_{i-1}) eliminating residual trends is not an option as they are linearly related to the zero order term x_i. Using higher order terms for the dependent variable percent permafrost cover on itself is a viable alternative for eliminating residuals (Box and Jenkins, 1976). Scientifically this is rational as permafrost cover at a given mean annual temperature should be correlated with the permafrost at a slightly warmer or cooler temperature when it is in equilibrium. The past permafrost cover represents the maximum extent of permafrost and should thus be in or very close to equilibrium. Examination of the first five autocorrelations of past permafrost cover residuals do indeed demon-



PRESENT DISTRIBUTION:

$y_i = -26.2x_i + 19.5 \quad r^2 = 0.96$

STD ERR = 6.4

PAST DISTRIBUTION:

A) $y_i = -21.4x_i + 0.6 \quad r^2 = 0.92$

STD ERR = 8.6

B) $y_i = 0.3y_{(i-1)} - 14.6x_i - 0.1 \quad r^2 = 0.92$

STD ERR = 8.3

Fig. 5. Regression of mean annual temperature in 0.1 °C increments to percentage of permafrost cover for the present-day and for the recent past. The distribution models are bounded by the standard error of the estimate which is a measure of the standard deviation of the errors of the regression. Model A of the past distribution of percentage permafrost cover represents a regression without using higher order terms of the dependent variable. Model B of the past distribution includes the first order term of the dependent variable in the regression.

TABLE I

Cross correlations between the independent variable mean annual temperature and the dependent variable permafrost cover for the three proposed models. Values are significant** if they are larger than twice the standard error

Dependent variable = present permafrost			Dependent variable = past permafrost			Dependent variable = past permafrost		
$y_i = -26.2x_i + 19.5$			$y_i = -21.4x_i + 0.6$			$y_i = 0.31y_{i-1} - 14.6x_i - 0.1$		
Zero order cross correlation -1.68×10^{-13}			Zero order cross correlation 3.38×10^{-9}			Zero order cross correlation 1.06×10^{-14}		
No.	1–10	11–20	No.	1–10	11–20	No.	1–10	11–20
1	–0.01	0.00	1	0.01	0.27	1	0.01	0.24
2	0.00	–0.05	2	0.03	0.31**	2	0.04	0.27
3	–0.07	–0.01	3	0.06	0.48**	3	0.05	0.29
4	–0.04	0.00	4	0.08	0.43**	4	0.04	0.29
5	–0.07	–0.25	5	0.08	0.41**	5	0.09	0.18
6	–0.03	–0.18	6	0.12	0.30**	6	0.13	0.14
7	–0.03	–0.20	7	0.17	0.23	7	0.07	0.05
8	–0.07	–0.16	8	0.13	0.12	8	0.13	–0.04
9	–0.05	0.02	9	0.17	0.00	9	0.17	–0.03
10	–0.04	0.04	10	0.22	–0.03	10	0.21	–0.01
EST OF STD ERR	0.14	0.16	EST OF STD ERR	0.13	0.15	EST OF STD ERR	0.13	0.15

TABLE II

Autocorrelations of the residuals of the dependent variable percent permafrost cover. Values are significant** if they are larger than twice the standard error

Dependent variable = present permafrost $y_i = -26.2x_i + 19.5$		Dependent variable = past permafrost $y_i = -21.4x_i + 0.6$	
No.		No.	
1	-0.08	1	0.31**
2	0.01	2	0.36**
3	0.23	3	0.33**
4	-0.17	4	-0.07
5	-0.26	5	0.07
EST OF STD ERR	0.14	EST OF STD ERR	0.13

strate that in a linear model the first to third order autocorrelations are significant (Table II). When a new model is established between mean annual temperature and past percent permafrost cover that includes the first order permafrost cover as an explanatory variable the standard error of the estimate decreases by 0.3 (Figure 5) and the cross correlations between the residuals and the independent variable are no longer significant (Table I).

Warming since the Little Ice Age has had little effect on the percentage of permafrost occurrence in areas where the mean annual temperature is greater than 0.5 °C or less than –3.5 °C (Figure 5). Areas where mean annual temperatures are above 0.5 °C were not cold enough to develop permafrost. Conversely, in areas where mean annual temperatures are presently less than –3.5 °C, no appreciable change in permafrost distribution has occurred, as permafrost has merely persisted. Under future climatic change scenarios, permafrost should continue to persist in bogs where the mean predicted annual temperature is below –3.5 °C. In areas where predicted mean annual temperatures are between 0.5 and –3.5 °C permafrost will degrade, but the pattern of degradation will be unpredictable as the system is in disequilibrium with climate. Autocorrelations of the residuals of present percent cover of permafrost support this hypothesis as they are not significant to the fifth order (Table II). Thus, permafrost cover in any area is not related to cover in areas that are slightly warmer or cooler; this would be expected in a nonequilibrium system.

Although permafrost has thawed extensively since the Little Ice Age, as documented by internal lawns (Vitt *et al.*, 1994a), a model of permafrost distribution today and in the recent past demonstrates that for areas with modern temperatures between –3.5 °C and 0.5 °C permafrost has increased in cover (Figure 5). This can be attributed to the persistence of relict permafrost. Since the Little Ice Age, mean annual temperature isotherms have shifted northward, as has permafrost. However, temperature isotherms have shifted a greater distance north than has permafrost (Figures 3 and 4). The lag in degradation results from the insulating capacity of *Sphagnum*, allowing permafrost to exist under warmer conditions than predicted in the past (Figure 5). Thus, where mean annual temperatures increase, large amounts of permafrost will persist. Degradation models that predict melting of permafrost must therefore take into account the disequilibrium response that occurs in peatlands.

6. Conclusions

Analyses of the distribution of bog landforms indicate that permafrost degradation has occurred in western continental Canada. It has occurred in response to climate warming since the Little Ice Age and has not responded in an equilibrium mode. This disequilibrium degradation response is indicated by the presence of relict permafrost in areas where current temperatures are between 0.5 to –3.5 °C. The presence of relict permafrost suggests that models which use equilibrium response paradigms to evaluate permafrost degradation with predicted greenhouse induced warming are suspect.

Acknowledgements

This study was made possible through a Natural Sciences and Engineering Research Council of Canada (NSERC) grant and a Forestry Canada Joint Research Agreement to Dale Vitt. Constructive comments and suggestions from Drs. M. Apps, E. Gorham and N. Roulet greatly improved this manuscript as did numerous field discussions with Dr. R. Belland. Mr. F. Halsey provided the computer program to examine the residuals and impact of higher order terms in the model for which the authors are grateful. Thanks are also extended to Sandra Vitt and Hilarie Stevens for generating some of the graphics.

References

Allard, M. and Seguin, M. K.: 1987, 'Le Pergélisol au Québec Nordique: Bilan et Perspectives', *Géogr. Physiq. Quatern.* **41**, 141–152.

Anisimov, O. A.: 1989, 'Changing Climate and Permafrost Distribution in the Soviet Arctic', *Phys. Geogr.* **10**, 285–293.

Box, G. E. P. and Jenkins, G. M.: 1976, *Time Series Analysis: Forecasting and Control*, Holden-Day Inc., 575 pp.

Brown, R. J. E.: 1966, 'The Relationship between Mean Annual Air and Ground Temperatures in the Permafrost Regions of Canada', Proceedings of the International Permafrost Conference, National Research Council Publication **1287**, 241–246.

Brown, R. J. E.: 1967, 'Permafrost in Canada', Geological Survey of Canada Map 1246A.

Brown, R. J. E.: 1969, 'Jointing, Aspect and the Orientation of Scarp-Face Dry Valleys, near Ivinghoe, Buckinghamshire', *Transact. Instit. Brit. Geogr.* **48**, 61–73.

Budyko, M. I., Yefimova, N. A., and Lokshina, I. Y.: 1990, 'Anticipated Modifications of Global Climate', Izvestiya Akademii Nauk U.S.S.R., Seriya Geograficheskaya **1989**, 45–55 (in Russian; English translation appears in *Soviet Geography* **31**, 11–24).

Burn, C. R., Michel, F. A., and Smith, M. W.: 1986, 'Stratigraphic, Isotopic, and Mineralogical Evidence for an Early Holocene Thaw Unconformity at Mayo, Yukon Territory', *Canad. J. Earth Sci.* **23**, 794–803.

Campbell, I. D. and McAndrews, J. H.: 1994, 'Forest Disequilibrium Caused by Rapid Little Ice Age Cooling', *Nature* **366**, 336–338.

Cermack, V.: 1973, 'Paleoclimatic Significance of Measuring Temperature of Permafrost', in *Permafrost*, U.S.S.R. Contribution, Second International Conference 1973, National Academy of Sciences, Washington D.C., pp. 112–113.

Dionne, J.-C. and Seguin, M. K.: 1992, 'Recherches sur le Pergélisol dans la Région de Blanc-Sablon, Québec', Geological Survey of Canada Paper **92-1**, 59–65.

French, H. M.: 1970, 'Soil Temperature in the Active Layer', Beaufort Plain', *Arctic* **23**, 229–239.

Gorham, E.: 1991, 'Northern Peatlands: Role in the Carbon Cycle and Probable Responses to Climatic Warming', *Ecolog. Applic.* **1**, 182–195.

Grove, J. M.: 1988, *The Little Ice Age*, Meuthen, New York, 498 pp.

Halsey, L. A., Vitt, D. H., and Zoltai, S. C.: 1993, 'Distribution of Past and Present Ombrotrophic and Permafrost Landform Features', Province of Alberta Maps, Edmonton (1 : 1,000,000 map).

Harris, S. A.: 1986, 'Permafrost Distribution, Zonation and Stability along the Eastern Ranges of the Cordillera of North America', *Arctic* **39**, 29–38.

Heginbottom, J. A.: 'The Mapping of Permafrost', *Canad. Geogr.* **28**, 78–83.

Hopkins, D. M.: 1959, 'Some Characteristics of the Climate in Forest and Tundra Regions of Alaska', *Arctic* **12**, 215–220.

Johnston, G. H.: 1981, *Permafrost: Engineering Design and Construction*, John Wiley and Sons, Toronto.

Jacoby, G. C. and D'Arrigo, R.: 1992, 'Spatial Patterns of Tree-Growth Anomalies from the North American Boreal Treeline in the Early 1800s, Including the Year 1816', in Harrington, C. R. (ed.), *The Year without a Summer? World Climate in 1816*, Canadian Museum of Nature, Ottawa, pp. 255–265.

Kudryavtsev, V. A., Kondrat'eva, K. A., and Romanovskii, N. N.: 1980, 'Zonal and Regional Patterns of the Permafrost Region in the U.S.S.R.', in Proceedings of the Third International Conference of Permafrost, English Translation, Part 1, National Research Council of Canada, pp. 37–389.

Kwong, Y.T.J., and Gan, T.Y.: 1994, Northward Migration of Permafrost along the Mackenzie Highway and Climatic Warming, *Clim. Change* **26**, 399–419.

Lagarec, D.: 1982, 'Cryogenetic Mounds as Indicators of Permafrost Conditions, Northern Quebec', in Proceedings of the Fourth Canadian Permafrost Conference, pp. 43–48.

Lough, J. M.: 1992, 'Climate in 1816 and 1811–20 as Reconstructed from Western North American Tree-Ring Chronologies', in Harrington, C. R. (ed.), *The Year without a Summer? World Climate in 1816*, Canadian Museum of Nature, Ottawa, pp. 97–114.

Luckman, B. H., Holdsworth, G., and Osborn, G. D.: 1993, 'Neoglacial Glacier Fluctuations in the Canadian Rockies', *Quatern. Res.* **39**, 144–153.

Mackay, J. R.: 1975, 'Relict Ice Wedges, Pelly Island, N.W.T.', *Geological Survey of Canada* Paper **75-1A**, 469–470.

Mollard, J. D. and Janes, J. R.: 1984, *Airphoto Interpretation and the Canadian Landscape*, Canada Department of Energy, Mines and Resources, Ottawa, 416 pp.

Nelson, F. E.: 1986, 'Permafrost Distribution in Central Canada: Applications of a Climate-Based Predictive Model', *Annals Assoc. Amer. Geogr.* **76**, 550–569.

Nelson, F. E.: 1989, 'Permafrost Zonation in Eastern Canada: A Review of Published Maps', *Phys. Geogr.* **10**, 233–248.

Nicholson, B. J. and Vitt, D. H.: 1990, 'The Paleoecology of a Peatland Complex in Continental Western Canada', *Canad. J. Botany* **68**, 121–138.

Nicholson, F. H.: 1978, 'Permafrost Distribution and Characteristics near Schefferville, Quebec', Proceedings of the Third International Permafrost Conference, Edmonton, Alberta, National Research Council of Canada, Ottawa, pp. 427–433.

Orlóci, L. and Kenkel, N. C.: 1985, *Introduction to Data Analysis with Examples from Populations and Community Ecology*, International Co-operative Publishing House, Fairland, 339 pp.

Péwé, T. L.: 1983, 'Alpine Permafrost in the Contiguous United States: A Review', *Arctic Alpine Res.* **15**, 145–156.

Rockware, Inc.: 1991, *MacGridzo*, Rockware Inc., Wheat Ridge, 254 pp.

Schweingruber, F. H., Briffa, K. R., and Jones, P. D.: 1991, 'Yearly Maps of Summer Temperatures in Western Europe from A.D. 1750 to 1975 and Western North America from 1600–1982', *Vegetatio* **92**, 5–71.

Schweger, C. E. and Hickman, M.: 1989, 'Holocene Paleohydrology of Central Alberta: Testing the General-Circulation-Model Climate Simulations', *Canad. J. Earth Sci.* **26**, 1826–1833.

Sjörs, H.: 1959, 'Bogs and Fens in the Hudson Bay Lowlands', *Arctic* **12**, 3–19.

Tarnocai, C.: 1972, 'The Use of Remote Sensing Techniques to Study Peatland and Vegetation Types, Organic Soils and Permafrost in the Boreal Region of Manitoba', Proceedings of the First Canadian Symposium on Remote Sensing, Department of Energy, Mines and Resources, Ottawa, pp. 323–335.

Tedrow, J. C. F. and Harris, H.: 1960, 'Tundra Soils in Relation to Vegetation, Permafrost, and Glaciation', *Oikos* **11**, 237–249.

Thie, J.: 1974, 'Distribution and Thawing of Permafrost in the Southern Part of the Discontinuous Permafrost Zone in Manitoba', *Arctic* **27**, 189–200.

Tyrtikov, A. P.: 1964, 'Principles of Geocryology', Academy of Science of the U.S.S.R., Moscow, National Research Council Tech. Translation 1163, pp. 399–421.

Viereck, L. A.: 1973, 'Ecological Effects of River Flooding and Forest Firest on Permafrost in the Taiga of Alaska', Permafrost; North American Contribution, Second International Permafrost Conference, Yakutsk, U.S.S.R., National Academy of Science Publication **2115**, 60–67.

Vitt, D. H. (Project Leader): 1992, 'The Peatlands of Alberta: A 1 : 1,000,000 Summary Map', Nicholson, B. J. and Halsey, L. A. (eds.), Alberta Forestry, Lands and Wildlife and Maps Alberta, Edmonton.

Vitt, D. H., Halsey, L. A. and Zoltai, S. C.: 1994a, 'The Bog Landforms of Continental Western Canada Relative to Climate and Permafrost Patterns', *Arctic Alpine Res.* **26**, 1–13.

Vitt, D. H., Bayley, S. E., and Jin, T.-L.: 1994b, 'Seasonal Variation in Water Chemistry over a Bog-Rich Fen Gradient in Continental Western Canada', *Canad. J. Fish. Aquatic Sci.* (in press).

Woo, M., Lewkowicz, A. G., and Rouse, W. R.: 1992, 'Response of the Canadian Permafrost Environment to Climatic Change', *Phys. Geogr.* **13**, 287–317.

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', *Canad. J. Forest Res.* **2**, 291–302.

Zoltai, S. C.: 1993, 'Cyclic Development of Permafrost in the Peatlands in the Western Arctic and Subarctic of Canada', *Canad. J. Earth Sci.* **12**, 28–43.

Zoltai, S. C., Taylor, S., Jeglum, J. K., Mills, G. G., and Johnson, J. D.: 1988, 'Wetlands of Boreal Canada', in Rubec, C. D. A. (Co-ordinator), *Wetlands of Canada*, Polyscience Publications Inc., Montreal, pp. 97–154.

(Received 10 January, 1994; in revised form 4 January, 1995)