Chapter 12. Carbon Cycles in the Permafrost Region of North America

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KEY FINDINGS

- Much of northern North America (more than 6 million km^2) is characterized by the presence of permafrost, soils or rocks that remain frozen for at least two consecutive years. This permafrost region contains approximately 25% of the world's total soil organic carbon, a massive pool of carbon that is vulnerable to release to the atmosphere as CO_2 in response to an already detectable polar warming.
- The soils of the permafrost region of North America contain 213 Gt of organic carbon, approximately 61% of the carbon in all soils of North America.
- The soils of the permafrost region of North America are currently a net sink of approximately 11 Mt C yr^{-1}.
- The soils of the permafrost region of North America have been slowly accumulating carbon for the last 5-8 thousand years. More recently, increased human activity in the region has resulted in permafrost degradation and at least localized loss of soil carbon.
- Patterns of climate, especially the region's cool and cold temperatures and their interaction with soil hydrology to produce wet and frozen soils, are primarily responsible for the historical accumulation of carbon in the region. Non-climatic drivers of carbon change include human activities, including flooding associated with hydroelectric development, that degrade permafrost and lead to carbon loss. Fires, increasingly common in the region, also lead to carbon loss.
- Projections of future warming of the polar regions of North America lead to projections of carbon loss from the soils of the permafrost region, with upwards of 78% (34 Gt) and 41% (40 Gt) of carbon stored in soils of the Subarctic and Boreal regions, respectively, being severely or extremely severely affected by future climate change.
- Options for management of carbon in the permafrost region of North America, including construction methods that cause as little disturbance of the permafrost and surface as possible, are primarily those which avoid permafrost degradation and subsequent carbon losses.

- Most research needs for the permafrost region are focused on reducing uncertainties in knowing how much carbon is vulnerable to a warming climate and how sensitive that carbon loss is to climate change. Development and adoption of measures that reduce or avoid the negative impact of human activities on permafrost are also needed.

INTRODUCTION

It is especially important to understand the carbon cycle in the permafrost region of North America because the soils in this area contain large amounts of organic carbon, carbon that is vulnerable to release to the atmosphere as carbon dioxide and methane in response to climate warming. It is predicted that the average annual air temperature in the permafrost region will increase 3–4°C by 2020 and 5–10°C by 2050 (Hengeveld, 2000). The soils in this region contain approximately 61% of the organic carbon occurring in all soils in North America (Lacelle *et al*., 2000) even though the permafrost area covers only about 21% of the soil area of the continent. Release of even a fraction of this carbon in greenhouse gases could have global consequences.

Permafrost is defined, on the basis of temperature, as soils or rocks that remain below 0^{o}C for at least two consecutive years (van Everdingen, 1998 revised May 2005). Permafrost terrain often contains large quantities of ground ice in the upper section of the permafrost. If this terrain is well protected by forests or peat, this ground ice is generally in equilibrium with the current climate. If this insulating layer is not sufficient, however, even small temperature changes, especially in the southern part of the permafrost region, could cause degradation and result in severe thermal erosion (thawing). For example, some of the permafrost that formed in central Alaska during the Little Ice Age is now degrading in response to warming during the last 150 years (Jorgenson *et al*., 2001).

The permafrost region in North America is divided into four zones on the basis of the percentage of the land area underlain by permafrost (Fig. 12-1). These zones are the Continuous Permafrost Zone (≥90 to 100%), the Discontinuous Permafrost Zone (≥50 to <90%), the Sporadic Permafrost Zone (≥10 to <50%), and the Isolated Patches Permafrost Zone (0 to <10%) (Brown *et al*., 1997).

Figure 12-1. Permafrost zones in North America (Brown *et al*., 1997).

These permafrost zones encompass three major ecoclimatic provinces (ecological regions) (Fig. 12-2): the Arctic (north of the arctic tree line), the Subarctic (open canopy coniferous forest), and the Boreal (closed canopy forest, either coniferous or mixed coniferous and deciduous). Peatlands (organic wetlands characterized by more than 40 cm of peat accumulation) cover large areas in the Boreal, Subarctic, and southern part of the Arctic ecoclimatic provinces.

Figure 12-2. Arctic, Subarctic, and Boreal ecoclimatic provinces (ecological regions) in North America (Ecoregions Working Group, 1989; Baily and Cushwa, 1981).

Although northern ecosystems (Arctic, Subarctic, and Boreal) in North America cover approximately14% of the global land area, they contain approximately 25% of the world's total soil organic carbon (Oechel and Vourlitis, 1994). In addition, Oechel and Vourlitis (1994) indicate that the tundra (Arctic) ecosystems alone contain approximately 12% of the global soil carbon pool, even though they account for only 6% of the total global land area. The soils of the permafrost region of North America are currently a carbon sink and are unique because they are able to actively sequester carbon and store it for thousands of years.

The objectives of this chapter are to give the below-ground carbon stocks and to explain the mechanisms associated with the carbon cycle (sources and sinks) in the soils of the permafrost region of North America.

PROCESSES AFFECTING THE CARBON CYCLE IN A PERMAFROST ENVIRONMENT

Soils of the Permafrost Region

Soils cover approximately 6,211,340 km^2 of the area of the North American permafrost region (Tables 12-1 and 12-2), with approximately 58% of the soil area being occupied by permafrost-affected (perennially frozen) soils (Cryosols/Gelisols) and the remainder by non-permafrost soils. Approximately 17% of this area is associated with organic soils (peatlands), the remainder with mineral soils. It is important to distinguish between mineral soils and organic soils in the region because different processes are responsible for the carbon cycle in these two types of soils.

Table 12-1. Areas of mineral soils in the various permafrost zones.

Table 12-2. Areas of peatlands (organic soils) in the various permafrost zones.

Mineral Soils

The schematic diagram in Fig. 12-3 provides general information about the carbon sinks and sources in mineral soils. Most of the permafrost-affected mineral soils are carbon sinks because of the process of cryoturbation, which moves organic matter into the deeper soil layers. Other processes, such as decomposition, wildfires, and thermal degradation, release carbon into the atmosphere and, thus, act as carbon sources.

Figure 12-3. Carbon cycle in permafrost-affected upland (mineral) soils, showing below-ground organic carbon sinks and sources.

For unfrozen soils and noncryoturbated frozen soils in the permafrost region, the carbon cycle is similar to that in soils occurring in temperate regions. In these soils, organic matter is deposited on the soil surface. Some soluble organic matter may move downward, but because these soils are not affected by cryoturbation, they have no mechanism for moving organic matter from the surface into the deeper soil layers and preserving it from decomposition and wildfires. Most of their below-ground carbon originates from roots and its residence time is relatively short.

The role of cryoturbation: Although permafrost-affected ecosystems produce much less biomass than do temperate ecosystems, permafrost-affected soils that are subject to cryoturbation (frost-churning), a cryogenic process, have a unique ability to sequester a portion of this organic matter and store it for thousands of years. A number of models have been developed to explain the mechanisms involved in cryoturbation (Mackay, 1980; Van Vliet-Lanoë, 1991; Vandenberghe, 1992). The most recent model involves the process of differential frost heave (heave–subsidence), which produces downward and lateral movement of materials (Walker *et al*., 2002; Peterson and Krantz, 2003).

Part of the organic matter produced annually by the vegetation is deposited as litter on the soil surface, with some decomposing as a result of biological activity. A large portion of this litter, however, builds up on the soil surface, forming an organic soil horizon. Cryoturbation causes some of this organic material to move down into the deeper soil layers (Bockheim and Tarnocai, 1998). Soluble organic materials move downward because of the effect of gravity and the movement of water along the thermal gradient toward the freezing front (Kokelj and Burn, 2005). Once the organic material has moved down to the cold, deeper soil layers where very little or no biological decomposition takes place, it may be preserved for many thousands of years. Radiocarbon dates from cryoturbated soil materials ranged between 490 and 11,200 yr BP (Zoltai *et al*., 1978). These dates were randomly distributed within the soil and did not appear in chronological sequence by depth (the deepest material was not necessarily the oldest), indicating that cryoturbation is an ongoing process.

The permafrost table (top of the permafrost) is very dynamic and is subject to deepening due to factors such as removal of vegetation and/or the insulating surface organic layer, wildfires, global climate change, and other natural or human activities. When this occurs, the seasonally thawed layer (active layer) becomes deeper and the organic material is able to move even deeper into the soil (translocation). However, if such factors cause thawing of the soil and melting of the ground ice, some or all of the organic materials locked in the system could be exposed to the atmosphere. This change in soil environment gives rise to both aerobic and anaerobic decomposition, releasing carbon into the atmosphere as carbon dioxide and methane, respectively (Fig. 12-3). At this stage, the soil can become a major carbon source.

If, however, the permafrost table rises (and the active layer becomes shallower) because of reestablishment of the vegetation or buildup of the surface organic layer, this deep organic material becomes part of the permafrost and is, thus, more securely preserved. This is the main reason that permafrost-affected soils contain high amounts of organic carbon not only in the upper (0–100 cm) layer, but also in the deeper layers. These cryoturbated, permafrost-affected soils are effective carbon sinks.

Peatlands (Organic Soils)

The schematic diagram in Fig. 12-4 provides general information about the processes driving the carbon sinks and sources in peatland soils. The water-saturated conditions, low soil temperatures, and acidic conditions of northern peatlands provide an environment in which very little decomposition occurs; hence, the litter is converted to peat and preserved. This gradual buildup process has been ongoing in peatlands during the last 5,000–8,000 years, resulting in peat deposits that are an average of 2–3 m thick and, in some cases, up to 10 m thick. At this stage, peatlands can act as very effective carbon sinks for many thousands of years (Fig. 12-4).

Figure 12-4. Carbon cycle in permafrost peatlands, showing below-ground organic carbon sinks and sources.

Carbon dynamics**:** Data for carbon accumulation in various peatland types in the permafrost regions are given in Table 12-3. Although some values for the rate of peat accumulation are higher (associated with unfrozen peatlands), the values for frozen peatlands, which are more widespread, generally range around 13 g C m^{-2} yr^{-1}. Peat accumulations in the various ecological regions were calculated on the basis of the thickness of the deposit and the date of the basal peat. The rate of peat accumulation is generally highest in the Boreal region and decreases northward (Table 12-3). Note, however, that if the surface of the peat deposit has eroded, the calculated rate of accumulation (based on the age of the basal peat and a decreased deposit thickness) will appear to be higher than it should be. This is probably the reason for some of the high rates of peat accumulation found for the Arctic region, which likely experienced a rapid rate of accumulation during the Hypsithermal Maximum with subsequent erosion of the surface of some of the deposits reducing their thicknesses. Wildfires, decomposition, and leaching of soluble organic compounds release approximately one-third of the carbon input, causing most of the carbon loss in these peatlands.

Table 12-3. Organic carbon accumulation and loss in various Canadian peatlands. Positive values indicate net flux into the atmosphere (source); negative values indicate carbon sequestration (land sinks).

BELOW-GROUND CARBON STOCKS

The carbon content of mineral soils to a 1-m depth is 49–61 kg m^{-2} for permafrost-affected soils and 12–17 kg m^{-2} for unfrozen soils (Tables 12-4 and 12-5). The carbon content of organic soils (peatlands) for the total depth of the deposit is 81–129 kg m^{-2} for permafrost-affected soils and 43–144 kg m^{-2} for unfrozen soils (Tables 12-4 and 12-5) (Tarnocai, 1998 and 2000).

Table 12-4. Soil carbon pools and fluxes for the permafrost areas of Canada. Positive flux numbers indicate net flux into the atmosphere (source); negative values indicate carbon sequestration (land sinks).

Table 12-5. Average organic carbon content for soils in the various ecological regions (Tarnocai 1998 and 2000).

Soils in the permafrost region of North America contain 213 Gt of organic carbon (Tables 12-6 and 12-7), which is approximately 61% of the organic carbon in all soils on this continent (Lacelle *et al.*, 2000). Mineral soils contain approximately 99 Gt of organic carbon in the 0- to 100-cm depth (Table 12-6). Although peatlands (organic soils) cover a smaller area than mineral soils (17% vs 83%), they contain approximately 114 Gt of organic carbon in the total depth of the deposit, or more than half (54%) of the soil organic carbon of the region (Table 12-7).

Table 12-6. Organic carbon mass in mineral soils in the various permafrost zones.

Table 12-7. Organic carbon mass in peatlands (organic soils) in the various permafrost zones.

CARBON FLUXES

Mineral Soils

Very little information is available about carbon fluxes in both unfrozen and perennially frozen mineral soils in the permafrost regions. For unfrozen upland mineral soils, Trumbore and Harden (1997) report a carbon accumulation of 60–100 g C m^{-2} yr^{-1} (Table 12-4). They further indicate that the slow decomposition results in rapid organic matter accumulation, but the turnover time due to wildfires (every 500–1000 years) eliminates the accumulated carbon except for the deep carbon derived from roots in the subsoil. The turnover time for this deep carbon is 100–1600 years. Therefore, the carbon stocks in these unfrozen soils are low, and the turnover time of this carbon is 100 to 1000 years.

As with unfrozen mineral soils, very little information has been published on the carbon cycle in perennially frozen mineral soils. The carbon cycle in these soils differs from that in unfrozen soils in that, because of cryogenic activities, these soils are able to move the organic matter deposited on the soil surface into the deeper soil layers. Assuming that cryoturbation was active in these soils during the last six thousand years (Zoltai *et al*., 1978), an average of 9 Mt C have been added annually to these soils. Most of this carbon has been cryoturbated into the deeper soil layers, but some of the carbon in the surface organic layer is released by decomposition and, periodically, by wildfires. The schematic diagram in Fig. 12-5 shows the carbon cycle in these soils.

Figure 12-5. Carbon cycle in perennially frozen mineral soils in the permafrost region.

Peatlands (Organic Soils)

Peatland vegetation deposits various amounts of organic material (litter) annually on the peatland surface. Reader and Stewart (1972) found that the amount of litter (dry biomass) deposited annually on the bog surface in Boreal peatlands in Manitoba, Canada was 489–1750 g m^{-2}. Approximately 25% of the original litter fall was found to have decomposed during the following year. In the course of the study, they found that the average annual accumulation rate was 10% of the annual net primary production. Robinson *et al*. (2003) found that, in the Sporadic Permafrost Zone, mean carbon accumulation rates over the past 100 years for unfrozen bogs and frost mounds were 88.6 and 78.5 g m^{-2} yr^{-1}, respectively. They also found that, in the Discontinuous Permafrost Zone, the mean carbon accumulation rate during the past 1200 years in frozen peat plateaus was 13.31 g m^{-2} yr^{-1}, while in unfrozen fens and bogs the comparable rates were 20.34 and 21.81 g m^{-2} yr^{-1}, respectively.

Because peatlands cover large areas in the permafrost region of North America, their contribution to the carbon stocks is significant (Table 12-5). Zoltai *et al*. (1988) estimated that the annual carbon accumulation capacity of Boreal peatlands is approximately 9.8 Mt. Gorham (1988), in contrast, estimated that Canadian peatlands accumulate approximately 30 Mt of carbon annually.

Currently, wildfires are probably the greatest natural force in converting peatlands to a carbon source. Ritchie (1987) found that the western Canadian Boreal forests have a fire return interval of 50–100 years, while Kuhry (1994) indicated that, for wetter Sphagnum bogs, the interval is 400–1700 years. For peat plateau bogs, each fire resulted in an average decrease in carbon mass of 1.46 kg m^{-2} and an average decrease in height of 2.74 cm, which represents about 150 years of peat accumulation (Robinson and Moore, 2000). In recent years, the number of these wildfires has increased, as has the area burned, releasing increasing amounts of carbon into the atmosphere.

The schematic diagram presented in Fig. 12-6 summarizes the carbon cycle in peatlands in the permafrost region. Based on average values for the rate of peat accumulation, approximately 17 g C m^{-2} yr^{-1}, or 18 Mt C, is added annually to peatlands in this region of North America. Approximately 1.46 kg C m^{-2} is released to the atmosphere every 600 years by wildfires in the northern boreal peatlands. In addition, decomposition of unfrozen peatlands releases approximately 2.0 g C m^{-2} yr^{-1}, and a further 2.0 g C m^{-2} yr^{-1} is released by leaching of dissolved organic carbon (DOC), leading to a carbon decrease of approximately 4 Mt annually, not including that released by wildfires (Fig. 12-6). Note that these values are based on current measurements. However, rates of peat accumulation have varied during the past 6000–8000 years, with periods during which the rate of peat accumulation was much higher than at present.

Figure 12-6. Carbon cycle in peatlands in the permafrost region.

Total Flux

Based on the limited data available for this vast, and largely inaccessible, area of the continent, approximately 27 Mt C yr^{-1} is deposited on the surface of mineral soils and peatlands (organic soils) in the permafrost region of North America. Approximately 8 Mt yr^{-1} of surface carbon (excluding vegetation) is released by decomposition and wildfires, and by leaching into the water systems. Thus, the soils in the permafrost region of North America currently act as a sink for approximately 19 Mt C yr^{-1} and as a source for approximately 8 Mt C yr^{-1} and are, therefore, a net carbon sink (Figs. 12-5 and 12-6).

POSSIBLE EFFECTS OF GLOBAL CLIMATE CHANGE

The permafrost region is unique because the soils in this vast area contain large amounts of organic materials and much of the carbon has been actively sequestered by peat accumulation (organic soils) and cryoturbation (mineral soils) and stored in the permafrost for many thousands of years. Historical patterns of climate are responsible for the large amount of carbon found in the soils of the region today, but cryoturbation is a consequence of the region’s current cool to cold climate and the effects of that climate on soil hydrology. As a result, patterns of climate and climate change are dominant drivers of carbon cycling in the region. Future climate change will determine the fate of that carbon and whether the region will remain a slow but significant carbon sink, or whether it will reverse and become a source, rapidly releasing large amounts of CO_2 and methane to the atmosphere.

Peatlands

A model for estimating the sensitivity of peatlands to global climate change was developed using current climate (1x CO_2), vegetation, and permafrost data together with the changes in these variables expected in a 2x CO_2 environment (Kettles and Tarnocai, 1999). The data generated by this model were used to produce a peatland sensitivity map. Using GIS techniques, this map was overlaid on the peatland map of Canada to determine both the sensitivity ratings of the various peatland areas and the associated organic carbon masses. The sensitivity ratings, or classes, used are no change, very slight, slight, moderate, severe, and extremely severe. Because global climate change is expected to have the greatest impact on the ecological processes and permafrost distribution in peatlands in the severe and extremely severe categories (Kettles and Tarnocai, 1999), the areas and carbon masses of peatlands in these two sensitivity classes are considered to be most vulnerable to climate change. The sensitivity ratings are determined by the degree of change in the ecological zonation combined with the degree of change in the permafrost zonation, with the greater the change, the more severe the sensitivity rating. For example, if a portion of the Subarctic becomes Boreal in ecology and the associated sporadic permafrost disappears (no permafrost remains in the region), the sensitivity of this region is rated as extremely severe. If however, a portion of the Boreal remains Boreal in ecology, but the discontinuous permafrost disappears (no permafrost remains in the region), the sensitivity of this region is rated as severe.

The peatland sensitivity model indicates that the greatest effect of global climate change will occur in the Subarctic region, where about 85% (314,270 km^2) of the peatland area and 78% (33.96 Gt) of the organic carbon mass will be severely or extremely severely affected by climate change, with 66% of the area and 57% of the organic carbon mass being extremely severely affected (Fig. 12-7) (Tarnocai, in press). The second largest effect will occur in the Boreal region, where about 49% (353,100 km^2) of the peatland area and 41% (40.20 Gt) of the organic carbon mass will be severely or extremely severely affected, with 10% of both the area and organic carbon mass being extremely severely affected. These two regions contain almost all (99%) of the Canadian peatland area and organic carbon mass that is predicted to be severely or extremely severely affected (Fig. 12-7) (Tarnocai, in press).

Figure 12-7. The organic carbon mass in the various sensitivity classes for the Subarctic and Boreal Ecoclimatic Provinces (ecological regions) (Tarnocai, in press).

In the Subarctic region and the northern part of the Boreal region, where most of the perennially frozen peatlands occur, the increased temperatures are expected to cause increased thawing of the perennially frozen peat. Thawing of the ice-rich peat and the underlying mineral soil will initially result in water-saturated conditions. These water-saturated conditions, together with the higher temperatures, result in anaerobic decomposition, leading to the production of CH_4.

In the southern part of the Boreal region, where the peatlands are generally unfrozen, the main impact is expected to be drought conditions resulting from higher summer temperatures and higher evapotranspiration. Under such conditions, peatlands become a net source of CO_2 because the oxygenated conditions lead to aerobic decomposition (Melillo *et al*., 1990; Christensen, 1991). These dry conditions will likely also increase wildfires and, eventually, burning of peat, leading to the release of CO_2 to the atmosphere.

Permafrost-Affected Mineral Soils

The same model described above was used to determine the effect of climate change on mineral permafrost-affected soils. The model suggests that approximately 21% (11.9 Gt) of the total organic carbon in these soils could be severely or extremely severely affected by climate warming (Tarnocai, 1999). The model also suggests that the permafrost will probably disappear from the soils (the soils will become unfrozen) in the Sporadic and Isolated Patches permafrost zones. The main reason for the high sensitivity of mineral soils in these zones is that soil temperatures at both the 100- and 150-cm depths are only slightly below freezing (–0.3°C). The slightest disturbance or climate warming could initiate rapid thawing in these soils, with resultant loss of carbon (Tarnocai, 1999).

NON-CLIMATIC DRIVERS

Wildfires are an important part of the ecology of Boreal and Subarctic forests and are probably the major non-climatic drivers of carbon change in the permafrost region. There has been a rapid increase in both the frequency of fires and the area burned as a result of warmer and drier summers and increased human activity in the region. According to observations of natives, not only has the frequency of lightning strikes increased in the more southerly areas, but they have now appeared in more northerly areas where they were previously unknown. Because lightning is the major cause of wildfires in areas of little habitation, it is likely largely responsible for the increase in wildfires now being observed.

Increased human activity as a result of the construction of pipelines, roads, airstrips, and mines, expansion of agriculture, and development and expansion of town sites has disturbed the natural soil cover and exposed the organic-rich soil layers, leading to increased soil temperatures and, hence, decomposition of the exposed organic materials. Burgess and Tarnocai (1997), studying the Norman

Wells Pipeline, provide some examples of the effect of pipeline construction on frozen peatlands and permafrost in Canada.

Shoreline erosion along rivers, lakes, and oceans and thermal erosion (thermokarst) are also common processes in the permafrost region, exposing the carbon-rich frozen soil layers to the atmosphere and making the organic materials available for decomposition. As a result, carbon is released into the atmosphere as either CO_2 or methane, or it enters the water system as dissolved organic carbon.

Large hydroelectric projects in northern areas, such as Southern Indian Lake in Manitoba and the James Bay region of Quebec, have flooded vast areas of peatlands and initiated permafrost degradation and decomposition of organic carbon, some of which is released into the atmosphere as methane. Of greater immediate concern, however, is the carbon that has entered the water system as dissolved organic carbon. These compounds include contaminants such as persistent organic pollutants [e.g., PCBs, DDT, HCH, and chlorobenzene (AMAP, 2004)] that have been widely distributed in northern ecosystems over many years, much of it deposited by snowfalls, concentrated by cryoturbation, and stored in the organic soils. Of particular concern is the release of methylmercury because peatlands are net producers of this compound (Driscoll *et al*., 1998; Suchanek *et al*., 2000), which is a much greater health hazard than inorganic or elemental mercury. Natives in the regions where these hydroelectric developments have taken place have developed mercury poisoning after ingesting fish contaminated by this mercury, leading to serious health problems for many of the people. This is an example of what can happen when permafrost degrades as a result of human activities. When climate warming occurs, the widespread degradation of permafrost, with the resulting release of such dangerous pollutants into the water systems, could cause serious health problems for fish, animals, and humans that rely on such waters.

OPTIONS FOR MANAGEMENT OF CARBON IN THE PERMAFROST REGION

Although wildfires are the most effective mechanism for releasing carbon into the atmosphere, they are also an important factor in maintaining the integrity of northern ecosystems. Therefore, such fires are allowed to burn naturally and are controlled only if they are close to settlements or other manmade structures.

The construction methods currently used in permafrost terrain are designed to cause as little surface disturbance as possible and to preserve the permafrost. Thus, the construction of pipelines, airstrips, and highways is commonly carried out in the winter so that the heavy equipment used will cause minimal surface disturbance.

The greatest threat to the region is a warmer (and possibly drier) climate, which would drastically affect not only the carbon cycle, but also the biological systems, including human life. Unfortunately, we know very little about how to manage the natural systems in this new environment.

DATA GAPS AND UNCERTAINTIES

The permafrost environment is a very complex system, and the data available for it are very limited with numerous gaps and uncertainties. Information on the distribution of soils in the permafrost region is based on small-scale maps, and the carbon stocks calculated for these soils are derived from a relatively small number of datasets. Although there is some understanding of the carbon sinks and sources in these soils, the limited amount of data available make it very difficult, or impossible, to assign reliable values. Only limited amounts of flux data have been collected for the permafrost-affected soils and, in some cases, it has been collected on sites that are not representative of the overall landscape. This makes it very difficult to scale this information up for a larger area. As Davidson and Janssens (2006) state:

> "…the unresolved question regarding peatlands and permafrost is not the degree to which the currently constrained decomposition rates are temperature sensitive, but rather how much permafrost is likely to melt and how much of the peatland area is likely to dry significantly. Such regional changes in temperature, precipitation, and drainage are still difficult to predict in global circulation models. Hence, the climate change predictions, as much as our understanding of carbon dynamics, limit our ability to predict the magnitude of likely vulnerability of peat and permafrost carbon to climate change."

To obtain more reliable estimates of the carbon sinks and sources in permafrost-affected soils, we need much more detailed data on the distribution and characteristics of these soils. Carbon stock estimates currently exist only for the upper 1 m of the soil. Limited data from the Mackenzie River Valley in Canada indicate that a considerable amount of soil organic carbon occurs below the 1-m depth, even at the 3-m depth. Future estimates of carbon stocks should be extended to cover a depth of 0–2 m or, in some cases, even greater depths. More measurements of carbon fluxes and inputs are also needed if we are to understand the carbon sequestration process in these soils in the various permafrost zones. Our understanding of the effect that rapid climate warming will have on the carbon sinks and sources in these soils is also very limited. Future research should focus in greater detail on how the interactions of climate with the biological and physical environments will affect the carbon balance in permafrost-affected soils.

The changes that are occurring, and will occur, in the permafrost region are almost totally driven by natural forces and so are almost impossible for humans to manage on a large scale. Human activities, such as they are, are aimed at protecting the permafrost and, thus, preserving the carbon. Perhaps we humans should realize that there are systems (e.g., glaciers, ocean currents, droughts, and rainfall) that will be impossible for us to manage. We simply must learn to accept them and, if possible, adapt.

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Table 12-1. Areas of mineral soils in the various permafrost zones

Permafrost zones	Area ($10^3 \times km^2$)		
	Canada[a]	Alaska[b]	Total
Continuous	2001.80	353.46	2355.26
Discontinuous	636.63	479.15	1115.78
Sporadic	717.63	110.98	828.61
Isolated Patches	868.08	0.73	868.81
Total	4224.14	944.32	5168.46

[a] Calculated using the Soil Carbon of Canada Database (Soil Carbon Database Working Group, 1993).

[b] Calculated using the Northern and Mid Latitudes Soil Database (Cryosol Working Group, 2001).

Table 12-2. Areas of peatlands (organic soils) in the various permafrost zones

Permafrost zones	Area ($10^3 \times km^2$)		
	Canada[a]	Alaska[b]	Total
Continuous	176.70	51.31	228.01
Discontinuous	243.51	28.74	272.25
Sporadic	307.72	0.62	308.34
Isolated Patches	221.23	13.05	234.28
Total	949.16	93.72	1042.88

[a] Calculated using the Peatlands of Canada Database (Tarnocai *et al*., 2005).

[b] Calculated using the Northern and Mid Latitudes Soil Database (Cryosol Working Group, 2001).

Table 12-3. Organic carbon accumulation and loss in various Canadian peatlands. Positive values indicate net flux into the atmosphere (source); negative values indicate carbon sequestration (land sinks)

Peatlands	**Amount of carbon**
Boreal peatlands	–9.8 Mt yr^{-1}[a]
All Canadian peatlands	–30 Mt yr^{-1}[b]
All mineral and organic soils	–18 mg m^{-2} yr^{-1}[c]
Rich fens	–13.58 g m^{-2} yr^{-1}[d]
Poor fens (unfrozen, Discontinuous Permafrost Zone)	–20.34 g m^{-2} yr^{-1}[d]
Peat plateaus (frozen, Discontinuous Permafrost Zone)	–13.31 g m^{-2} yr^{-1}[d]
Collapse fens	–13.54 g m^{-2} yr^{-1}[d]
Bogs (unfrozen, Discontinuous Permafrost Zone)	–21.81 g m^{-2} yr^{-1}[d]
Dissolved organic carbon (DOC)	+2 g m^{-2} yr^{-1}[e]
Arctic peatlands	–0 to –16 cm/100 yr[f]
Subarctic peatlands	–2 to –5 cm/100 yr[f]
Boreal peatlands	–2 to –11 cm/100 yr[f]
Carbon release by each fire in northern boreal peatlands	+1.46 kg C m^{-2}[g]
Carbon release by fires in all terrain	+27 Mt yr^{-1}[h]
Carbon release by fires in Western Canadian peatlands	+5.9 Mt yr^{-1}[h]

[a] Zoltai *et al*., 1988.
[b] Gorham, 1988.
[c] Liblik *et al*., 1997.
[d] Robinson and Moore, 1999.
[e] Moore, 1997.
[f] Calculated based on the thickness of the deposit and the date of the basal peat (National Wetlands Working Group, 1988).
[g] Robinson and Moore, 2000.
[h] Turetsky *et al*., 2004.

Table 12-4. Soil carbon pools and fluxes for the permafrost areas of Canada. Positive flux numbers indicate net flux into the atmosphere (source); negative values indicate carbon sequestration (land sinks)

	Peatlands		**Mineral soils**		
Type	**Perennially frozen**	**Unfrozen**	**Perennially frozen**	**Unfrozen**	**Total**
Current area ($\times 10^3$ km^2)	422[a]	527[a]	2088[b]	2136[b]	5173
Current pool (Gt)	47[c]	65[a]	56[c]	28[b]	196
Current atm. flux (g m^{-2} yr^{-1})	–5.7[d]	–15.2[e]			
Carbon accumulation (g m^{-2} yr^{-1})	–13.3[f]	–20.3 to –21.8[f]		–60 to –100[g]	
Carbon release by fires (g m^{-2} yr^{-1})[h]	+7.57[i]				
Methane flux (g m^{-2} yr^{-1})		+2.0[j]			

[a] Calculated using the Peatlands of Canada Database (Tarnocai *et al*., 2005).
[b] Calculated using the Soil Carbon of Canada Database (Soil Carbon Database Working Group, 1993).
[c] Tarnocai, 1998.
[d] Using C accumulation rate of 0.13 mg ha^{-1} yr^{-1} (this report).
[e] Using C accumulation rate of 0.194 mg ha^{-1} yr^{-1} (Vitt *et al*., 2000).
[f] Robinson and Moore, 1999.
[g] Trumbore and Harden, 1997.
[h] Fires recur every 150–190 years (Kuhry, 1994; Robinson and Moore, 2000).
[i] Robinson and Moore, 2000.
[j] Moore and Roulet, 1995.

Table 12-5. Average organic carbon content for soils in the various ecological regions (Tarnocai, 1998 and 2000)

Ecological regions	Average carbon content (kg m^{-2})			
	Mineral soils[a]		Organic soils (peatlands)[b]	
	Frozen	Unfrozen	Frozen	Unfrozen
Arctic	49	12	86	43
Subarctic	61	17	129	144
Boreal	50	16	81	134

[a] For the 1-m depth.
[b] For the total depth of the peat deposit.

Table 12-6. Organic carbon mass in mineral soils in the various permafrost zones

Permafrost zones	Carbon mass[a] (Gt)		
	Canada[b]	Alaska[c]	Total
Continuous	51.10	9.04	60.14
Discontinuous	10.33	4.82	15.15
Sporadic	9.15	0.75	9.90
Isolated Patches	13.59	0	13.59
Total	84.17	14.61	98.78

[a] Calculated for the 0–100 cm depth.

[b] Calculated using the Soil Carbon of Canada Database (Soil Carbon Database Working Group, 1993).

[c] Calculated using the Northern and Mid Latitudes Soil Database (Cryosol Working Group, 2001).

Table 12-7. Organic carbon mass in peatlands (organic soils) in the various permafrost zones

Permafrost zones	Carbon mass[a] (Gt)		
	Canada[b]	Alaska[c]	Total
Continuous	21.82	1.46	23.28
Discontinuous	26.54	0.84	27.38
Sporadic	30.66	0.27	30.93
Isolated Patches	32.95	0	32.95
Total	111.97	2.57	114.54

[a] Calculated for the total depth of the peat deposit.

[b] Calculated using the Peatlands of Canada Database (Tarnocai *et al*., 2005).

[c] Calculated using the Northern and Mid Latitudes Soil Database (Cryosol Working Group, 2001).

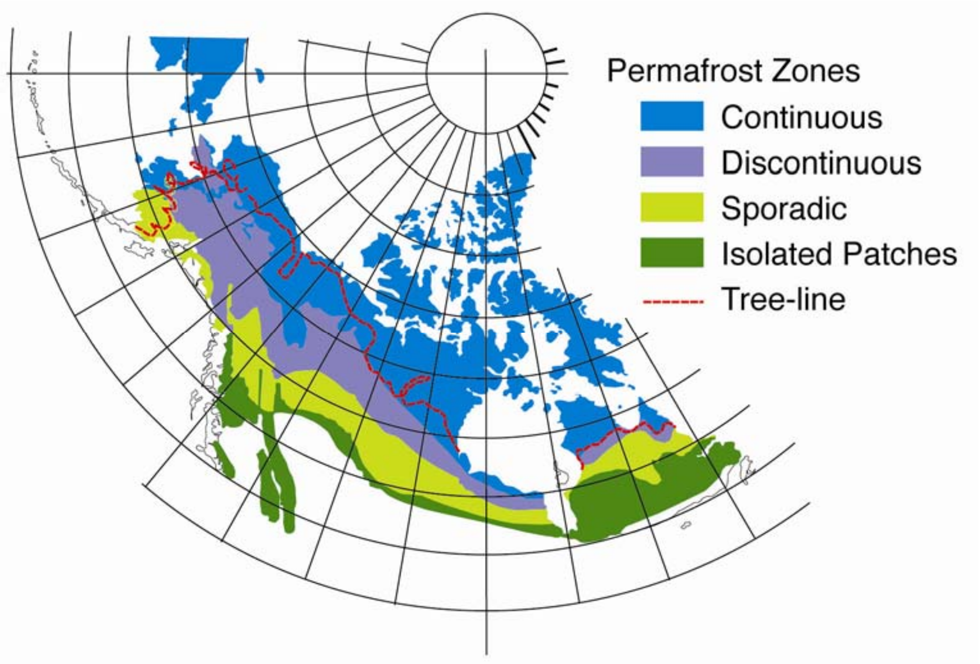


Fig. 12-1. Permafrost zones in North America (Brown *et al*., 1997).

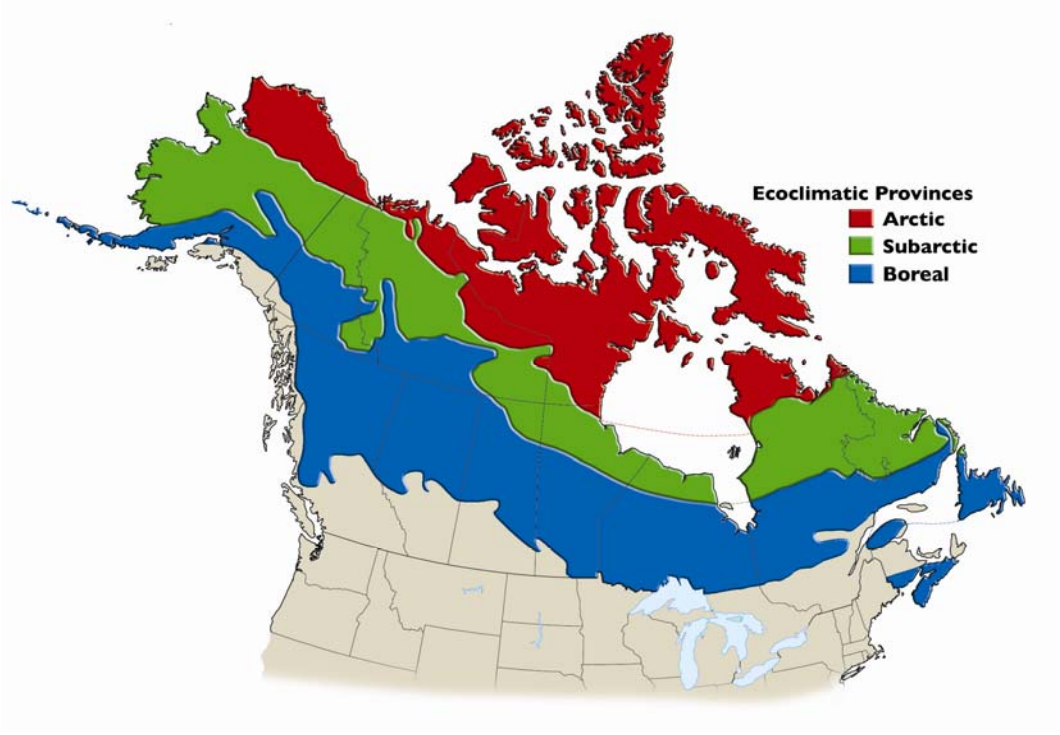


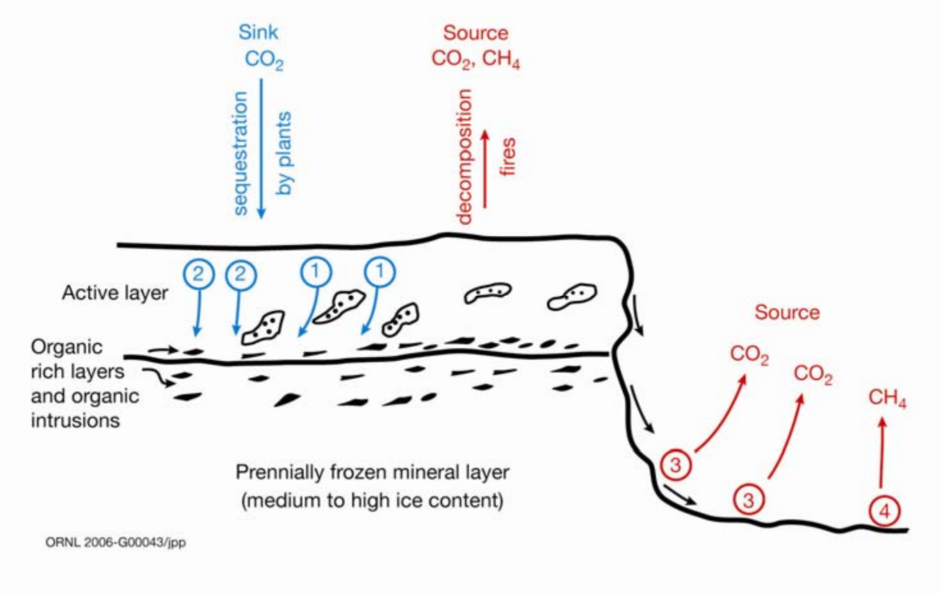
Fig. 12-2. Arctic, Subarctic, and Boreal ecoclimatic provinces (ecological regions) in North America (Ecoregions Working Group, 1989; Baily and Cushwa, 1981).

Carbon sinks

Permafrost-affected soil with a thick surface organic layer, dark-colored organic intrusions in the brown soil layer, and an underlying frozen, high-ice-content layer. The organic intrusions were translocated from the surface by cryoturbation. (Mackenzie Valley, Canada)

Carbon sources

Eroding high-ice-content permafrost soil composed of a dark frozen soil layer with an almost pure ice layer below. The thawing process generated a flow slide in which high-organic- content soil materials slumped into the water-saturated environment. (Mackenzie Delta area, Canada)



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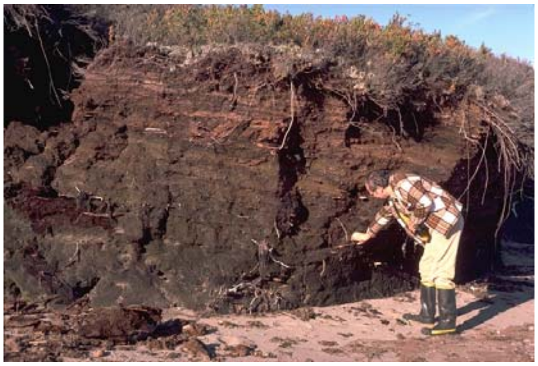
Perennially frozen deposit composed of an active layer that freezes and thaws annually and an underlying perennially frozen layer that has a high ice content.

Organic material deposited annually on the soil surface builds up as an organic soil layer. Some of this surface organic material is translocated into the deeper soil layers by cryoturbation (1). In addition, soluble organic matter is translocated into the deeper soil layers by movement of water to the freezing front and by gravity (2). Because these deeper soil layers have low temperatures (0 to -15°C), the organic material decomposes very slowly. Thus more organic material accumulates as long as the soil is frozen. In this state, the permafrost soil acts as a carbon sink.

Thermal erosion initiated by climate warming, wildfires or human activity causes the high-ice-content mineral soils to thaw, releasing the organic materials locked in the system. In this environment aerobic (3) and anaerobic (4) decomposition occurs releasing carbon dioxide and methane. In this state, the soil is a source of carbon.

Fig. 12-3. Carbon cycle in permafrost-affected upland (mineral) soils, showing below-ground organic carbon sinks and sources.

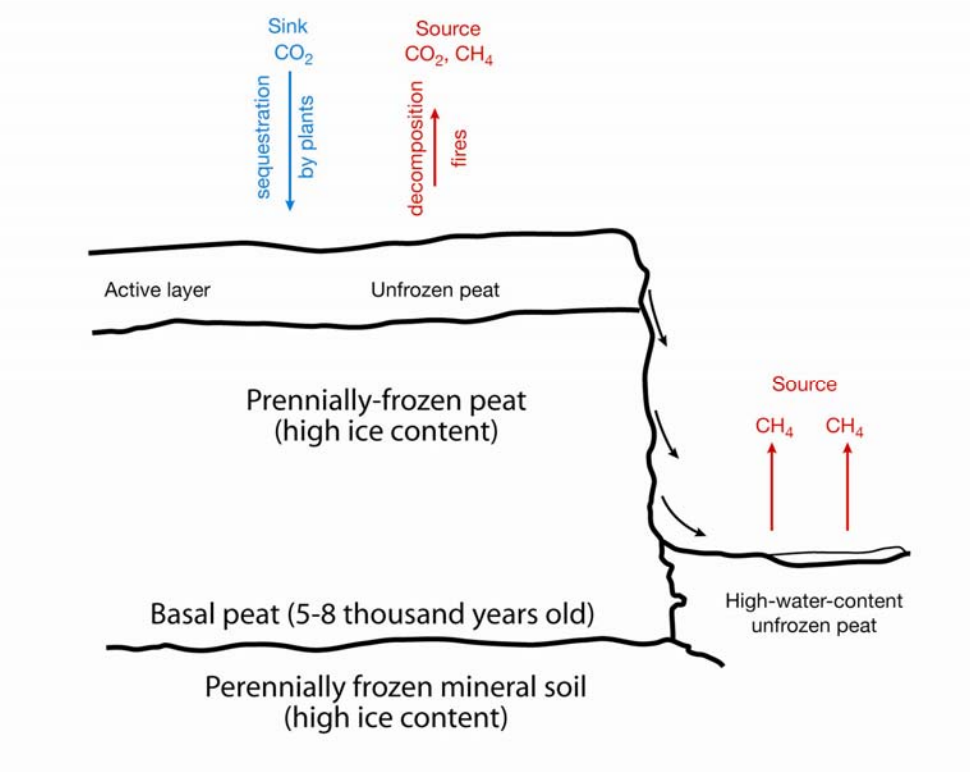
Carbon sinks



Perennially frozen peat deposit with multiple dark-colored peat layers. (Mackenzie River Delta area, Canada)

Carbon sources

Eroding perennially frozen peat deposit, showing the large blocks of peat slumping into the water- saturated collapsed area. (Fort Simpson area, Canada)



Perennially frozen peat deposits consist of an active layer that freezes and thaws annually and an underlying perennially frozen layer composed of ice-rich frozen peat and mineral materials.

Organic material is deposited annually on the peatland surface. Although a large portion (≥90%) of this organic material decomposes, the remainder is added to the peat deposit, producing an annual peat accumulation. The low soil temperatures (0 to –15°C) and the water-saturated and acid conditions cause this added organic carbon to be preserved and stored. This has been occurring for the last 5–8 thousand years. In this state, the peatland is a carbon sink.

Thermal erosion (thawing) of frozen peat deposits occurs as a result of climate change, wildfires, or human disturbances, releasing large amounts of water from the melting ice. This is mixed with the slumped peat material, initiating anaerobic decomposition in the much warmer environment. Anaerobic decomposition produces methane, which is expelled into the atmosphere. In this state, the peatland is a source of carbon.

Fig. 12-4. Carbon cycle in permafrost peatlands, showing below-ground organic carbon sinks and sources.

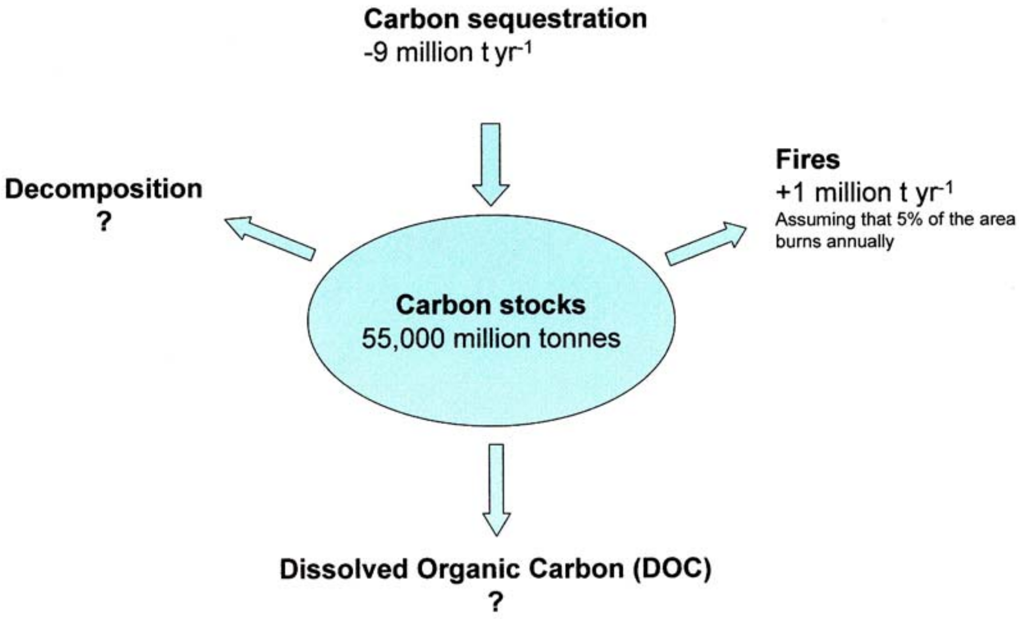


Fig. 12-5. Carbon cycle in perennially frozen mineral soils in the permafrost region.

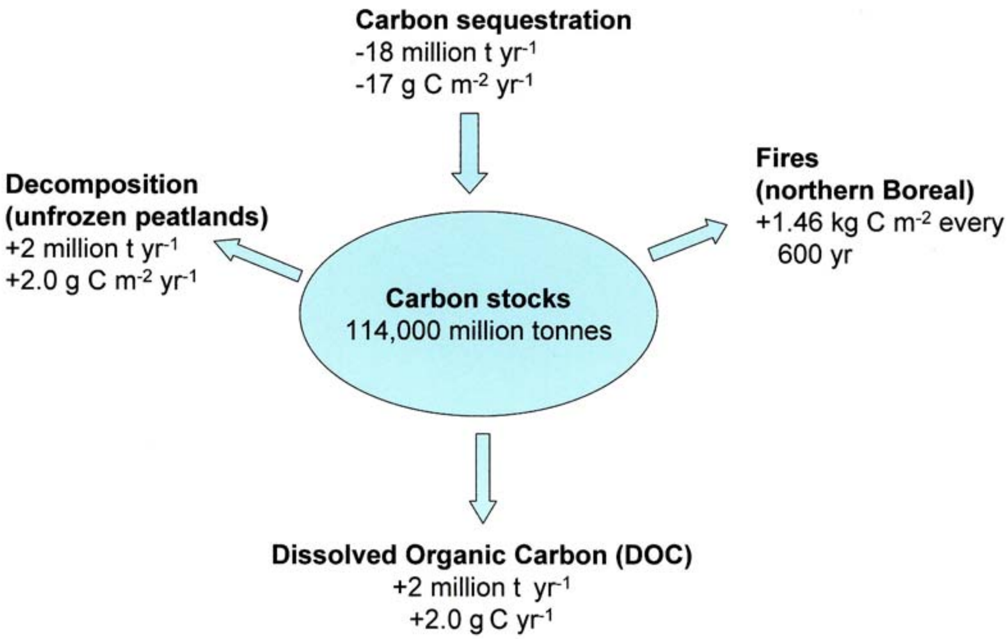


Fig. 12-6. Carbon cycle in peatlands in the permafrost region.

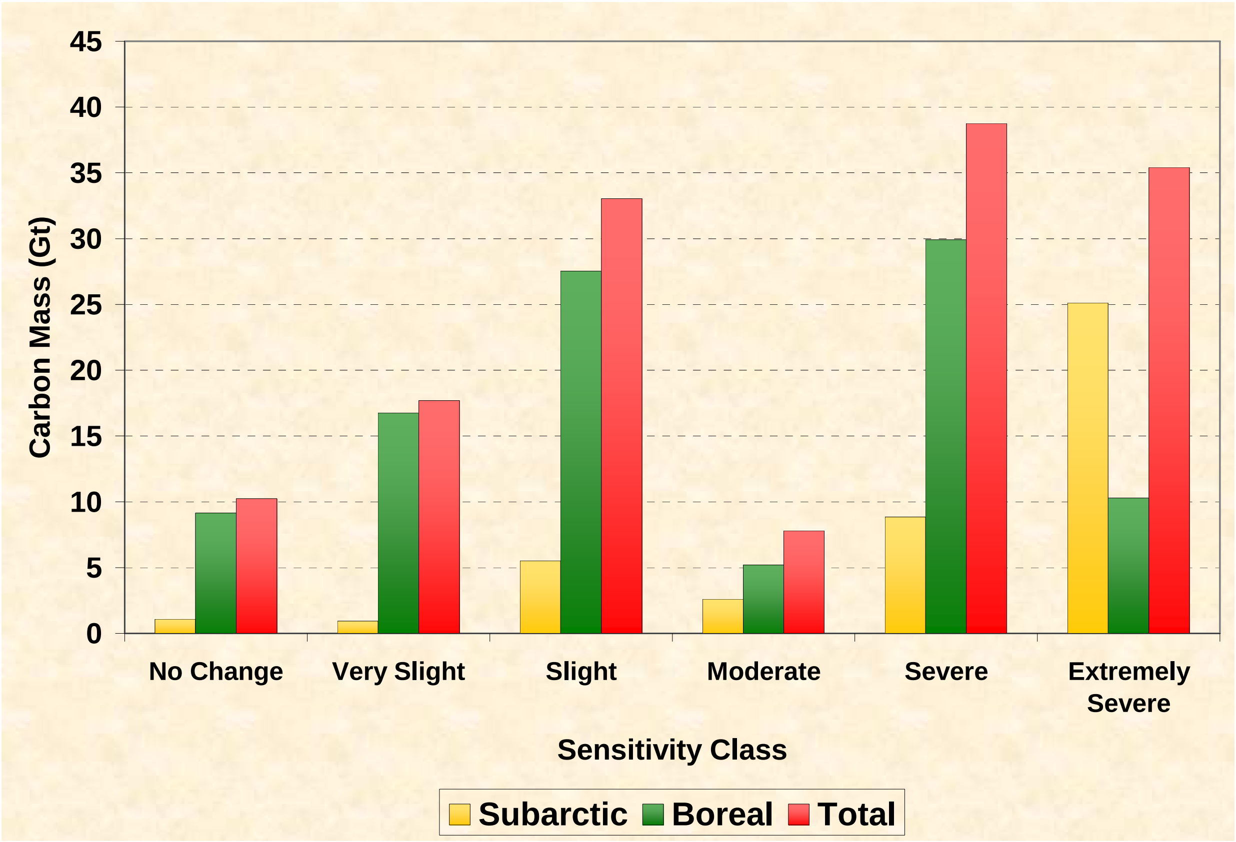


Fig. 12-7. The organic carbon mass in the various sensitivity classes for the Subarctic and Boreal Ecoclimatic Provinces (ecological regions) (Tarnocai, in press).