Effects of fires on carbon cycling in North American boreal peatlands

S.C. Zoltai, L.A. Morrissey, G.P. Livingston, and W.J. de Groot

Abstract: Boreal peatlands occupy about 1.14 x 10^6 km^2 in North America. Fires can spread into peatlands, burning the biomass, and if moisture conditions permit, burning into the surface peat. Charred layers in peat sections reveal that historically bogs in the subhumid continental regions and permafrost peatlands of the subarctic regions have been the most susceptible to fires. Fire return periods were estimated from the numbers and ages of the charred peat layers. Based on average moisture conditions of the surface, about 0.5% of the peatlands (6420 km^2) can be expected to burn annually, but the surface peat layer is expected to burn only in a small portion of this area (1160 km^2). Carbon losses from aboveground combustion, in the form of CO_2, CO, CH_4, and nonmethane hydrocarbons, are the highest in forested swamps at 2.03 Tg C·year^{-1}. Carbon losses due to combustion of surface peat is the highest in the driest peatlands (e.g., raised bogs underlain by permafrost) at 5.82 Tg C·year^{-1}. The total estimated carbon release due to aboveground combustion is 2.92 Tg C·year^{-1} and due to belowground peat combustion is 6.72 Tg C·year^{-1}. These estimates of direct carbon emissions to the atmosphere due to wildfires suggest a globally significant, but relatively small source in contrast with emissions from wildfires in uplands. The effects of a possible climate change are expected to be most prominent in the continental and northern parts of North America. A lower water table would result in increased CO_2 but decreased CH_4 emissions from the peatlands. A drier climate may mean increased fire frequency and intensity, resulting in more fires in peatlands and an increased probability of the fires consuming part of the peat.

Key words: fire, peatlands, carbon, boreal, permafrost, gas flux.

Résumé : Les tourbières boréales occupent environ 1,14 × 10^6 km^2 en Amérique du Nord. Les feux peuvent s'éteindre dans les tourbières, consumant ainsi la biomasse, et si les conditions d'humidité le permettent, s'enfoncer dans la surface de la tourbe. Les couches brûlées observées dans des sections de tourbe révèlent qu'historiquement les tourbières des régions continentales subhumides ainsi que les tourbières sur permafrost des régions subarctiques ont été les plus susceptibles au feux. On évalue les cycles de retour des feux sur la base des nombres et des âges des couches de tourbes brûlées. En se basant sur les conditions d'humidité de la surface, on peut s'attendre à ce qu'environ 0,5% des tourbières (6420 $km^{2)}$ brûlent chaque année, mais ce n'est que dans une faible proportion de ces surfaces (1160 km^2) que le dessus de la tourbe est susceptible de brûler. Les pertes en carbone provenant de la combustion au dessus du sol, sous forme de CO_2, CO, CH_4 et d'hydrocarbures non méthanique, sont les plus fortes dans les marécages arborées, avec 2,03 Tg C·anneé$^{-1}$. Les pertes en carbones dues à la combustion de la tourbe superficielle est la plus élevée dans les tourbières les plus sèches (p. ex. les tourbières hautes reposant sur le permafrost) avec 5,82 Tg C·anneé$^{-1}$. On estime que la quantité de carbone libéré est de 2,92 Tg C·anneé$^{-1}$ pour la combustion au dessus du sol et de 6,72 Tg C·anneé$^{-1}$ pour la combustion de la tourbe sous la surface. Ces estimations des émissions directes de carbone dans l'atmosphère, causées par le feu, suggèrent qu'il s'agit d'un apport généralement important, mais relativement faible comparativement aux émissions provenant des feux de forêts sur les terres hautes. On s'attend à ce que les effets d'un changement possible du climat affectent surtout les parties continentales et nordiques de l'Amérique du Nord. Un abaissement de la nappe phréatique induirait une augmentation du CO_2, mais une diminution des émissions de CH_4, à partir des tourbières. Un climat plus sec pourrait se traduire par une augmentation de la fréquence et de l'intensité des feux, conduisant à plus de feux dans les tourbières et une probabilité accrue que ces feux consument une partie de la tourbe.

Mots clés : feu, tourbières, carbone, boréale, permafrost, flux des gaz.

Introduction

Peatlands are an integral part of the boreal landscape, occupying about 3.37 × 10^6 km^2 worldwide (Zoltai and Martikainen 1996), yet their role and significance in the global carbon budget under present and projected climatic regimes remains uncertain. Defined by their deep, organic-rich deposits, peatlands formed over the past several 1000 years in areas in which climate and topography favoured the net accumulation of organic detritus (peat) (Gorham 1991). An estimated 397 Pg (Zoltai and Martikainen 1996) to 455 Pg (Gorham 1991) of carbon in the form of recalcitrant or frozen organic material is

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stored in northern peatlands, exceeding the organic stores of any other terrestrial biome on Earth.

Under present climatic conditions, the net global rate of peat accumulation is estimated to exceed the net rate of depletion owing to aerobic and anaerobic microbial decomposition and fire. Projections of climatic change expected over the next several decades, however, suggest a possible dramatic warming (2–8°C) of the northern high latitudes (Houghton et al. 1995; Mitchell et al. 1990). This would almost certainly increase the rate of depletion of the vast carbon stores underlying northern peatlands, not only changing the present peat formation/depletion balance (Gorham 1991), but also adding to the already increasing atmospheric burden of greenhouse gases, such as carbon dioxide (CO_2) and methane (CH_4) (Houghton et al. 1995). Possible responses of northern peatlands to projected climatic changes include increased carbon loss due to increased thaw depths and extended thaw periods, increased rates of microbial activity due to increased soil temperatures and, pending a reduction in summer soil water content of the surface peats (Manabe and Wetherald 1986), an increase in the importance of aerobic microbial decomposition and wildfires (Wein 1989).

In this paper, we examine the effects and importance of wildfires on the peatlands of North America in terms of net carbon release and sequestration under present and projected climatic regimes. Wildfires are a common occurrence in boreal forests and do spread into adjacent peatlands, burning the vegetation and, depending on the kind of peatland and soil moisture conditions, consuming the upper layers of the peat itself. Drawing on information from various sources including unpublished field data, we develop here a first estimate of carbon loss from peatlands due to fire and identify those areas most needing further study.

Peatland environments

In northern peatlands, having typically formed in poorly drained areas, soil carbon losses from the majority of the peat profile are primarily limited to anaerobic microbial decomposition due to the waterlogged and resultant anoxic and cool conditions a few centimeters or decimeters beneath the surface. Peat contains organic materials in various states of decomposition and, by definition, contains less than 25% inorganic material on a dry weight basis (Andrejko et al. 1983). To distinguish between peatlands and peaty mineral soils, an arbitrary minimum depth limit of the organic deposits is often defined; in Canada this depth is 40 cm (Canada Soil Survey Committee 1978) and in the conterminous United States it varies between 20 and 30 cm (Heinselman 1963). On these bases, it is estimated that 1.14×10^6 km^2 of peatlands is distributed across North America. Over 1×10^6 km^2 of peatlands occupies the boreal and subarctic regions of Canada (1.008×10^6 km^2; Tarnocai 1984) and Alaska (6.5×10^4 km^2; Histosols, Rieger et al. 1979). In addition, there is 68 000 km^2 of peatlands in the north-central and northeastern conterminous United States (Gorham 1990). It is estimated that about 76 Tg C is sequestered annually for long-term storage as peat in the peatlands of North America (Gorham 1991).

Peatlands differ greatly in their characteristics, having developed under the influence of their individual hydrological (water quantity and quality), climate, and vegetation regimes. Peatlands also differ in size depending on the regional topography, ranging from small basin peatlands of a few square kilometers or less surrounded by drylands, to large peatland complexes, such as the Hudson Bay lowlands, covering thousands of square kilometers. In the boreal region, three peatland classes can be recognized: bogs, fens, and swamps. Bogs are *Sphagnum* moss dominated peatlands (Zoltai and Vitt 1995) that depend on precipitation for their water and nutrient supply. Bogs support open-canopied, stunted black spruce in the low rainfall continental areas but are generally treeless in the high rainfall regions. Fens are moss- and sedge-dominated peatlands, with or without trees, that have a slow-moving water table, the water originating in the surrounding mineral soil deposits. Swamps are forested wetlands with marked seasonal water-level fluctuations and relatively strong water flow. In the north, peat thickness in swamps often exceeds 40 cm and closed-canopy conifer forests typically dominate; in the south, deciduous trees are more common.

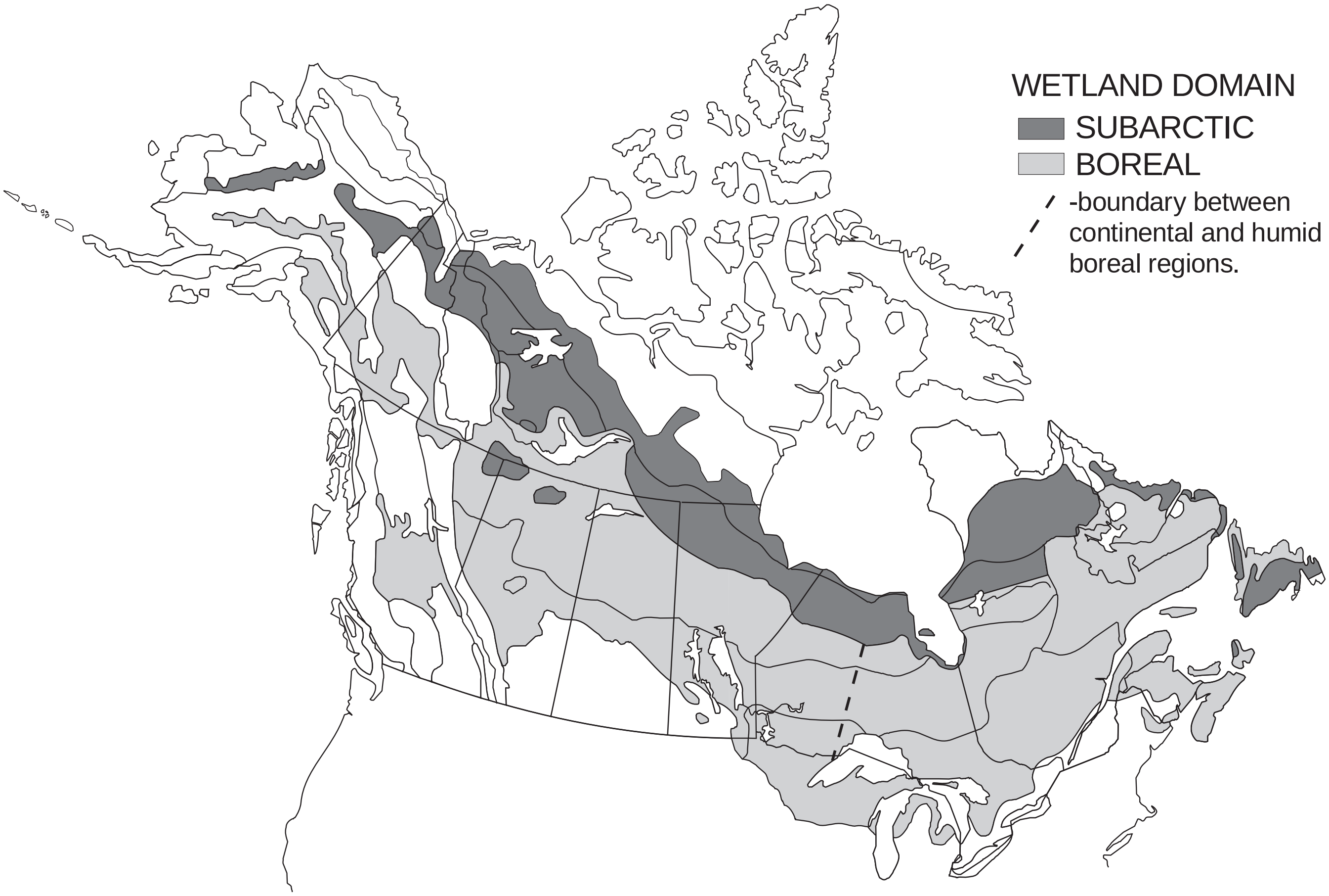
Regionality

Climate is a dominant factor in the development of peatlands. Long-term and seasonal temperature and precipitation regimes determine the regional hydrology and, to a large extent, the kind of vegetation that will develop there (Gignac et al. 1991) and its productivity. These factors also interact to affect the pathways and rates of decomposition, and thus the net rate of peat accumulation. Wetland domains were established for Canada based on similarities in wetland developmental processes in areas of comparable hydrology and water quality (National Wetlands Working Group 1986). For the purposes of this discussion, the Boreal and Subarctic wetland domains were extended into comparable areas of the neighbouring United States, using the same criteria (Fig. 1).

Within each wetland domain, there exists both a north–south temperature gradient and an east–west moisture gradient. Regional temperature control is well illustrated by the occurrence of permafrost in peatlands. Permafrost is absent in the southern reaches of the Boreal Wetland Domain, occurs sporadically in the form of discontinuous lenses in the northern reaches, and is continuous at the northern limits of the Subarctic Domain (Zoltai 1995). The presence of permafrost significantly affects the temperature and moisture conditions of the peatland surface, as well as the surface topography. Peatlands underlain by permafrost are often elevated 1 m or more above adjacent unfrozen peatlands and are thus often more well drained. In the south, permafrost peatlands support closed-canopy coniferous forests that give way northward to open, stunted, black spruce and lichen communities and ultimately to woody shrub or herbaceous communities.

Temperature and precipitation patterns also differ regionally from east to west across the continent. The interior of the continent between the Rocky Mountains and the Great Lakes is subject to a subhumid continental climate, whereas more humid and tempered environments exist both near the Pacific and Atlantic coasts. The influence of the resultant east–west moisture gradient on peatland development is well illustrated by the occurrence of raised bogs, i.e., peat mounds which are upwards of 10 m in height and cover upwards of hundreds of hectares. Raised bogs are common in the humid Boreal Wetland Domain and in the eastern Maritime regions and contain many pools of surface water. The number and extent of the

Fig. 1. Boreal and Subarctic wetland domains of North America.



pools and of the raised bogs themselves, however, decrease to the west. In the continental interior, raised bogs are only about 50 cm in height, as the low precipitation levels do not support rapid peat accumulation, and pools are no longer present (Glaser and Janssens 1986). Peatland vegetation communities also differ along the east–west moisture gradient: bogs are generally treeless in the wetter humid regions but support tree growth in the drier continental interior (Glaser 1992).

Fire in peatlands

Regional differences in the frequency, extent, and intensity of fires in peatlands are closely related to climatic controls. The importance and role of fire, therefore, differs significantly between peatland types, between the continental and humid regions of the Boreal Wetland Domain, and between the Boreal and Subarctic wetland domains. Fires are frequent in the peatlands of the Subarctic Wetland Domain, as shown by charcoal layers in the peat. In one location nine layers were detected, three of which were of sufficient severity to cause the thawing of permafrost (Zoltai 1993). Evidences of fires in the form of multiple charcoal layers are also common in bogs of the continental Boreal Wetland Domain. In one case, 29 charcoal layers were found in a 1.6-m-thick bog deposit (Kuhry 1994). In contrast, fires do not appear to be frequent in peatlands of the humid Boreal Wetland Domain. Peat profile descriptions from this region either do not include charcoal layers (Warner et al. 1991), or suggest that fires were small, patchy, and did not burn into the peat itself (Wein et al. 1987; Foster and Glaser 1986).

Table 1. Depth to water table or to permafrost (mean ± SE) in various peatland types of the subhumid Boreal Wetland Domain.

Peatland type	No. of sites	Mean depth (cm)
Open fen	77	1.3±1.3
Shrubby fen	48	13.6±2.0
Treed fen	83	19.7±1.4
Conifer swamp	21	31.1±3.1
Bog	107	35.0±1.6
Permafrost bog	56	52.8±2.2

The position of the water table in peatlands relative to the surface is of paramount importance when assessing the susceptibility of peatlands to fire, because it has a direct bearing on the moisture content of the surface peat. Table 1 summarizes observations of water table depth over four summers from a variety of peatlands in the continental Boreal Wetland Domain. A wide range in depths to the water table is evident between the various kinds of peatlands. The position of the water table is deepest on bogs, followed by coniferous swamps, treed fens, and shrubby fens, and is the shallowest or even above the surface in the open, graminoid fens. In perennially frozen peatlands, the permafrost table may impede the downward movement of water, thus fostering either water logging of the active thaw layer or the formation of steep moisture gradients,

Table 2. Aboveground standing biomass in various northern peatlands (kg·ha^{-1}).

Peatland	Moss	Herb	Shrub	Tree	Total	Location	Source
Open fen	—	7 380	—	—	7 380	Central Minnesota	Bernard 1974
Open fen	?	5 150	—	—	5 150	Rocky Mountains, Alberta (“wet fen”)	Gorham and Somers 1973
Shrubby fen	875	7 922	16 264	—	25 061	Southern Manitoba (“lagg”)	Reader and Stewart 1972
Treed fen	—	1 869	293	98 075	100 237	Central Minnesota (“fen forest”)	Reiners 1972
Open bog	1 313	—	4 233	—	5 546	Southern Manitoba (“bog”)	Reader and Stewart 1972
Treed bog	927	—	5 015	3 998	9 940	Southern Manitoba (“muskeg”)	Reader and Stewart 1972
Treed bog	3 200	140	4 940	30 980	39 260	Northern Minnesota (“raised bog”)	Grigal et al. 1985
Forested bog	2 000	—	1 386	43 158	46 544	Southern Manitoba (“bog forest”)	Reader and Stewart 1972
Forested bog	3 800	220	1 025	100 730	105 775	Northern Minnesota (“perched bog”)	Grigal et al. 1985
Conifer swamp	—	542	—	159 406	159 948	Central Minnesota	Reiners 1972

where the surface may have a low moisture content, but the peat above the permafrost table may be nearly saturated. In other situations, as occurs in the Subarctic Wetland Domain, peat surfaces elevated by permafrost may become desiccated and subsequently burn readily. In such cases, fires may remove a sufficient thickness of the surface peat to cause thawing of the underlying permafrost (Zoltai 1993).

Seasonal variations in the position of the water table also occur in response to weather conditions. In bogs, the water table may fall by a factor of two below its original position in times of drought, whereas water table fluctuations in fens are less extreme, as indicated by the depth of the anaerobic decomposition layer. In general, seasonal fluctuations are less than the average depths of the water tables, although early season flooding following snow melt is common in many peatlands. The susceptibility of any particular peatland to burning, therefore, varies both between years and within any given growing season.

Given favourable fuel continuity and weather conditions, fires can sweep across almost any wetland, consuming some or all of the aboveground biomass (surface fires). Observations show that in some cases fires also consume part of the underlying peat, generally consuming the surface 10 to 15 cm of litter and peat (shallow peat fires). In extremely droughty years or after the water table has been lowered artificially, fires can burn deep into the peat (deep peat fires). Smouldering, rather than flaming combustion, however, often characterizes peatland fires owing to the moist and, within the peat, often oxygen-limiting substrate conditions.

Surface fires

Fire may spread across peatlands, burning the aboveground biomass only. Reports indicate that such fires tend to be patchy, owing to variations in fuel continuity and the presence of surface water (Foster and Glaser 1986; Wein et al. 1987; Jasieniuk and Johnson 1982). On the basis of fuel types present and surface wetness (depth to water table), susceptibility to fire appears to be the highest in permafrost peatlands, followed by swamps, bogs, and fens.

Uncertainties in estimating the amount of biomass consumed in surface fires in peatlands arise from uncertainties in the quantities of available standing live and dead fuel material and in the fraction consumed, which is dependent on fuel type and moisture conditions. Estimates of living aboveground biomass range from 1200 kg dry weight·ha^{-1} for nonforested bogs to over 10 000 kg dry weight·ha^{-1} for black spruce bogs and peatlands (Mitsch and Gosselink 1986). Standing biomass is generally low in open, graminoid fens and treeless bogs, averaging about 5500 kg dry weight·ha^{-1} but increases to about 10 000 kg dry weight·ha^{-1} as the amount of woody vegetation increases (Table 2). Forested and shrub bogs and fens average about 30 000 kg dry weight·ha^{-1}, but this amount increases in the south. At 150 000 kg dry weight·ha^{-1}, conifer swamps have the greatest amount of standing biomass of the northern peatlands examined.

Observations of the fraction of biomass consumed in peatland surface fires are very limited. Kasischke et al. (1995) report that 35–37% of the biomass is consumed in treed peatlands. Open-treed black spruce bogs have about 7500–8000 kg biomass·ha^{-1} available for burning in the tree crowns (Forestry Canada Fire Danger Group 1992), of which 50–90% is typically consumed. Estimates of ground and surface material consumption in peatlands (based on open-treed understory estimates) range from 5000 to 10 000 kg biomass·ha^{-1} for moderate intensity surface fires, to as high as 15 000 kg biomass·ha^{-1} under drier burning conditions (Kiil 1975; de Groot and Alexander 1986). By contrast, the dry biomass (standing dead and litter) of graminoid-dominated peatlands may be completely consumed by fire (Cofer et al. 1990), leaving no partially burned charcoal residue.

Shallow peat fires

Shallow peat fires consume not only the standing biomass but also burn into the underlying peat. The moisture content of the surface peat determines whether the peat can ignite and sustain combustion. Chistjakov et al. (1983) found that peat can ignite from small ignition sources at moisture contents below 20–30% m.c. (moisture content by dry weight) and can sustain combustion independently at moisture levels below 235% m.c. An external heat source such as burning surface debris can greatly increase the maximum peat moisture contents that sustain combustion. Frandsen (1987) found continued smouldering in peat moss at 93–103% m.c., using a small ignition source of short (3 min) duration. Burning thresholds of 140–310% m.c. were determined by Hawkes (1993), using various external radiated heat treatments in peat material. Sofronov and Volokitina (1986) reported a maximum peat moisture content of 200% for vertical penetrating smouldering fires and 400–500% m.c. for horizontal spreading fires, while Chistjakov et al. (1983) suggest that an upper moisture content limit may be as high as 500%, based on peat caloric content that may reach 6600 kcal·kg^{-1} (1 cal = 4.1868 J). Once started,

Table 3. Thickness and moisture content of ignitable surface peat (<25% moisture by dry weight) in various peat landforms.

		Ignitable surface			
Peat landform	No. of sites	No. of sites	% total number of sites	Thickness[a] (cm)	Moisture content[a] (% dry weight)
Conifer swamps	21	3	14	6.3±1.3	16.3±1.4
Basin bogs	57	3	5	9.0±2.1	14.3±0.3
Domed bogs	11	—	0	—	—
Northern plateau bogs	20	—	0	—	—
Flat bogs	11	1	9	5	16
Shore bogs	2	—	0	—	—
Palsa bogs[b]	9	1	11	20	25
Peat plateau bogs[b]	20	—	0	—	—
Total, all bogs and swamps	151	5	4	10.4±2.8	16.8±2.1

[a] Mean ± SE.
[b] Permafrost peat landforms.

Table 4. Thickness and moisture content of combustible surface peat (<235% moisture by dry weight) in various peat landforms.

		Combustible surface			
Peat landform	No. of sites	No. of sites	% total number of sites	Thickness[a] (cm)	Moisture content[a] (% dry weight)
Conifer swamps	21	8	38	9.4±0.9	76.0±15.0
Basin bogs	57	11	19	8.0±1.3	88.2±19.0
Domed bogs	11	4	36	10.5±2.7	111.5±10.2
Northern plateau bogs	20	2	10	4.5±1.5	148.0±65.2
Flat bogs	11	4	36	5.8±1.5	138.5±44.6
Shore bogs	2	1	50	15	177
Palsa bogs[b]	9	6	66	16.0±3.4	78.3±17.9
Peat plateau bogs[b]	20	15	75	6.7±1.3	107.3±12.9
Total, all bogs and swamps	151	43	33	8.7±0.9	105.2±9.2

[a] Mean ± SE.
[b] Permafrost peat landforms.

fires may also smoulder in peat for long periods of time before extinguishing, sometimes burning over winter.

Table 3 summarizes observations of moisture content of surface peat measured in 151 different peatlands at widely separated locations during four summers in the subhumid Boreal Wetland Domain. These data indicate that under normal conditions, a small proportion of bogs have moisture levels at or below ignition levels (<25% m.c.). Bogs with the highest relief (palsas) have the lowest surface peat moisture content and thus the highest proportion of ignitable peat, while peatlands with flat relief typically have very low or no ignitable peat.

The proportion of bogs with surface peat layers that can sustain combustion (<235% m.c.) is much higher than those which are ignitable (Table 4). Because they are elevated above the local water table, bogs underlain by permafrost are typically the most likely of the peatlands to have peat with moisture contents within combustible levels. About one half to one third of the rest of the bogs had combustible surface peat. The thickness of the combustible peat layers observed was generally low, between 5 and 10 cm, but was the greatest in those bogs with the greatest vertical relief, i.e., the palsa bogs (Table 4).

Charcoal evidence shows that peat combustion occurs primarily in bogs, based on the number of charred layers and the thickness of such layers. Kuhry (1994) found that fire frequencies shown by charcoal layers were negatively correlated with rates of peat height and carbon accumulation in eight bogs. In bogs with three to four fires in 1000 years, the peat and carbon accumulation rate was less than one half of that in the same bogs with less than one fire per 1000 years.

Conifer swamps frequently occur in the transition zone between lowland peatlands and upland forests. Tables 3 and 4 indicate that low moisture conditions in the surface peat layers of conifer swamps occurs relatively often, suggesting that they are susceptible to fires spreading from the surrounding areas. However, no charcoal has been reported from swamp peat, possibly because charcoal would be difficult to distinguish from the well-humified peat underlying these communities.

Of the fen peatlands sampled, none were observed to have surface peats within the ignition moisture range, and only very few (<1%) had peat within the combustible moisture range (Tables 3 and 4). In addition, only one instance of charcoal occurrence in fens has been reported (Kuhry 1994). Although direct observations and air photos indicate that graminoid fens do burn, particularly during fall senescence, the data suggests that such burns tend to occur in the herbaceous overstory and not in the surface peats. Thus without evidence of charcoal in the underlying deposits, historical reconstruction of the fire history in fens is difficult.

Based on the moisture content of the surface peat in bogs, swamps, and permafrost peatlands (Tables 3 and 4), conditions for surface peat fires are largely limited to the top 10–15 cm. Once ignited, the heat of the fire may desiccate the underlying peat, allowing the burning of the top 20 cm, a depth commonly observed in burned peat substrates (Dyrness and Norum 1983). Peat fires are rare in fens, as the water table is usually sufficiently high to prevent any more than the singeing of the surface peat.

Deep peat fires

Anecdotal evidence refers to fires smouldering for years up to 1 m below the surface. However, the occurrences of deep fires are rare and restricted to disturbed areas where the water table has been lowered either by natural or anthropogenic processes. In some permafrost peatlands the subsiding peat banks may ignite during a fire and the dry peat may support smouldering fire burning up to 50 cm into the peat.

Peatlands intended for agricultural development are often drained by ditching and the peat is subsequently burned, usually to the underlying mineral soil (Wein 1983). Accidental deep peat burning has been observed along roads where waste peat from ditches may ignite from a forest fire and smoulder over winter (Ross W. Wein, personal communication). One such instance was observed by one of us (S.C.Z.) in northern Manitoba, near Gillam, where peat was smouldering along a road in the fall of 1995. The peat was probably ignited by a forest fire that swept across the area in 1992.

Postfire recovery

To estimate the carbon losses due to peatland fires, the potential loss of biomass accumulation as a consequence of the fire must be assessed. Fires can cause a temporary loss or reduction of carbon sequestration potential through the destruction of peatland vegetation. This loss is very short lasting in some peatlands, especially those dominated by graminoid species, where resprouting is expected to take place in the same or following growing season. In other peatlands, the reestablishment of peat-forming vegetation may take longer, but in about 20 years most peatlands are expected to be completely restored. Tree species, especially black spruce, are readily reestablished after a fire but may take several decades before the prefire tree biomass is reached.

The relatively rapid restoration of the vegetation was noted in different peatlands under various climatic regimes. In many areas, pioneer low-biomass cup lichens (*Cladonia* spp.) and mosses (*Polytrichum* spp., *Ceratodon purpureus*) are the early colonizers (Jasieniuk and Johnson 1982; Glaser 1992; Kuhry 1994). In other areas, vascular plants such as fireweed (*Epilobium angustifolium*) and cottongrass (*Eriophorum viridicarinatum*) invade the freshly burned peatlands. The roots of many ericaceous shrubs, willows (*Salix* spp.), and swamp birch (*Betula pumila*) survive the fires and resprout vigorously soon after the fire.

Peat-forming *Sphagnum* species may regain domination in 10–20 years after the fire, depending on the moisture conditions in the peatland. Clymo and Duckett (1986) demonstrated that *Sphagnum fuscum* can regenerate from stems up to 30 cm below the surface, representing a ready supply of regenerative material. Kuhry (1994) found that the prefire vegetation assemblages, dominated by *S. fuscum*, return within a few centimetres in the peat profile, suggesting that the effects of local bog fires are short lived.

Revegetation of permafrost peatlands follows a sequence similar to the unfrozen peatlands. Kiil (1975) found that within 15 years of a fire Labrador tea (*Ledum groenlandicum*) covers 85% of the surface and within 30 years the *Cladina* cover is 50% to a depth of 3 cm. Black spruce can be expected to revegetate the burned peatlands during the first 10 years after a fire.

The temporary decreases in the rate of peat accumulation are minor over a period of a few decades after a fire but might become significant if the fires cause a long-term change in the environment. In some cases fire triggers the degradation of permafrost. The possibility and extent of permafrost degradation depends on the regional climate: it is more severe in the south than in the north. The degradation is manifested by the subsidence of the former permafrost surface (thermokarst development) below the level of the surrounding fen or bog, forming internal lawns (depressions; Vitt et al. 1994) where peat-forming vegetation is rapidly established. In the more northerly areas, permafrost can redevelop after the *S. fuscum* thickness exceeds 40 cm. This cycle of fire, permafrost collapse, *Sphagnum* development, permafrost formation, and reestablishment of black spruce forest on permafrost, followed by another fire, can be as short as 500 years, but usually it is considerably longer (Zoltai 1993).

Estimates of annual biomass losses to fires

Uncertainties in current wildfire estimates in northern peatlands are large and observations are very limited (see Payette et al. 1989; Timoney and Wein 1991). Estimates of the areal extent of peatlands (Table 5) are based on the best available information (Tarnocai 1984; Rieger et al. 1979; Gorham 1990), and the partitioning of peatlands into broad classes was based on regional information (Vitt et al. 1994) extended across North America. The proportion of peat surfaces with moisture regimes in the ignitable and combustible range was used to estimate the extent of peat fires and the amount of biomass consumed under average climatic conditions. Losses through deep peat fires are not included, because these are stochastic events that in many cases are related to anthropogenic activities. Similarly, peat burned for fuel or used as a soil additive is not included in this estimate.

Little information is available on the length of fire cycles in various kinds of peatlands. There are some general observations (Jasieniuk and Johnson 1982) that fires occur in uplands about twice as frequently as in peatlands. Rowe (1983) estimated that the fire cycle is 120 years on bog borders and 140 years on deep peat. Based on such observations and examination of air photos and fire maps, we estimated that the fire return period for surface fires is between 75 and 1000 years (Table 5), depending on the region and the kind of peatland. Shallow peat fires are known to occur less frequently. Based on the frequency of charcoal layers (cf. Kuhry 1994) in peat deposits, it is estimated that the fire return period for shallow peat fires is between 250 and 1000 years (Table 6).

On the basis of available information (Table 2), the standing biomass was assumed to be 5 $t \cdot ha^{-1}$ on subarctic and humid boreal bogs, 10 $t \cdot ha^{-1}$ on fens, boreal bogs and subarctic

Table 5. Estimates of annual biomass loss from northern fens, bogs, and swamps due to surface fires.

	Region	Peatland area (km^2)	Fire return period (years)	Long-term average annual burn area (km^2)	Estimated biomass burned (10^3 t)
Fens	Subarctic	280 000	300	935	327
	Boreal, continental	144 000	300	480	168
	Boreal, humid	102 000	1 000	100	35
Bogs	Subarctic	10 000	150	65	11
	Boreal, continental	63 000	150	420	147
	Boreal, humid	100 000	800	125	22
Permafrost bogs	Subarctic	343 000	100	3 430	1 200
	Boreal, continental	4 000	150	25	26
	Boreal, humid	—	—	—	—
Forested swamps	Subarctic	—	—	—	—
	Boreal, continental	44 000	75	585	3 071
	Boreal, Humid	51 000	200	255	1 339
Total		1 141 000	—	6 420	6 346

Table 6. Estimates of annual peat biomass loss from northern bogs and swamps due to peat fires.

	Region	Peatland area (km^2)	Low-surface moisture area (km^2)	Fire return period (years)	Long-term average annual burn area (km^2)	Peat biomass burned (10^3 t)
Bogs	Subarctic	10 000	3 000	400	7.5	59.4
	Boreal, continental	63 000	21 000	400	52.5	415.8
	Boreal, humid	100 000	25 000	1 000	25	198
Permafrost bogs	Subarctic	343 000	240 000	250	960	12 418.6
	Boreal, continental	4 000	3 000	250	12	155.2
	Boreal, humid	—	—	—	—	—
Swamps	Subarctic	—	—	—	—	—
	Boreal, continental	44 000	14 000	200	70	859.3
	Boreal, humid	51 000	13 000	400	32.5	399
Total		615 000	319 000	—	1 159.5	14 505.3

permafrost peatlands, 30 t·ha^{-1} on boreal permafrost peatlands, and 150 t·ha^{-1} on forested swamps.

The areal extent of peat fires was estimated by assuming that all peatlands for which the moisture content of the surface peat layer was below the sustained combustion level (<235% m.c. by dry weight, Table 4) were burned. It was also assumed that peat fires would consume a significant portion of the total amount of peat available for combustion, estimated at 66% of the top 20 cm of peat layer. The peat biomass consumed by fire was calculated on the basis of the bulk density of surface peat from the continental Boreal and Subarctic wetland domains, as follows: bog peat, 0.060 g·cm^{-3}; permafrost peat, 0.098 g·cm^{-3}; and swamp peat, 0.093 g·cm^{-3} (S.C. Zoltai, unpublished data).

On these bases and on a long-term average, we estimate that about 6.3 Tg of surface biomass from the northern peatlands of North America can be expected to burn annually. In addition, as much as 14.5 Tg of peat may also be expected to be consumed by wildfires annually. Thus the total expected annual loss in North American peatlands due to wildfires is about 20.8 Tg of biomass. This would correspond to about 10 Tg of carbon lost directly to the atmosphere through fires.

Gas fluxes

Fires in northern peatlands influence carbon emissions to the atmosphere directly through biomass burning and indirectly through their impacts on ecosystem processes. Fire immediately redistributes carbon as gaseous emissions, ash, and charcoal, although secondary postburn emissions due to soil microbial activity both in peatlands that have burned and peatlands located downstream within the watershed of a burned area may actually far exceed direct losses. We present here estimates of the amounts of carbon released during fire in North American boreal peatlands, differentiating above- and below-ground contributions, and briefly discuss the potential impacts on biogenic emissions following fire. Uncertainties regarding carbon release to the atmosphere during and following fire, however, are large, particularly with regard to the areal extent of peatlands subject to fire, the quantity of above- and below-ground biomass consumed by combustion, the relative emission rates of the carbon species released, and the significance of postburn biogenic carbon emissions.

Combustion in natural ecosystems is rarely complete; thus combustion byproducts include carbon monoxide (CO), methane (CH_4), and nonmethane hydrocarbons (NMHC), in addition to carbon dioxide (CO_2). The emission ratios of these species, i.e., the amount released relative to the amount of carbon dioxide released, varies with respect to the fuel type, its moisture content, and the mode of combustion, e.g., flaming, smouldering, or mixed flaming and smouldering. Therefore, combustion emission ratios are expected to differ by peatland

Table 7. Combustion emission ratios assigned to each peatland type.

	Aboveground combustion			Belowground combustion		
	CO	CH_4	NMHC	CO	CH_4	NMHC
Fens	8.78	0.78	0.84	0	0	0
Bogs, permafrost bogs, and swamps	11.5	1.12	1.14	12.1	1.21	1.08

Table 8. Estimated direct carbon emissions (Tg C·year^{-1}) from wildfires in North American peatlands.

	CO_2	CO	CH_4	NMHC	Total
Aboveground combustion					
Fens	0.215	0.019	0.002	0.002	0.238
Bogs	0.073	0.008	0.001	0.001	0.083
Permafrost bogs	0.497	0.057	0.006	0.006	0.566
Forested swamps	1.786	0.205	0.020	0.020	2.031
Total	2.571	0.289	0.029	0.029	2.918
Belowground combustion					
Fens	0.000	0.000	0.000	0.000	0.000
Bogs	0.273	0.033	0.003	0.003	0.312
Permafrost bogs	5.092	0.616	0.062	0.055	5.825
Forested swamps	0.510	0.062	0.006	0.006	0.584
Total	5.875	0.711	0.071	0.064	6.721
Total above- and below-ground combustion					
Fens	0.215	0.019	0.002	0.002	0.238
Bogs	0.346	0.041	0.004	0.004	0.395
Permafrost bogs	5.589	0.673	0.068	0.061	6.391
Forested swamps	2.296	0.267	0.026	0.026	2.615
Total	8.445	1.000	0.100	0.093	9.639

type and between above- and below-ground combustion. In the absence of observations on carbon emissions due to fire in northern peatlands, emission ratios reported in the literature for analogous ecosystems (Levine et al. 1993, p. 302; Cofer et al. 1990) were assigned to each peatland class (Table 7) in proportion to expected above- and below-ground fuel types (herbaceous, woody, peat) and combustion modes (flaming, smouldering, mixed). Carbon emissions were then derived by multiplying the assigned emission ratios by estimates of above- and below-ground carbon loss due to fire (Tables 5 and 6).

Estimates of direct carbon emissions to the atmosphere due to wildfires in North American boreal peatlands (Table 8) suggest they are a globally significant but relatively small source in contrast to either emissions from wildfires in adjacent upland forests or emissions from microbial decomposition in peatlands. Assuming that 90% of the carbon released during biomass burning is in the form of CO_2 (Levine et al. 1993), total carbon emissions due directly to wildfires from North American boreal peatlands is estimated at 9.6 Tg C·year^{-1} or nearly 10% of the carbon released during wildfires in boreal ecosystems across all of Russia (Dixon and Krankina 1993). Atmospheric loading of CO_2 due to wildfires in boreal peatlands (8.4 Tg C·year^{-1}) is roughly one third of that released due to burning of peat for fuel (26 Tg C·year^{-1}) (Gorham 1991). Emissions of CO, CH_4, and NMHCs are estimated at 1.0, 0.1, and 0.09 Tg C·year^{-1} with emissions from peat fires averaging about 2.2- to 2.5-fold greater than from aboveground peatland fires. Methane emissions due to peatland fires are about 0.5% of the net 19.5 Tg CH_4 contributed annually by microbial activity in northern wetlands (Bartlett and Harriss 1993).

Carbon emissions due to wildfires in northern peatlands are projected to be among the highest and lowest for any ecosystem yet observed. Incomplete combustion within the peat layer is estimated to contribute at least 70% or 6.7 Tg C·year^{-1} of total carbon emissions due to fires, even though the areal extent of peat fires is less than one-fifth that of surface fires (Tables 5 and 6). Fires in the areally extensive and remote subarctic bogs underlain by permafrost contribute over 85% of the estimated carbon emissions due to peat fires. On a per unit area basis, estimated annual carbon emissions due to peat fires in bogs and forested swamps averaged 5.8 kg C·m^{-2}, ranging between 3.7 and 6.0 kg C·m^{-2}. In contrast, the higher soil moisture contents characteristic of herbaceous peatlands lead not only to greatly reduced fire susceptibility but also to combustion that is rapid, complete, and limited to the aboveground biomass. Carbon emissions due to aboveground peatland fires (2.9 Tg C·year^{-1}) averaged only 0.16 kg C·m^{-2} for bogs and fens but 2.4 kg C·m^{-2} for forested swamps. Fire in forested swamps thus represents the largest of all aboveground peatland fire sources, despite accounting for only 13% of the aboveground peatland area burned. The total amount of carbon released during fires in North American peatlands averaged over the aboveground burn area (1.50 kg C·m^{-2}) is comparable to values estimated for burning in boreal forests, which range from 1.13 kg C·m^{-2} (Cahoon et al. 1994; Stocks 1991) to 2.35 kg C·m^{-2} (Kasischke et al. 1995). These estimates are not independent, however, as the upland forest estimates include the contributions of some peatlands (e.g., see Kasischke et al. 1995). Given that the carbon released on a per unit area basis during fire from peatlands and upland forests is comparable, the significant difference in their global contributions thus appears to be due to differences in their respective areas susceptible to burning.

Wildfires are a major factor affecting boreal ecosystems (Wein and MacLean 1983). Fire results not only in the immediate pulse of carbon to the atmosphere, most of which is reaccumulated in plant biomass through vegetation regrowth (Houghton 1991), but also in a change in the structure, productivity, and biogeochemical dynamics of boreal ecosystems for decades thereafter. Postburn enhancement of biogenic emissions both in peatlands that have burned and peatlands located downstream or downwind of a burned area may have much more significant consequences than those due directly to burning. Near-term postburn effects on fire-disturbed areas include the immediate loss of primary productivity, increased soil respiration and rates of decomposition of remaining organic matter in response to increased nutrient availability and soil warming, water table fluctuations, and in permafrost areas, increased thermokarst development. Long-term effects include increased productivity and changes in plant community succession, including paludification and terrestrialization. Similarly, changes in the quantity or distribution of water, nutrients, or sediments to peatlands located downstream or downwind of burned areas may significantly affect trace gas emissions and plant community succession.

An understanding of combustion and ecosystem processes that control trace gas release during and following fire is required to gain insight into the potential short- and long-term response of boreal peatlands to wildfire. Lack of observations in boreal ecosystems prohibits estimating emissions from peatlands following fire at this time with any certainty, although the significance of postburn emissions is almost certain. For example, recent studies report two- to eight-fold increases in CO_2 emissions from boreal forest soils (Dixon and Krankina 1993; Levine 1991; Melillo et al. 1988) and twofold increases in CH_4 emissions from wetlands (Levine et al. 1990) following fire. In addition, removal of the insulating peat layer during peatland fires is known to often lead to an increase in soil temperatures and in the depth of the active layer in permafrost regions. Increased rates of microbial decomposition, in response to the warmer soil temperatures, are thus expected to lead to severalfold higher emissions of CO_2 and CH_4 (Livingston and Morrissey 1991; Peterson and Billings 1975). Increased nutrient availability due to the distribution of ash, dissolved materials, or sediments following fire to often nutrient-poor peatlands may also enhance microbial and plant productivity in peatlands receiving these materials. Experimental application of ash following burning in a Canadian wetland increased CH_4 emissions eightfold (Hogg et al. 1992). Thus, postburn fertilization of adjacent peatlands by fire may provide a much larger contribution to atmospheric trace gases than instantaneous emissions from burning peatlands.

Effects of climate change

Predicted climatic changes over the next century in response to increasing concentrations of greenhouse gases in the atmosphere (Houghton et al. 1995; Manabe et al. 1991) are expected to have a significant impact on the carbon dynamics of northern peatlands, particularly storage of carbon and release and uptake of CO_2 and CH_4 to and from the atmosphere (Shugart et al. 1992; Bonan 1991; Tans et al. 1990). Present-day peatlands formed over the past several 1000 years because net carbon gains due to primary productivity exceeded carbon losses due to decomposition of soil organic matter and wildfires. The present carbon stores of northern peatlands is estimated to be 455 Pg (Gorham 1991). Uncertainties as to whether peatlands will continue to accumulate carbon or whether their vast carbon reserves will be added to the already increasing atmospheric burden of greenhouse gases remain a major issue in efforts to project changes in carbon dynamics and potential climatic feedbacks in the face of climate change (Gorham 1991, 1995).

Climate models predict a significant warming (4–8°C) of northern high-latitude terrestrial areas over the next century, manifested by significantly warmer winters, slightly warmer summers, and a longer growing season (Houghton et al. 1995). Predicted changes in precipitation patterns are less certain but suggest a slight increase in precipitation over some terrestrial areas, a drying of the continental interiors, and an increase in the occurrence of extreme events, such as prolonged drought. The projected changes are substantial and they could contribute to increased fire activity in the boreal regions. In the Mackenzie Valley south of the 60° latitude, the water table is expected to drop under a $2 \times CO_2$ scenario to such an extent that peatlands will no longer exist when wetlands arrive at an equilibrium with the changed climate and peat deposits would be completely oxidized (Nicholson et al. 1997) by fire or aerobic decomposition. This would restrict the northerly distribution of peatlands by some 700 km. Similarly, it is estimated that permafrost would disappear from the peatlands south of the 65° latitude (Nicholson et al. 1997), representing a northward expansion of the permafrost-free peatlands by some 1000 km.

Interactions between environmental factors, biogeochemical dynamics, and vegetation community type and structure in northern peatlands are highly complex and regionally variable. Perhaps the most important factor defining the response of peatlands to a changing climate is soil moisture, as expressed by the position of the water table. Although rates of microbial decomposition, primary production, and evapotranspiration are temperature dependent, soil moisture directly or indirectly determines (*i*) the pathways and rates of transport of nutrients, gases, and heat into and out of the soil; (*ii*) whether microbial decomposition will proceed via aerobic or anaerobic pathways; (*iii*) the composition and structure of the overlying vegetation community; and (*iv*) susceptibility of the vegetation and surface peats to fire. For example, if climatic change does not significantly alter soil moisture conditions, then no change in the decomposition pathways or susceptibility of peatlands to wildfires should be expected, regardless of temperature increases. Increased rates of microbial decomposition in response to increased soil temperatures and longer frost-free seasons, however, may result in higher annual carbon losses, although these losses may well be balanced by possible increases in net annual primary productivity (Oechel and Billings 1992).

In contrast, a drying of the surface layers in peatlands would immediately result in a shift from anaerobic to aerobic microbial decomposition in the well-drained layers and thus to higher rates of decomposition, even without a change in soil temperature. A shift to aerobic decomposition would also result in a dramatic increase in CO_2 emissions (Silvola et al. 1994; Moore and Knowles 1989) and a concomitant decrease in CH_4 emissions (Martikainen et al. 1994; Crill et al. 1993; Roulet et al. 1992; Morrissey and Livingston 1992). The presence of oxygen in the soil profile following lowering of the water table not only inhibits CH_4 production but also supports microbial communities that consume CH_4 either produced in underlying anaerobic zones or diffused into the surface layers of the peat from the atmosphere.

Forestry studies demonstrate that lowering of the water table in previously waterlogged peatlands stimulates carbon loss in peat, greatly decreases peat accumulation, and generally leads to increased carbon accumulation in the living biomass (Zoltai and Martikainen 1996). As a result, the near-term effect on the net ecosystem carbon balance may be an increase in carbon storage. Laine et al. (1997) and Sakovets and Germanova (1992) reported four- to seven-fold net increases in carbon storage in the living biomass of forested peatlands, despite carbon loss from the peat. Regional differences in peatland types and successional changes in the vegetation community, however, will also affect carbon balances (Laine et al. 1994). The draining and conversion of northern peatlands for agricultural use rather than forestry, for example, is estimated to result in a per unit area carbon loss of 1500 $g \cdot m^{-2} \cdot year^{-1}$ because of increased peat decomposition (Nykänen et al. 1995). The global significance of northern peatland conversion to agriculture is presently low. Successional changes or persistent droughts in present key agricultural areas, however, could create pressure to increase the use of peatlands for agricultural purposes to meet the demands of the increasing human population (Zoltai and Martikainen 1996).

Any climatic change that results in a drying of the surface peats or a lowering of the water table also will increase the susceptibility of boreal peatlands to fire (Stocks 1990; Flannigan and Harrington 1988; Simard et al. 1985). How climate change will be regionally manifested will thus determine the geographical distribution of burns, fire frequency, areal extent of burns, and depth to which peats burn (King and Neilson 1992). The greatest increase in fire susceptibility is expected to occur in the Continental Boreal and Subarctic regions as opposed to areas influenced by the most northern or maritime climates, where only small changes in water table levels are expected. Simulation studies of fire occurrence in eastern Canada based on anticipated climate changes suggest longer fire seasons of greater severity, particularly in late summer (Street 1989). In similar studies, Wotton and Flannigan (1993) and Flannigan and Van Wagner (1991) suggested that the length of the fire season in boreal ecosystems could increase by up to 30% in response to anticipated climatic changes and that over 40% increases in fire frequency and area burned could be realized. The observed increase in the incidence and severity of fires across Canada and Russia in association with the drier and warmer weather conditions of the 1980s may provide evidence for these projections (footnote 3; Krankina 1992).

A changed climatic regime is expected to cause extensive degradation of the permafrost in northern areas (Woo et al. 1992). Fires would exacerbate this process by removing the surface peat and creating a heat-absorbing black surface. Permafrost peatlands, elevated above the water table of the surroundings, would subside as the permafrost thaws, submerging the peat into pools of water, resulting in increased CH_4 emissions (Bubier et al. 1995). However, peat-forming plants are expected to rapidly colonize the wet depressions, sequestering carbon in their biomass and thus mitigating the loss of carbon due to permafrost subsidence.

Conclusions

Wildfires are an integral part of northern ecosystems, affecting the carbon and nutrient dynamics of both upland forests and peatlands. On average, about 0.5% of the areal extent of northern peatlands is burned annually, releasing 9.6 Tg (20.8×10^3 t) of carbon into the atmosphere. Although given suitable moisture conditions peatland fires may consume some or all of the standing biomass, surface fires are a relatively small source of carbon. Incomplete combustion within the upper peat layer (0–20 cm depth) is estimated to contribute at least 70% of the total carbon emissions released due to fires in peatlands even though the extent of shallow peat fires is less than 20% that of surface fires. Fires in peatlands are highly variable regionally and seasonally. Over 85% of the estimated carbon emissions due to peat fires under present climatic conditions are from remote subarctic bogs underlain by permafrost. Atmospheric loading of CO_2 due to wildfires in boreal peatlands is estimated at 8.4 Tg $C \cdot year^{-1}$. In addition, emissions of CO, CH_4, and nonmethane hydrocarbons are estimated at 1.0, 0.1, and 0.09 Tg $C \cdot year^{-1}$. These estimates of direct carbon emissions to the atmosphere due to wildfires in North American boreal peatlands suggests that they are a globally significant but relatively small source in contrast to either emissions from wildfires in the adjacent and areally extensive upland forests or emissions from microbial decomposition in peatlands.

Fire affects the structure, productivity, and biogeochemical dynamics of the area burned, in addition to impacting the carbon, nutrient, and hydrologic dynamics of an often much larger area located downstream or downwind of the burned area. Although few in number, existing studies suggest postburn microbial emissions in these affected areas may be severalfold greater than preburn rates. Additional research is required to address the areal extent, magnitude, duration, and thus importance of these fertilization events.

Climate plays a critical role in the cycling of carbon between boreal ecosystems and the atmosphere. Anticipated increases in rates of decomposition and particularly in the occurrence and extent of wildfires in northern peatlands over the next 50–100 years in response to projected climatic changes are expected to result in both a dramatic decrease in carbon accumulation as peat and the release of large amounts of carbon into the atmosphere. Wildfires, in addition, are expected to be one of the primary mechanisms driving climate-induced vegetation change in boreal forests. Wildfires and fire management in northern ecosystems in future decades thus have the potential to be major factors in ecosystem and climate dynamics.

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