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Article abstract

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DEVELOPMENT OF A MODEL FOR ESTIMATING THE SENSITIVITY OF CANADIAN PEATLANDS TO CLIMATE WARMING*

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ABSTRACT Under current scenarios of increasing greenhouse gases, the expected increases in global temperatures have the potential to affect, in many areas, the peatlands that now cover 14 % of the soil area of Canada. A model for estimating peatland sensitivity to climate warming was developed using published information on the current state of climate, vegetation, and permafrost together with the changes expected with a doubling of CO_2. Calculations based on this sensitivity model and data for the areal extent and carbon content of organic soils in Canada, show that approximately 60 % of the area of Canadian peatlands is expected to be severely to extremely severely affected by climate warming. These peatlands, which are deemed most sensitive to climate warming, also contain 53 % of the 154 Gt of carbon found in organic soils.

RÉSUMÉ *Élaboration d'un modèle destiné à évaluer la sensibilité des tourbières du Canada au réchauffement du climat.* Selon les scénarios actuels qui prévoient une augmentation des gaz à effet de serre, l'augmentation prévue des températures à l'échelle du globe aura pour effet de toucher, dans de nombreuses régions du Canada, les tourbières qui occupent 14 % de la surface des sols. Nous avons élaboré un modèle capable d'estimer la sensibilité des tourbières au réchauffement climatique à partir de l'information publié sur l'état actuel du climat, de la végétation et du pergélisol ainsi que sur les changements prévus si la quantité de CO_2 doublait. Les calculs effectués à partir du modèle de sensibilité établi et des données sur la superficie et la teneur en carbone des sols organiques montrent qu'environ 60 % de l'étendue des tourbières risque d'être éprouvée de manière importante ou extrêmement importante par le réchauffement climatique. Ces tourbières, qui sont considérées comme étant très sensibles au réchauffement climatique, contiennent 53 % des 154 Gt du carbone trouvé dans les sols organiques.

ZUSAMMENFASSUNG *Modellentwicklung zur Einschätzung der Empfindlichkeit der kanadischen Torfmoore gegen die Klimaerwärmung.* Wenn man von gegenwärtigen Szenarios der Zunahme des Treibhauseffekts ausgeht, wird die erwartete Erhöhung der globalen Temperaturen sich in vielen Gebieten auf die Torfmoore auswirken, welche jetzt 14 % der Bodenoberfläche Kanadas einnehmen. Wir haben ein Modell zur Einschätzung der Empfindlichkeit der Torfmoore gegen die Klimaerwärmung entwickelt, wobei wir die veröffentlichte Information über den gegenwärtigen Stand von Klima, Vegetation und Permafrost, sowie die bei einer Verdoppelung des CO_2-Wertes erwarteten Veränderungen benutzt haben. Berechnungen auf der Basis dieses Empfindlichkeitsmodells und der Daten zur räumlichen Ausdehnung und dem Kohlenstoffgehalt der organischen Böden Kanadas zeigen, dass man damit rechnen muss, dass etwa 60 % des Gebiets der kanadischen Torfmoore stark bis extrem stark von der Klimaerwärmung betroffen sein wird. Diese Torfmoore, die man für extrem empfindlich gegen die Klimaerwärmung hält, enthalten 53 % der 154 Gt (Gigatonnen) des in den organischen Böden gefundenen Kohlenstoffs.

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INTRODUCTION

Under current scenarios of increasing greenhouse gases, many climate experts predict a doubling of CO_2 and an increase in average global temperature of 1.5 to 4.5 °C by the year 2030 (Watson *et al.*, 1990; Houghton *et al.*, 1996). In peatlands, this change is expected to affect such aspects as hydrology (drying), carbon accumulation, plant communities, and permafrost distribution (Gorham, 1991; Zoltai, 1994; Halsey *et al.*, 1995). For example, large changes are expected in the vast peatland areas now covered with the boreal forest, especially those affected by permafrost (Gorham, 1991). In these areas the dominant black spruce would migrate northwards, as would the accumulation of greater amounts of dead biomass and the danger of increased insect and disease infestation. Also expected would be increases in rate and magnitude of forest fire-induced changes (Weber and Flannigan, 1997). In addition, some coastal boreal peatlands would be destroyed by the flooding accompanying the expected rise in sea level (Warrick and Oerlemans, 1990; Shaw *et al.*, 1994).

Information on the probable impact of the predicted climate change on critical aspects of the Canadian landmass is needed for scientific research purposes and for the formulation of government policy on how to mitigate or adapt to the resulting environmental changes. Estimation of the potential sensitivity of the different ecosystems in Canada requires models that provide spatial information on the potential effects of climate warming. In the first part of this paper we present a model for making a first estimate of potential peatland sensitivity to the climate changes that are projected to occur in Canada as a result of a doubling of atmospheric CO_2. Although the model was developed specifically for peatlands, it should be useful for estimating the potential sensitivity of related terrestrial ecosystems, particularly in the permafrost regions of Canada.

In the second part of the paper the potential peatland sensitivity model is used to estimate the magnitude of change expected to occur in Canadian peatlands because of climate warming. These peatlands cover more than 14 % of the soil area of Canada and occur primarily in permafrost-affected boreal and subarctic regions (Tarnocai *et al.*, 1995). A warmer climate is expected to significantly affect their form and distribution on the landscape. In addition, peatlands are important to climate warming scenarios because they fix CO_2 from the atmosphere as peat and emit CO_2 and CH_4 to the atmosphere as they decompose (Gorham, 1991). As a result, Canadian peatlands have the potential to significantly affect, as well as be affected by, climate warming processes.

DEVELOPMENT OF THE TERRAIN SENSITIVITY MODEL

The development or persistence of peatlands within the landscape is determined by interactions among numerous environmental components (Zoltai, 1988a). These components include hydrology, physical and chemical characteristics of the underlying surficial materials, topography, local climate, vegetation, fauna, and the presence or absence of permafrost. These interactions take place over an extended period of time within a range of climatic parameters (Zoltai and Tarnocai, 1976). Each of these abiotic and biotic components influences and is influenced by the other components. Once developed, most peatland ecosystems are generally stable, gradually adjusting to change over time unless affected by catastrophic events (Zoltai, 1988a). In order to determine which peatland areas may be affected by climate warming, it is necessary to develop a database containing systematic spatial information on environmental components crucial to peatland development and sustenance. It is also necessary to have information on projected changes to these environmental components as a result of climate warming. In this analysis, projections of the effects of the expected warming on climate, vegetation, and permafrost in Canada, made by other scientists for other purposes, have been used.

PREDICTED CHANGES IN ECOCLIMATIC REGIONS

Systematic spatial information on the current state of climate and vegetation in Canada is shown in the ecoclimatic map presented by the Ecoregions Working Group (1989). They divided Canada into Arctic, Subarctic, Boreal, Temperate, Grassland, and Cordilleran ecoclimatic provinces. Each of these provinces has a distinctive ecological response to climate, as expressed by vegetation and reflected in the distribution of soils, wildlife, and water. Similar criteria were used to develop a wetlands map of Canada (National Wetlands Working Group, 1988, back cover). Because wetlands with characteristic types and forms develop in locations that have similar topography, hydrology, and nutrient regimes, the map of wetland regions correlates closely to the ecoclimatic provinces map.

In recent years there has been increased public interest in human-induced climatic changes and their implications for our sustainable-resource economies (Working Group II, 1995). In order to assess the sensitivity of Canada's ecosystems to climatic change, Zoltai (1988b) and Rizzo (1988) estimated changes in ecoclimatic provinces resulting from a doubling of atmospheric CO_2 levels. In developing our terrain sensitivity model we used information derived from Zoltai's forecast, as shown in Figure 1b. Zoltai gave strong consideration to the distribution, composition, and morphology of surficial materials, as well as to temperature and moisture changes when predicting the alteration in boundaries of the present ecoclimatic regions under a 2x CO_2 scenario. For example, on Zoltai's map the northward migration of the Grassland Ecoclimatic Province in Saskatchewan and Manitoba is restricted where the landscape changes from level sedimentary bedrock covered with thick tills or lake sediments to the soil-poor, rugged bedrock of the Canadian Shield. The acidic, nutrient-poor soils typical of shield terrain would more likely sustain taiga vegetation than grassland vegetation.

Information on the present state of climate and vegetation (from the two maps described above), and the changes predicted to occur as a result of climate warming were used to

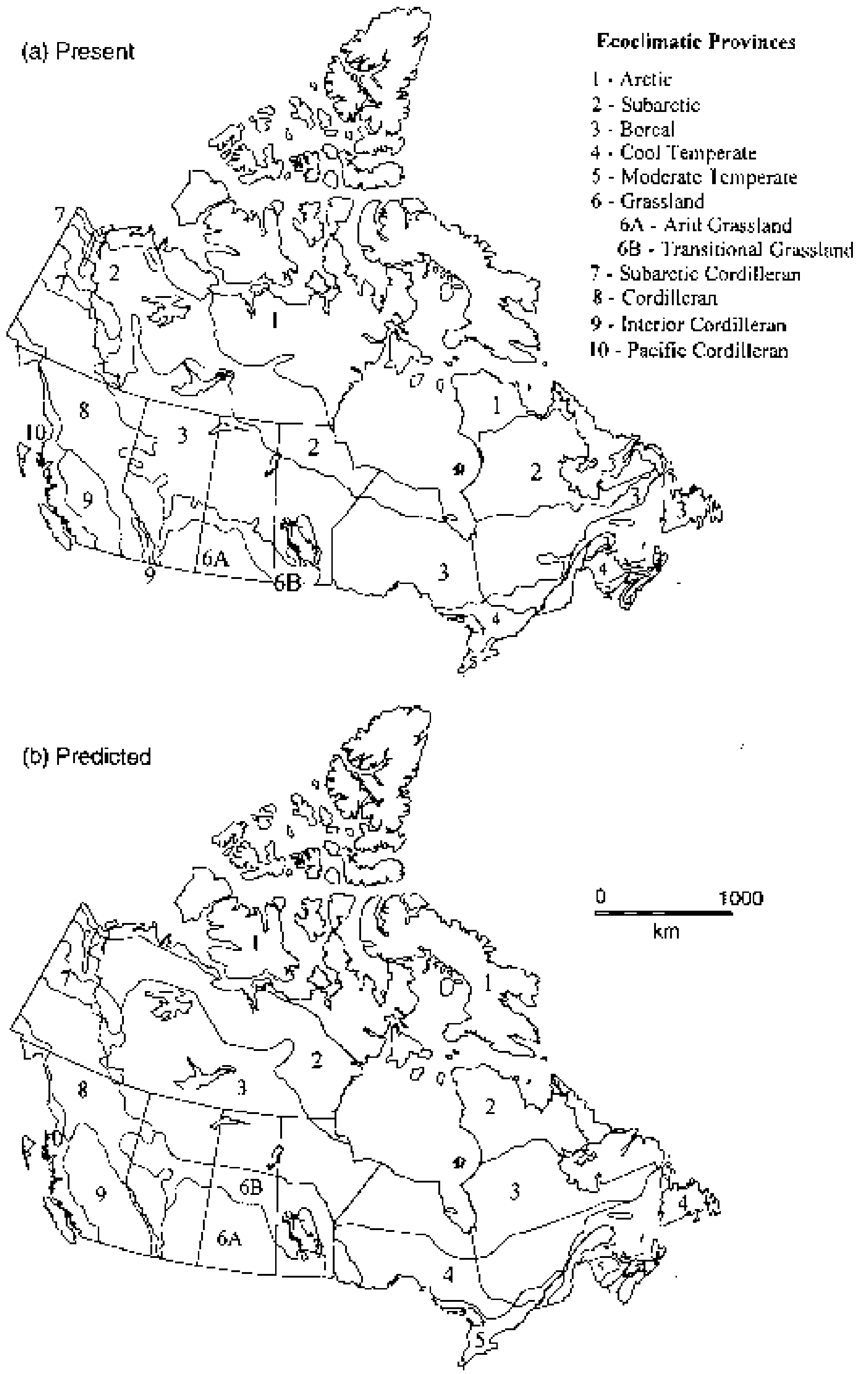


FIGURE 1. Ecoclimatic provinces in Canada (after Zoltai, 1988b): (a) present; and (b) predicted, based on a doubling of atmospheric CO_2.

Provinces écoclimatiques du Canada (selon Zoltai, 1988b) : situations (a) actuelle et (b) prévue si la quantié du CO_2 atmosphérique doublait.

delineate areas expected to be affected by ecosystem changes and to estimate the magnitude of such change. In order to compare the two types of information, the map showing the present distribution of ecoclimatic provinces (Fig. 1a) was overlaid by the map showing their expected distribution in a 2x CO_2 environment, based on Zoltai's forecast (Fig. 1b). This was accomplished by digitizing the two maps in Figure 1 and intersecting the polygons on each using ArcInfo GIS software. The resultant polygons on the derivative map produced from this operation (Fig. 2) indicate 21 possible scenarios, 11 with actual changes in ecoclimatic provinces and 10 with no change (Table I: "Ecoclimatic Prov-

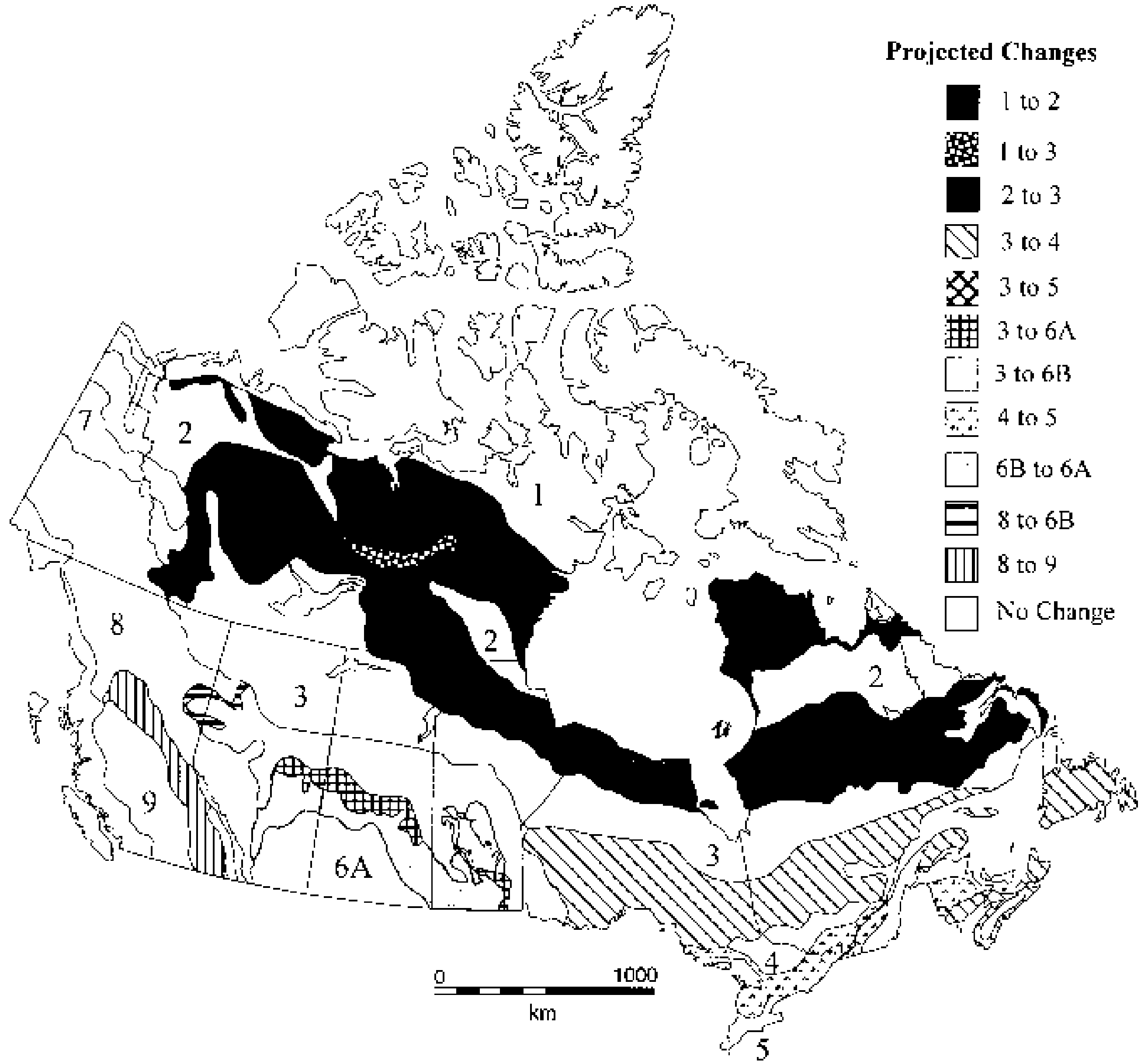


FIGURE 2. Expected changes in ecoclimatic provinces with predicted climate warming. Numbers listed in legend are explained in Figure 1.

Changements attendus avec le réchauffement climatique dans les provinces écoclimatiques. Les chiffres donnés en légende sont expliqués à la figure 1.

inces: Scenario"). The most pronounced changes are expected to occur in the current Boreal, Subarctic and Arctic ecoclimatic provinces, with the zone boundaries (*cf.* Figs. 1 and 2) expected to shift more than 300 km northwards in many areas.

PREDICTED CHANGES IN PERMAFROST DISTRIBUTION

There are strong interrelationships between the distributions of peatlands and permafrost because of the insulating properties of peat and the poor drainage conditions in peatlands (Zoltai, 1988a). For example, along the southern limit of discontinuous permafrost, the permafrost present exists as "islands" beneath peat and other organic sediments (French, 1989). Because changes in permafrost conditions disrupt the patterns of water flow and water chemistry in peatlands, such changes have the potential to strongly affect peatland distribution and morphology. As a result, when evaluating peatland sensitivity special consideration has been given to the predicted changes in permafrost distribution resulting from climate warming.

Systematic spatial information on the current thermal state of Canada's land surface is shown in the maps of permafrost distribution in Canada (Heginbottom *et al.*, 1995; Zoltai, 1995). Zoltai generated a regional map of the current

TABLE I

Ratings of scenarios of change or no change in ecoclimatic provinces and permafrost zones

Category	Ecoclimatic Provinces		Permafrost Zones		Final Sensitivity
	Scenario	Rating of Change	Scenario	Rating of Change	Rating
1	Arctic to Arctic	0	Continuous to Continuous	0	No Change
2	Arctic to Arctic	0	Continuous to Sporadic	4	Severe
3	Arctic to Arctic	0	Continuous to Widespread	1	Very Slight
4	Arctic to Subarctic	1	Continuous to Continuous	0	Very Slight
5	Arctic to Subarctic	1	Continuous to Sporadic	4	Extremely Severe
6	Arctic to Subarctic	1	Continuous to Widespread	1	Slight
7	Arctic to Subarctic	1	Widespread to Sporadic	2	Moderate
8	Arctic to Boreal	4	Continuous to Sporadic	4	Extremely Severe
9	Arctic to Boreal	4	Continuous to Widespread	1	Extremely Severe
10	Pacific Cordilleran to Pacific Cord.	0	Localized to None	1	Very Slight
11	Pacific Cordilleran to Pacific Cord.	0	None to None	0	No Change
12	Pacific Cordilleran to Pacific Cord.	0	Sporadic to None	4	Severe
13	Subarctic to Subarctic	0	Continuous to Localized	4	Severe
14	Subarctic to Subarctic	0	Continuous to Sporadic	4	Severe
15	Subarctic to Subarctic	0	Continuous to Widespread	1	Very Slight
16	Subarctic to Subarctic	0	Localized to Localized	0	No Change
17	Subarctic to Subarctic	0	Sporadic to Localized	3	Moderate
18	Subarctic to Subarctic	0	Sporadic to Sporadic	0	No Change
19	Subarctic to Subarctic	0	Widespread to Localized	3	Moderate
20	Subarctic to Subarctic	0	Widespread to None	4	Severe
21	Subarctic to Subarctic	0	Widespread to Sporadic	2	Slight
22	Subarctic to Boreal	2	Continuous to Localized	4	Extremely Severe
23	Subarctic to Boreal	2	Continuous to Sporadic	4	Extremely Severe
24	Subarctic to Boreal	2	Continuous to Widespread	1	Moderate
25	Subarctic to Boreal	2	Localized to Localized	0	Slight
26	Subarctic to Boreal	2	Localized to None	1	Moderate
27	Subarctic to Boreal	2	Sporadic to Localized	3	Extremely Severe
28	Subarctic to Boreal	2	Sporadic to None	4	Extremely Severe
29	Subarctic to Boreal	2	Sporadic to Sporadic	0	Slight
30	Subarctic to Boreal	2	Widespread to Localized	3	Extremely Severe
31	Subarctic to Boreal	2	Widespread to None	4	Extremely Severe
32	Subarctic to Boreal	2	Widespread to Sporadic	2	Severe
33	Boreal to Boreal	0	Localized to Localized	0	No Change
34	Boreal to Boreal	0	Localized to None	1	Very Slight
35	Boreal to Boreal	0	None to None	0	No Change
36	Boreal to Boreal	0	Sporadic to None	4	Severe
37	Boreal to Boreal	0	Widespread to Localized	3	Moderate
38	Boreal to Boreal	0	Widespread to None	4	Severe
39	Boreal to Cool Temperate	2	Localized to None	1	Moderate
40	Boreal to Cool Temperate	2	None to None	0	Slight
41	Boreal to Moderate Temperate	3	None to None	0	Moderate
42	Boreal to Arid Grassland	4	Localized to None	1	Extremely Severe
43	Boreal to Arid Grassland	4	None to None	0	Severe
44	Boreal to Transitional Grassland	4	Localized to None	1	Extremely Severe
45	Boreal to Transitional Grassland	4	None to None	0	Severe
46	Boreal to Transitional Grassland	4	Sporadic to None	4	Extremely Severe
47	Cool Temperate to Cool Temperate	0	None to None	0	No Change
48	Cool Temperate to Mod. Temperate	1	None to None	0	Very Slight

TABLE I (cont.)

Ratings of scenarios of change or no change in ecoclimatic provinces and permafrost zones

Category	Ecoclimatic Provinces Scenario	Rating of Change	Permafrost Zones Scenario	Rating of Change	Final Sensitivity Rating
49	Mod. Temperate to Mod. Temperate	0	None to None	0	No Change
50	Arid Grassland to Arid Grassland	0	None to None	0	No Change
51	Trans. Grassland to Arid Grassland	1	None to None	0	Very Slight
52	Subarctic Cord. to Subarctic Cord.	0	Continuous to Sporadic	4	Severe
53	Subarctic Cord. to Subarctic Cord.	0	Continuous to Widespread	1	Very Slight
54	Subarctic Cord. to Subarctic Cord.	0	Widespread to Localized	3	Moderate
55	Subarctic Cord. to Subarctic Cord.	0	Widespread to Sporadic	2	Slight
56	Cordilleran to Trans. Grassland	1	Localized to None	1	Slight
57	Cordilleran to Trans. Grassland	1	None to None	0	Very Slight
58	Cordilleran to Trans. Grassland	1	Sporadic to None	4	Extremely Severe
59	Cordilleran to Cordilleran	0	Localized to None	1	Very Slight
60	Cordilleran to Cordilleran	0	None to None	0	No Change
61	Cordilleran to Cordilleran	0	Sporadic to None	4	Severe
62	Cordilleran to Cordilleran	0	Widespread to Localized	3	Moderate
63	Cordilleran to Cordilleran	0	Widespread to None	4	Severe
64	Cordilleran to Interior Cordilleran	1	Localized to None	1	Slight
65	Cordilleran to Interior Cordilleran	1	None to None	0	Very Slight
66	Interior Cordilleran to Interior Cord.	0	Localized to None	1	Very Slight
67	Interior Cordilleran to Interior Cord.	0	None to None	0	No Change

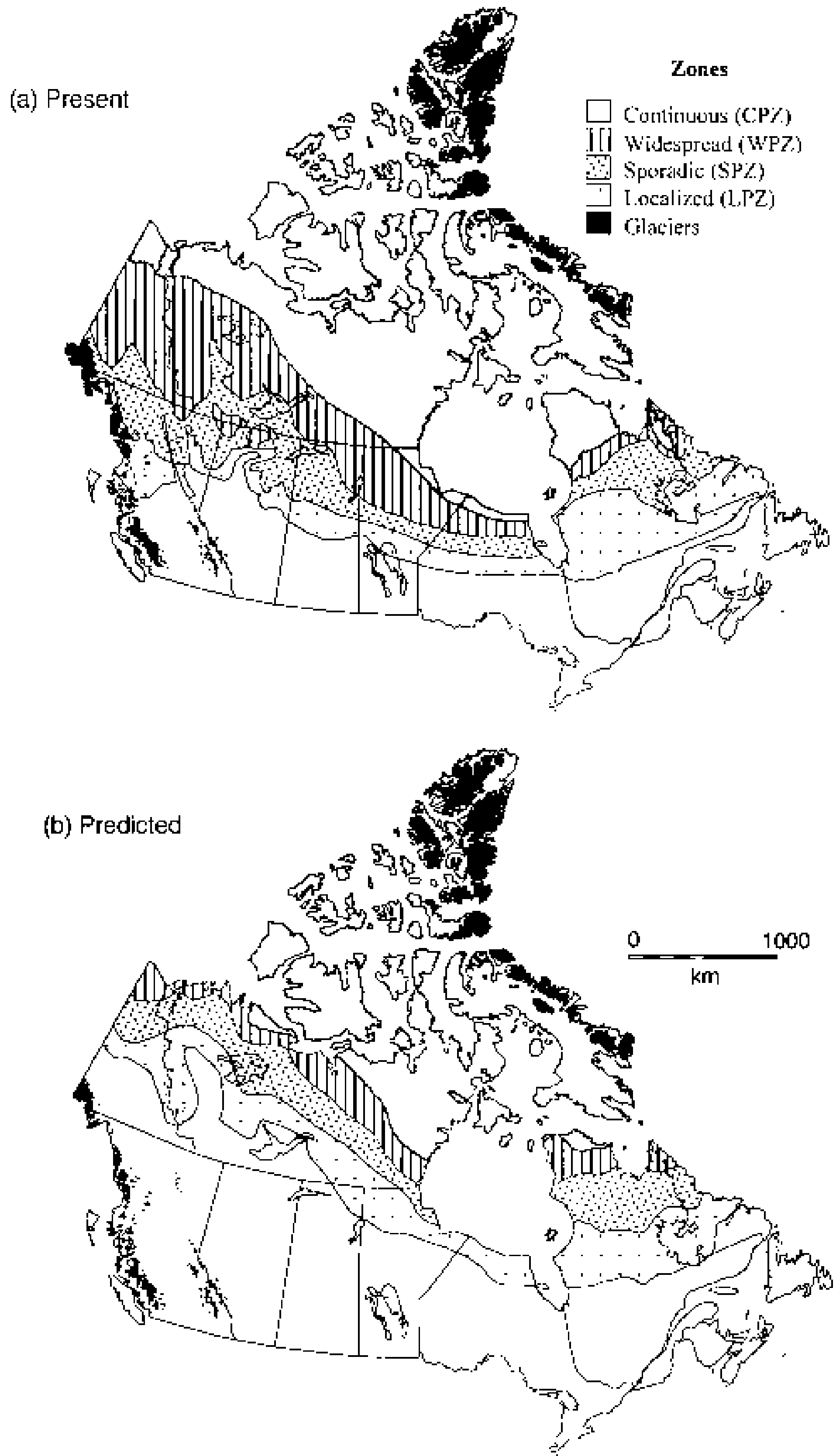
permafrost distribution in the Prairie provinces, Yukon, and the Northwest Territories west of Hudson Bay, which includes the majority of permafrost areas in Canada (Fig. 1 in Zoltai, 1995). This map is based on field data, including drill cores. Although no similar regional compilation is available for eastern Canada, information is available in the National Atlas compilation (Heginbottom *et al.*, 1995). This compilation is based on a framework of physiographic units described by Bostock (1970), with pertinent information relating to surface materials and permafrost being considered for each unit. Both Zoltai's map and the National Atlas compilation distinguish the following permafrost zones: permafrost-free, Localized (LPZ), Sporadic (SPZ), Widespread (WPZ), and Continuous (CPZ). The map of present-day permafrost distribution (Fig. 3a) is based on Zoltai's map for the Prairies and northern Canada west of Hudson Bay and on Heginbottom's compilation for the remaining areas of Canada.

Zoltai also produced a map of permafrost distribution in peatlands in western Canada at 6000 BP (Fig. 3 in Zoltai, 1995), during the xerothermic period, when summer temperatures in the continental parts of North America and Eurasia were 2–4 °C higher than at present (COHMAP Members, 1988). Zoltai's map, which covers most of the permafrost areas in Canada, is based on systematic analysis of data from macrofossil analysis and radiocarbon dating of numerous peat cores to determine whether permafrost was present or absent at the time of peat formation. No similar reconstructions have been carried out at a regional scale for eastern Canada. There are, however, at least two circumpolar- or global-scale reconstructions based on the manipulation of 2X CO^2 global circulation models (GCMs). Woo *et al.* (1992) generated a diagram showing projected shifts in the boundaries of discontinuous and continuous permafrost resulting from a surface temperature change of 4–5 °C. More recently, another analysis was undertaken by Anisimov and Nelson (1996) to predict permafrost distribution in northern circumpolar regions, based on 2 °C global warming. In their study, they manipulated GCMs and an empirical paleoreconstruction, based on paleobotanical and paleogeological data, to produce maps showing the new positions of permafrost zone boundaries. They also distinguished four permafrost zones corresponding to Zoltai's CPZ, WPZ, SPZ, and LPZ.

In this paper the western portion (excluding British Columbia) of the map showing predicted permafrost distribution (Fig. 3b) is based on the regional-scale reconstruction of Zoltai (1995). Elsewhere in Canada, where there are no similar reconstructions, the map is based on the predictions of Anisimov and Nelson (1996). Their projection was used because it appeared to correspond to Zoltai's in many places in western Canada, although the former was based on a global warming of 2–4 °C and the latter on 2 °C. When compared to Zoltai's reconstruction, the positions of the CPZ and WPZ boundaries are similar in many areas, though there is less correspondence between the predicted southern limits of the SPZ and LPZ. Although Anisimov and Nelson's projection is based on a smaller increase in global temperature, the southern limits of the SPZ and LPZ appear to lie more than 150 km farther south in their projection. On the map in Figure 3b, the southern limit of the LPZ in northwestern Ontario reflects Zoltai's compilation rather than the prediction of Anisimov and Nelson because Zoltai's LPZ boundary

FIGURE 3. Permafrost distribution in Canada: (a) present (after Zoltai,1995; Heginbottom *et al.*, 1995); and (b) predicted, based on a doubling of atmospheric CO_2 (after Zoltai, 1995; Anisimov and Nelson, 1996; Kettles *et al.*, 1997).

La répartition du pergélisol au Canada : situations (a) actuelle (selon Zoltai, 1995 ; Heginbottom et al.*, 1995) et (b) prévue si la quantité de CO_2 atmosphérique doublait (selon Zoltai, 1995 ; Anisimov et Nelson, 1996 ; Kettles* et al.*, 1997).*



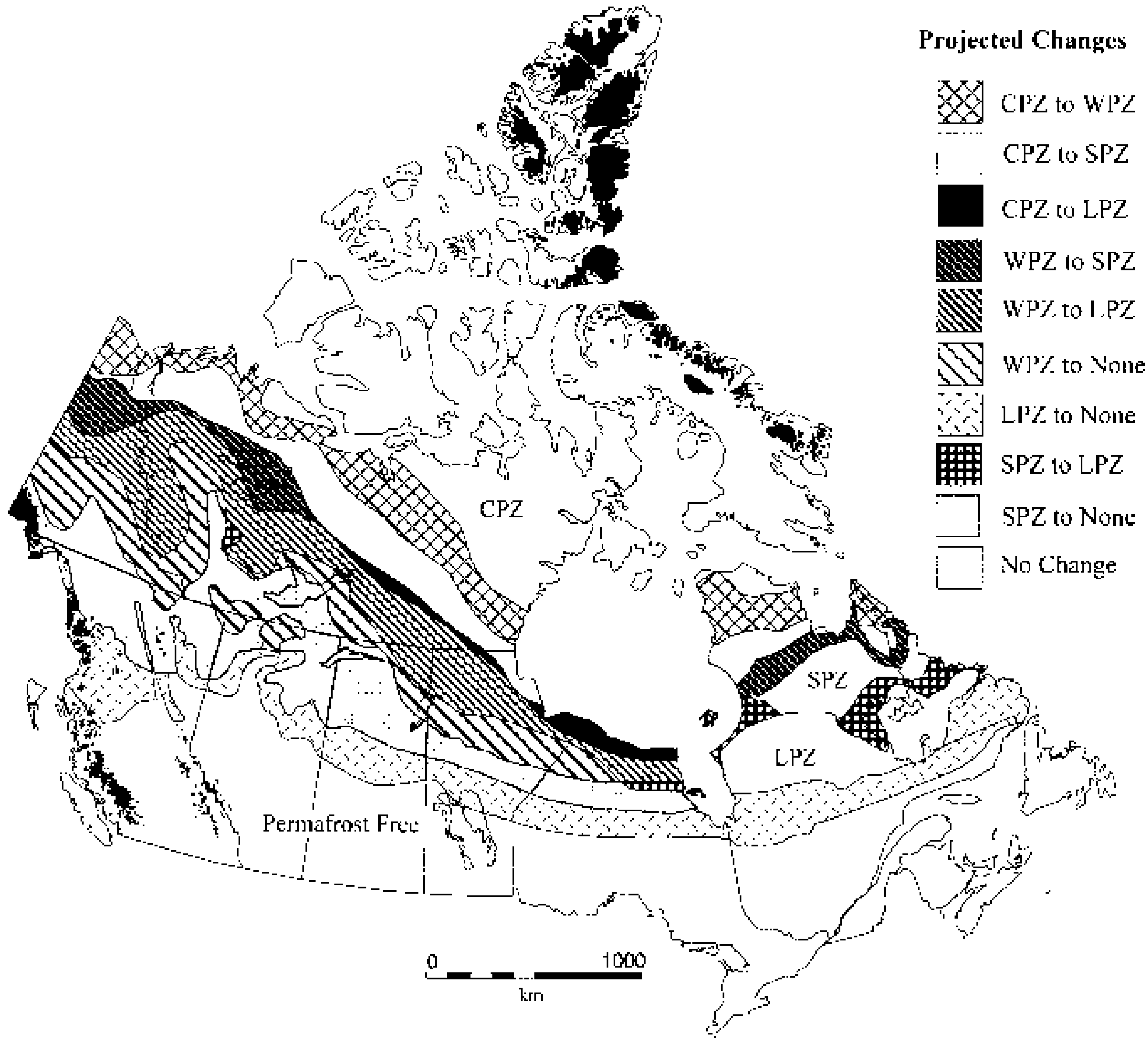


FIGURE 4. Expected changes in permafrost distribution with predicted climate warming. The permafrost zones are: CPZ – continuous, WPZ – widespread, SPZ – sporadic, and LPZ – localized. Glaciers are shown in black.

Changements attendus avec le réchauffement climatique dans la répartition du pergélisol. Les zones de pergélisol sont les suivantes : CPZ – continu, WPZ – largement répandu, SPZ – sporadique, et LPZ – localisé. Les glaciers sont en noir.

is based on data from numerous boreholes in adjacent areas of northeastern Manitoba. In addition, some modifications were made to Anisimov and Nelson's projection in small areas of northern Québec, Baffin Island, and northern British Columbia, based on altitude and local geology.

Information on current permafrost conditions was compared with information on changes predicted to occur in permafrost as a result of climatic warming to delineate areas expected to be affected by warming. In order to compare the two types of information, the map showing the present distribution of permafrost (Fig. 3a) was overlaid by the map showing the expected distribution of permafrost in a 2x CO_2 environment (Fig. 3b) using the GIS techniques described previously. The resultant derivative map (Fig. 4) indicates 13 possible scenarios, 9 with actual changes in permafrost zones and 4 with no change (Table I: "Permafrost Zones: Scenario"). The most pronounced changes are expected to occur in the present-day Boreal and Subarctic ecoclimatic provinces. In addition, it is predicted that the southern limits of discontinuous and continuous permafrost will to shift more than 300 km northward in many areas.

The present-day distribution of glaciers in Canada is shown in Figures 3 and 4. It should be noted that, although alpine glaciers are expected to shrink in some areas, there

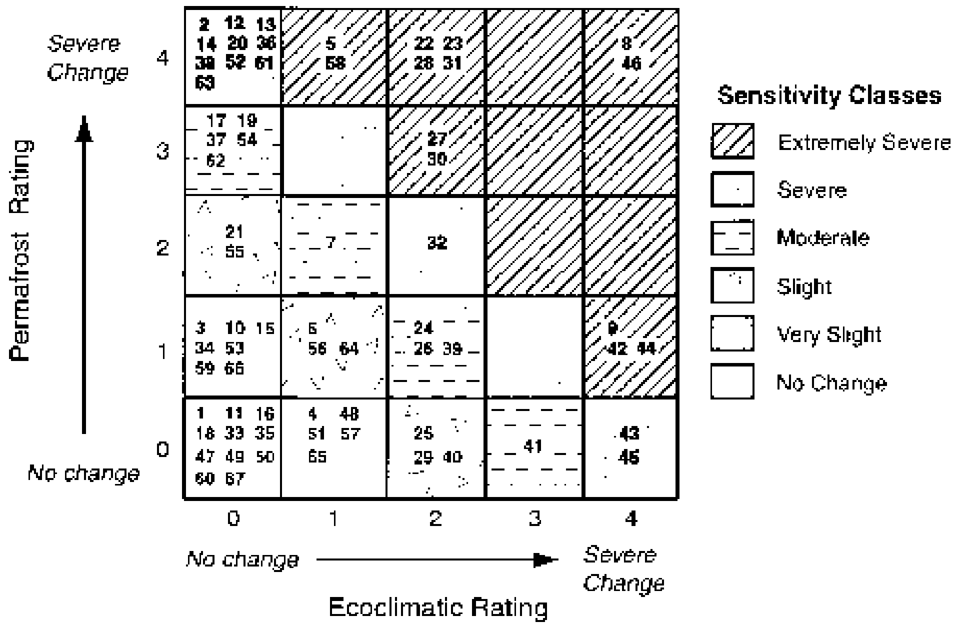


FIGURE 5. System for evaluating severity of changes in ecoclimatic provinces and permafrost zones. The numbers on the graph represent the 67 scenarios of change or no change listed in Table I. The final sensitivity ratings are the sum of the ratings of change for each ecoclimatic province and permafrost zone. These ratings are based on six classes of change: no change (0), very slight (1), slight (2), moderate (3), severe (4), and extre--mely severe (5 or greater).

Mode d'évaluation de l'importance des changements dans les provinces écoclimatiques et dans les zones de pergélisol. Les nombres représentent les 67 catégories de changement ou d'absence de changement données au tableau I. Le classement final de sensibilité représente la somme des classes de changement pour chacune des provinces écoclimatiques et des zones de pergélisol. Les six classes de changement sont les suivantes : aucun changement (0), très léger (1), léger (2), moyen (3), important (4), très important (5 ou plus).

are many uncertainties in predicting the effects of climate warming on their distribution (Warwick *et al.*, 1996). In addition, the changes in glacier distribution are expected to have a very minor effect on peatland distribution and processes. Therefore, for purposes of this study, glaciers were considered to be nonpermafrost areas, and any potential changes in their distribution were not considered.

DEVELOPMENT OF A POTENTIAL PEATLAND SENSITIVITY MAP

After the maps showing the predicted changes in the distribution of ecoclimatic provinces and permafrost zones (Figs. 2 and 4) were completed, the final potential peatland sensitivity map for Canada was generated in four steps.

The first step involved evaluating, one by one, the severity of the 21 scenarios of change in ecoclimatic provinces (Fig. 2; Table I) and the 13 scenarios of change in permafrost zones (Fig. 4; Table I). This was accomplished by first counting the number of units of change in permafrost zone or ecoclimatic province represented by the predicted change. Each unit of change represents a one-step change (*e.g.*, from the Widespread Permafrost Zone to the Sporadic). At its simplest, one-, two- or three-step changes in ecoclimatic province or permafrost zone were given numeric ratings of “1”, “2”, or “3”, respectively. In some cases, however, the numeric rating was weighted after subjectively evaluating the severity and areal extent of the disturbances expected to occur in peatlands as a result of the projected changes. At the end of this evaluation a numeric rating with a value between “0” (no change) and “4” (severe change) was assigned to each scenario of change. For example, the change from the Continuous Permafrost Zone to the Widespread was given a rating of “1”, but the change from the Continuous Permafrost Zone to the Sporadic was given a rating of “4” for “severe” instead of the “2” for “slight” it would have been given were the rating system based only on counting the number of units of change (Continuous to Widespread to Sporadic). The projected change was rated “severe” in this case because there would be extreme disruption of the hydrological balance and other functions in any peatlands that changed from being continuously frozen to only sporadically frozen. Another example of weighting was the rating of “4” given to those parts of the Boreal Ecoclimatic Province expected to become part of the Arid Grassland Ecoclimatic Province. The “severe” change rating was given in this case because peatlands in these areas are expected to dry out and, eventually, disappear completely. The ratings for each of the 34 different scenarios of change or no change are listed under “Ecoclimatic Provinces: Rating of Change” and “Permafrost Zones: Rating of Change” in Table I.

The second step involved using the GIS techniques described previously to compare the information on the maps showing predicted changes in ecoclimatic provinces and permafrost zones (Figs. 2 and 4). When the two maps were overlaid, the resultant derivative map was composed of 269 polygons, comprising the 67 different combinations of expected scenarios of change or no change (categories) in ecoclimatic provinces and permafrost zones listed in Table I.

The third step consisted of determining a final sensitivity rating for each of the 67 categories of change identified in the second step. This was carried out by first plotting, for each of the 67 categories, the value of the rating of change for ecoclimatic province against the value of the rating of change for permafrost zone (Fig. 5). The resulting data points, which represent the Final Sensitivity Ratings (Table I), are the sum of the ratings of change for each eco-

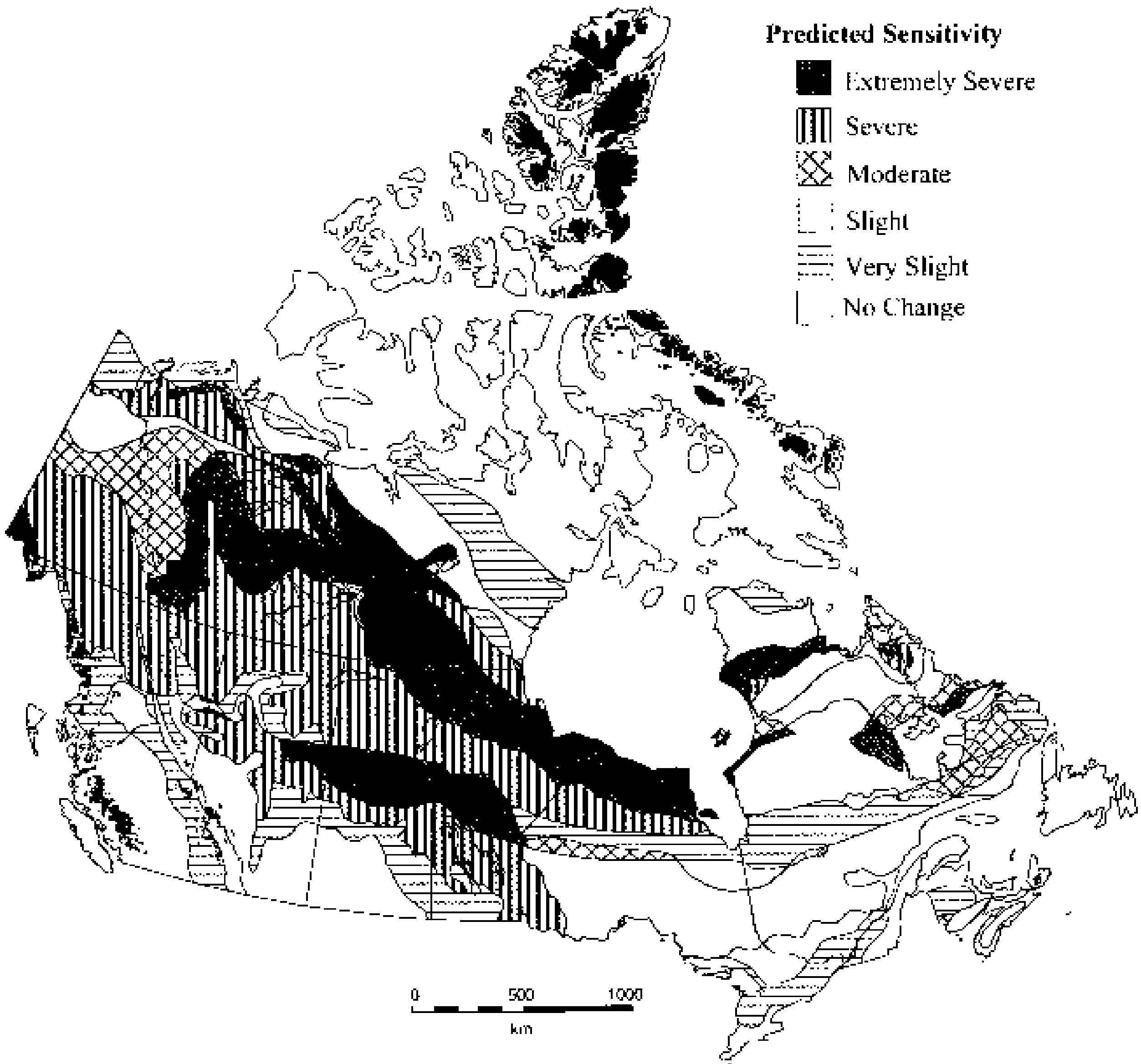


FIGURE 6. Potential peatland sensitivity map of Canada. Areas covered by glaciers, shown in black, have not been evaluated.

Carte de la sensibilté potentielle des tourbières du Canada. Les régions couvertes par les glaciers (en noir) n'ont pas été évaluées.

climatic province and permafrost zone. These final ratings are based on six classes of change: no change (0), very slight (1), slight (2), moderate (3), severe (4), and extremely severe (5 or greater).

The fourth step involved plotting the final peatland sensitivity map for Canada (Fig. 6). As described above, each of the 269 polygons on the final map are represented by one of the 67 categories of change (Table I). Individual polygons are differentiated, using patterns and gray tones, according to the final sensitivity rating for the category to which they belong. The potential sensitivity map generated during this study shows that the effects of climate warming, in terms of permafrost degradation and shift in ecoclimatic provinces, are not expected to be uniform within the individual present ecoclimatic provinces or permafrost zones in Canada. Effects are expected to be most severe in the southern parts of the present Subarctic and Boreal ecoclimatic provinces and in the current Widespread and Sporadic permafrost zones.

ESTIMATING THE MAGNITUDE OF EXPECTED CHANGE

The potential sensitivity map generated during this study was correlated with systematic information on peatland distribution to estimate the magnitude of change expected in Canadian peatlands with climate warming. At present, the most complete set of systematic data on Canadian peatlands is the Soil Carbon Database (Soil Carbon Data Base

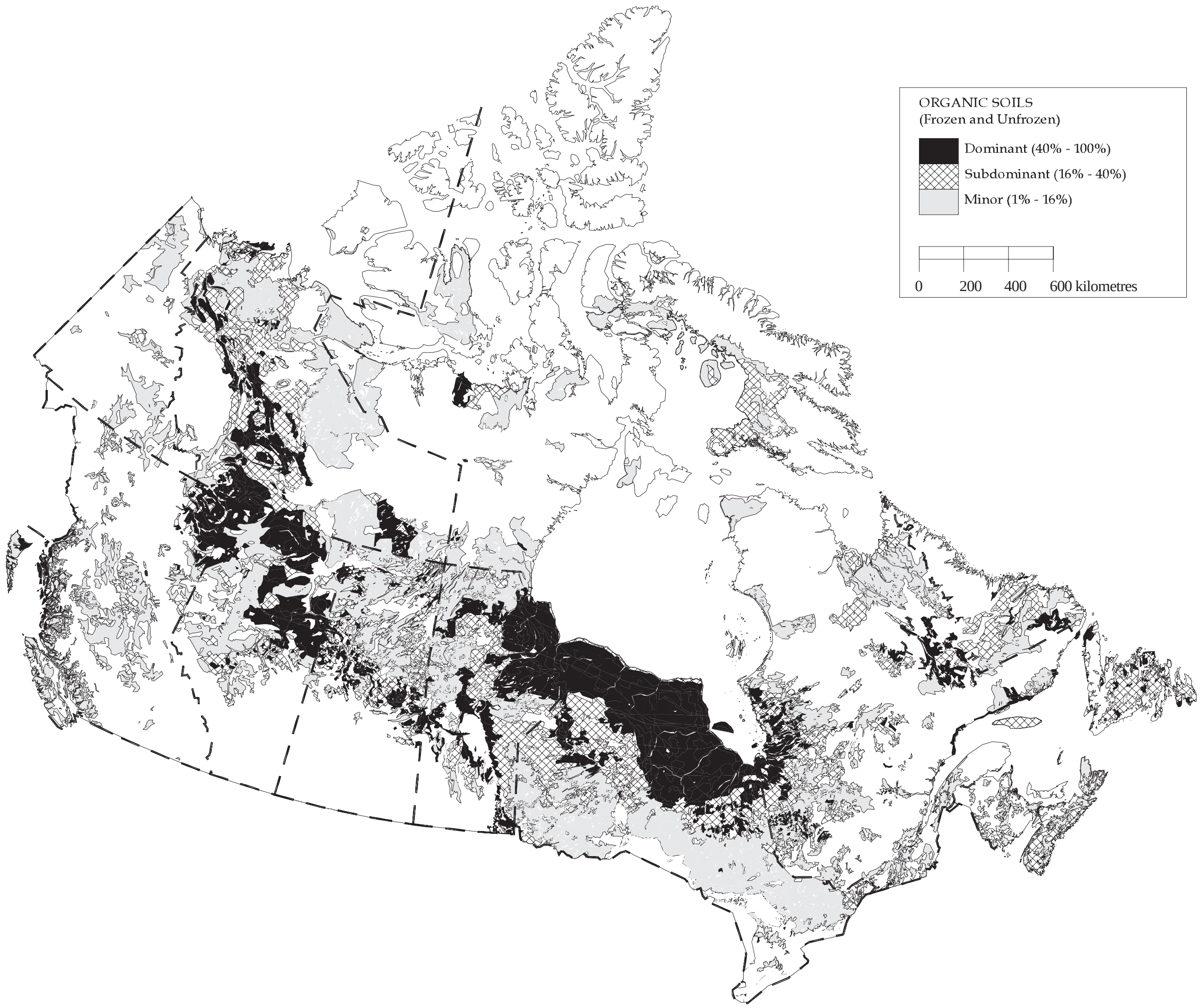


FIGURE 7. Distribution of organic soils in Canada (after Soil Carbon Data Base Working Group, 1993).

Répartition des sols organiques au Canada (selon le Soil Carbon Data Base Working Group, 1993).

Working Group, 1993), in which both frozen and unfrozen peatlands are represented by organic soils. Organic soils are defined as soils with >17 % organic carbon (most peat contains 35 to, in some cases, more than 45 % carbon) and organic accumulation thicknesses of at least 40 cm (Soil Classification Working Group, 1998). In the database there is information on the distribution and amount of organic carbon in both the entire depth of the organic soil (total soil) and the uppermost 30 cm (surface soil). The distribution of organic soils, based on the Soil Carbon Database, is shown in Figure 7. The dominant peatlands, consisting of areas with 40 to 134 kg/m^2 carbon, occur in the James Bay and Hudson Bay Lowlands, the Mackenzie River valley, northern Alberta, central Saskatchewan and central Manitoba.

In order to determine what proportion of the surface area in each ecoclimatic province is covered by organic soils, as well as the amounts of total and surface soil organic carbon, maps showing the amounts of total and surface organic carbon in organic soils (Tarnocai, 1998) were overlaid on the map showing the present ecoclimatic provinces (Fig. 1a) using the previously described GIS techniques. Calculations based on the resulting derivative maps show that organic soils cover 1.23 x 10^6 km^2, or 14 % of the soil area (excluding water, bedrock and glaciers) of Canada, and contain 59 % of the 262 Gt of soil carbon present in Canada (1 gigatonne=10^9 tonnes=10^{12} kg) (Table II). Most organic soils are found in the Boreal, Subarctic, and Arctic ecoclimatic provinces, where they cover 29 %, 23 %, and 2 % of the land area in each ecoclimatic province, respectively. Together, these three ecoclimatic provinces contain 95 % of the 154 Gt of the total soil organic carbon in organic soils in Canada and 56 % of the total soil organic carbon in all soils in Canada.

The final step in estimating the magnitude of the effect of climate warming on peatlands involved determining the total and surface soil organic carbon masses and the proportion of the land surface covered by organic soils that is expected

TABLE II

Total and surface soil organic carbon in organic soils and the areas covered in the various ecoclimatic provinces

Ecoclimatic	Total soil organic carbon				Surface soil organic carbon				Land area			
Provinces	All soils	Organic soils			All soils	Organic soils			All soils	Organic soils		
	(Gt)	(Gt)	% of all soils in ecoprov.*	% of all soils in Canada	(Gt)	(Gt)	% of all soils in ecoprov.*	% of all soils in Canada	($x10^3$ km^2)	($x10^3$ km^2)	% of all soils in ecoprov.*	% of all soils in Canada
Arctic	43	4.2	9.8	1.6	16.2	1.0	6.0	1.3	2375	49	2.1	0.6
Subarctic	75.7	53.2	70.3	20.3	16.6	6.7	40.2	9.3	1712	393	23.0	4.4
Boreal	111.8	89.1	79.7	34.0	26.1	13.2	50.5	18.3	2521	725	28.8	8.2
Subarctic Cordilleran	1.1	0.0^x	2.6	0.0	0.6	0.0°	0.8	0.0	137	$0^\#$	0.0	0.0
Cordilleran	12.1	2.8	23.1	1.1	4.6	0.5	11.2	0.7	913	28	3.1	0.3
Interior Cordilleran	1.5	0.5	34.9	0.2	0.6	0.1	17.2	0.1	149	6	4.0	0.1
Pacific Cordilleran	4.3	0.7	15.2	0.2	1.4	0.3	20.7	0.4	241	16	6.6	0.2
Cool Temperate	7	3.2	45.4	1.2	2.6	0.5	19.7	0.7	341	19	5.6	0.2
Moderate Temperate	0.2	0.0^x	14.0	0.0	0.1	0.0^+	6.7	0.0	29	$0^\#$	0.0	0.0
Grassland	5.6	0.1	2.0	0.0	3.3	0.0^x	0.8	0.0	460	1	0.2	0.0
Canada	262.3	153.8		58.6	72.1	22.3		30.9	8878	1238		13.9

* "ecoprov." is used to indicate ecoclimatic province; ^{x} 0.03 Gt; ° 0.005 Gt; $^+$ 0.007 Gt; $^\#$0.3 x 10^3 km^2.

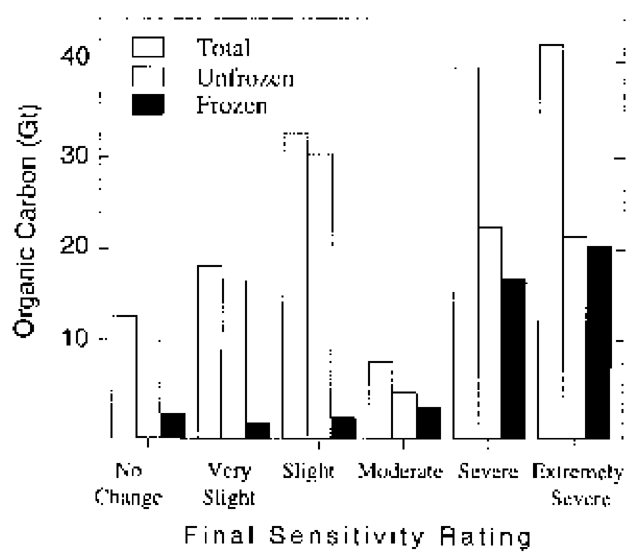


FIGURE 8. Organic carbon mass, by sensitivity rating, in frozen and unfrozen organic soils in Canada. Total organic carbon mass for organic soils in Canada is estimated to be 154 Gt.

Masse de carbone organique (Gt), par classe de sensibilité, dans les sols organiques gelés et non gelés. La masse totale de carbone organique au Canada est estimée à 154 Gt.

to be affected by warming. This was accomplished by combining maps showing total and surface organic carbon in organic soils and the present ecoclimatic province map with the potential peatland sensitivity map developed for this project. Calculations based on the resulting derivative map show that approximately 60 % of the total area of Canadian peatlands and 53 % of the organic carbon in these peatlands is expected to be severely to extremely severely affected, with 41 % of the unfrozen and 79 % of the frozen peatlands being so affected (Fig. 8).

The extensive peatlands in the Boreal and Subarctic ecoclimatic provinces are expected to be strongly affected by the projected changes in mean annual temperature (Table III). Fifty percent of the 89 Gt of organic carbon in organic soils and 58 % of the more than 725,000 km^2 of peatlands in the Boreal Ecoclimatic Province are considered to be severely to extremely severely sensitive (Fig. 9). In the Subarctic Ecoclimatic Province, 66 % of the 53 Gt of organic carbon in organic soils and 78 % of the 393,000 km^2 of peatlands have similar sensitivity ratings. Although the Arctic Ecoclimatic Province is the third largest peatland area, it has a small amount of organic carbon in organic soils (4 Gt) compared to the Boreal and Subarctic ecoclimatic provinces. In contrast to the other two regions, only 10 % of the more than 49,000 km^2 of peatlands in the Arctic Ecoclimatic Province and 12 % of the organic carbon mass in organic soils is expected to be severely affected by climate change.

TABLE III

Sensitivity ratings of organic carbon masses and areas for organic soils in various ecoclimatic provinces

Sensitivity rating	Sensitivity code	Total organic carbon mass		Surface organic carbon mass		Area covered by organic soils	
		(x 10^9 kg)	(%)	(x 10^9 kg)	(%)	(km^2)	(%)
Arctic							
Extremely Severe	5 to 8	355.15	8.4	61.54	6.4	3725	7.6
Severe	4	149.98	3.6	21.58	2.2	1256	2.6
Moderate	3	55.61	1.3	13.12	1.4	568	1.2
Slight	2	414.22	9.8	81.85	8.5	4658	9.5
Very Slight	1	760.35	18.1	137.29	14.2	9438	19.1
No Change	0	2473.04	58.8	653.24	67.3	29472	60.0
Total		4208.35	100.0	968.62	100.0	49117	100.0
Subarctic							
Extremely Severe	5 to 8	28810.18	54.2	3912.33	58.6	272202	69.3
Severe	4	6333.21	11.9	597.83	9.0	32488	8.3
Moderate	3	4745.01	8.9	463.05	6.9	23032	5.8
Slight	2	11224.34	21.1	1368.44	20.6	51138	13.0
Very Slight	1	777.60	1.5	128.04	1.9	5217	1.3
No Change	0	1301.61	2.4	202.20	3.0	8917	2.3
Total		53191.95	100.0	6671.89	100.0	392994	100.0
Boreal							
Extremely Severe	5 to 8	12774.22	14.3	1970.34	14.9	90024	12.4
Severe	4	32101.03	36.0	5823.38	44.2	333743	46.0
Moderate	3	3272.52	3.7	294.41	2.2	21575	3.1
Slight	2	19981.13	22.4	2254.16	17.1	111950	15.4
Very Slight	1	15177.81	17.0	2237.87	17.0	128719	17.7
No Change	0	5769.18	6.6	612.69	4.6	39483	5.4
Total		89075.89	100.0	13192.85	100.0	725494	100.0
Subarctic Cordilleran							
Extremely Severe	5 to 8						
Severe	4						
Moderate	3	0.06	0.2	0.01	0.2	1	0.3
Slight	2	28.60	99.8	4.50	99.8	343	99.7
Very Slight	1						
No Change	0						
Total		28.66	100.0	4.51	100.0	344	100.0
Cordilleran							
Extremely Severe	5 to 8	63.68	2.3	9.37	1.8	514	1.8
Severe	4	991.35	35.5	157.74	30.7	9953	35.8
Moderate	3	46.52	1.7	7.33	1.4	558	2.0
Slight	2	251.22	9.0	43.14	8.4	2608	9.4
Very Slight	1	482.91	17.3	100.85	19.6	5271	18.9
No Change	0	955.90	34.2	195.87	38.1	8923	32.1
Total		2791.58	100.0	514.30	100.0	27827	100.0
Interior Cordilleran							
Extremely Severe	5 to 8						
Severe	4						
Moderate	3						
Slight	2						
Very Slight	1	34.94	6.7	7.16	6.9	360	6.5
No Change	0	488.20	93.3	96.09	93.1	5196	93.5
Total		523.14	100.0	103.25	100.0	5556	100.0
Pacific Cordilleran							
Extremely Severe	5 to 8						
Severe	4	1.90	0.3	1.24	0.4	59	0.4
Moderate	3						
Slight	2						
Very Slight	1	55.23	8.5	25.15	8.7	1225	7.7
No Change	0	594.71	91.2	262.93	90.9	14672	91.9

TABLE III (cont.)

Sensitivity ratings of organic carbon masses and areas for organic soils in various ecoclimatic provinces

Sensitivity rating	Sensitivity code	Total organic carbon mass		Surface organic carbon mass		Area covered by organic soils	
		(x 10^9 kg)	(%)	(x 10^9 kg)	(%)	(km^2)	(%)
Total		651.84	100.0	289.32	100.0	15956	100.0
Cool Temperate							
Extremely Severe	5 to 8						
Severe	4						
Moderate	3	11.40	0.4	2.27	0.4	235	1.2
Slight	2	684.01	21.5	109.88	21.4	2224	11.5
Very Slight	1	990.42	31.2	163.57	31.9	8293	42.9
No Change	0	1492.42	46.9	237.44	46.3	8582	44.4
Total		3178.25	100.0	513.16	100.0	19334	100.0
Moderate Temperate							
Extremely Severe	5 to 8						
Severe	4						
Moderate	3						
Slight	2						
Very Slight	1	8.93	32.0	1.70	25.3	79	22.9
No Change	0	19.00	68.0	5.01	74.7	266	77.1
Total		27.93	100.0	6.71	100.0	345	100.0
Grassland							
Extremely Severe	5 to 8						
Severe	4	33.14	29.5	7.67	28.9	383	30.3
Moderate	3						
Slight	2						
Very Slight	1	78.48	70.0	18.75	70.5	876	69.2
No Change	0	0.52	0.5	0.17	0.6	6	0.5
Total		112.14	100.0	26.59	100.0	1265	100.0

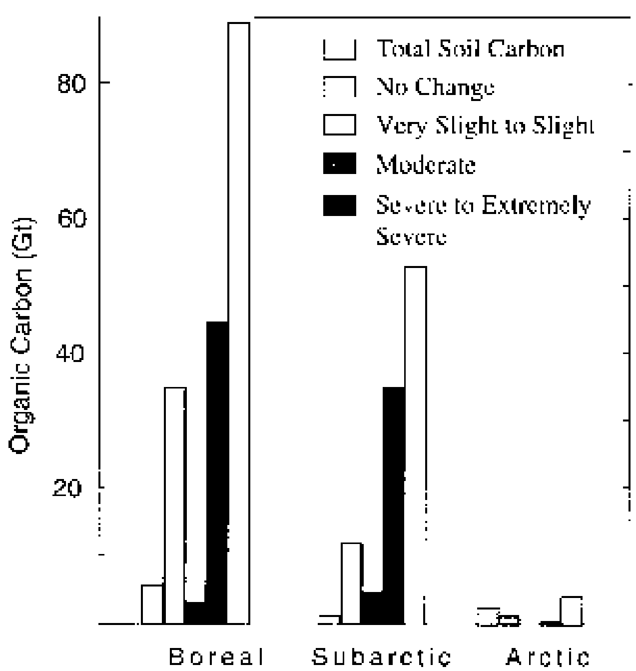


FIGURE 9. Total soil organic carbon, by sensitivity rating, in the Boreal, Subarctic and Arctic ecoclimatic provinces.

Carbone organique dans les sols, par classe de sensibilité, dans les provinces écoclimatiques du Boréal, du Subarctique et de l'Arctique.

EXPECTED IMPACT OF CLIMATE WARMING

Lowland polygons (both low- and high-centre forms) characterize the peatlands of the Arctic Ecoclimatic Province, especially the Low Arctic regions (Tarnocai and Zoltai, 1988). Although peat is currently accumulating in the Low Arctic, such accumulation is minimal in the Mid- and High Arctic. The Mid- and High Arctic areas, however, were favourable for active peatland development during the hypsithermal interval (Tarnocai, 1978; Tarnocai and Zoltai, 1988), when the climate was warmer than at present (Richie and Hare, 1971; Terasmae, 1972; Delorme *et al.*, 1977). It is predicted that a similar environment will again occur in the Arctic under a 2x CO_2 scenario, resulting in increased peat production and peatland development. This has also been suggested by Zoltai (1994).

In the Subarctic Ecoclimatic Province and the northern part of the Boreal Ecoclimatic Province, where peatlands are characterized by complexes of peat plateaus, polygonal peat plateaus, palsas and unfrozen fens (Zoltai *et al.*, 1988b), the increasing temperatures are expected to cause increased thawing of permafrost. Also projected are increases in the proportion of peatlands where peat is actively accumulating and increases in the growth of peat-forming vegetation because of the longer growing season (Zoltai, 1994). In the southern part of Boreal Ecoclimatic Province, peatlands are primarily unfrozen bogs and fens. Here, the main impact is expected to be a decrease in the precipitation and runoff water reaching the peatlands (Zoltai, 1994). Ombrotrophic peatlands and fens nourished by small catchment basins will likely be most affected, resulting in severe changes in vegetation, including the replacement of the bryophytes now present by other plants. They will also be more susceptible to forest fires, which will occur more frequently as a result of surface drying.

In the Grassland Ecoclimatic Province, increasing temperatures will increase the rate of evapotranspiration, thus lowering the summer water table and reducing runoff. This will result in severe drying of the wetlands (Zoltai, 1994). Higher temperatures in the Temperate and Cordilleran ecoclimatic provinces will also result in drying, leading to more frequent wildfires, thus reducing the area of peatlands.

In this paper, scant attention has been paid to peatland areas expected to be subject to the flooding associated with the climatically-induced rise in sea level that is also expected to occur with climate warming (Warrick and Oerlemans, 1990). Coastal areas with the potential to be destroyed or affected by flooding occur in the eastern parts of the Atlantic provinces, southern British Columbia, the Hudson Bay and James Bay Lowlands and the Arctic islands (Shaw *et al.*, 1994). It is expected that disturbances from flooding would change the patterns of organic matter accumulation and breakdown, and hence, the patterns of greenhouse gas emissions.

CONCLUSIONS

Existing spatial information on current climate, vegetation and permafrost distribution and projections of each, based on a doubling of atmospheric CO_2, were analyzed using GIS techniques to produce a terrain sensitivity map for Canada. By overlaying the terrain sensitivity map with the total and surface soil organic carbon maps for Canada, we were able to make a first approximation of the amount of soil organic carbon and the surface area covered by organic soils that were expected to be affected by the predicted changes in climate. On the basis of the terrain sensitivity map, calculations for organic soils, which represent the peatlands, show that 53 % of the organic carbon stored in peatlands and 60 % of the surface area of peatlands are expected to be severely to extremely severely affected by the predicted climate warming.

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