Permafrost, Phillips, Springman & Arenson (eds)
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Permafrost and peatland carbon sink capacity with increasing latitude

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ABSTRACT: The permafrost zone covers approximately 50% of the Canadian landmass, and ranges in distribution from continuous coverage in the arctic to sporadic coverage further south in the boreal zone. At its southern limit in the mid-boreal, permafrost is found almost exclusively in ombrotrophic peatlands. Carbon accumulation ($g\,C\,m^{-2}\,yr^{-1}$) in frozen peatlands at the southern limit (mean annual air temperature (MAAT) = 0 to -2°C) approaches that of unfrozen peatlands, though permafrost-affected peatlands have lower vertical growth rates ($cm\,yr^{-1}$) compared to adjacent peatland types. Further north in the high boreal and low subarctic zones (MAAT = -3 to -6°C), permafrost-affected peatlands sequester carbon at rates approximately half that of adjacent unfrozen peatlands. In the continuous permafrost zone (MAAT < -7°C), peatland carbon sequestration is currently minimal as evidenced by old near-surface radiocarbon dates. Decreasing mean annual air temperatures with increasing latitude appear to decrease rates of carbon accumulation as peat, resulting in a gradient of carbon sink capacity concurrent with increasing permafrost distributions. Permafrost controls on peat accumulation must be understood to predict the fate of soil carbon with climate warming.

1 INTRODUCTION

Peatlands are common and often dominant elements of northern high-latitude landscapes, and approximately 50% of peatlands in Canada are found in permafrost-affected regions. These ecosystems are characterized by cold waterlogged soils, low decomposition rates, and thick organic deposits. Permafrost in the Sporadic Permafrost Zone (SPZ) (Brown 1967) is almost exclusively limited to isolated frozen peat mounds in disequilibrium with current climate, representing relict features of the Little Ice Age that have been preserved by insulating peat (Vitt et al. 1994, 2000). Further north, permafrost in peatlands grades into larger peat plateau bogs intermixed with unfrozen peat landforms in the Discontinuous Permafrost Zone (DPZ), and then to expansive permafrost-dominated peat plateaus and polygonal peat plateaus in the Continuous Permafrost Zone (CPZ). At many northern sites, especially in the CPZ and sometimes the DPZ, the development of permafrost results in the deposition of sylvic peat, composed primarily of remains of ericaceous shrubs, feather mosses and lichens. Further south, in the SPZ and some sites in the DPZ, *Sphagnum* can still be a dominant peat-former even under permafrost conditions.

Northern peatlands have sequestered large amounts of carbon from the atmosphere as undecomposed organic matter (Gorham 1991). Several authors have suggested that the development of permafrost in a peatland terminates or severely restricts subsequent peat and carbon accumulation (Nichols 1969, Zoltai & Tarnocai 1975, Zoltai 1993). Many permafrost-affected peatlands are known to still be accumulating carbon at significant rates, especially in the discontinuous and sporadic permafrost zones (Ovenden 1990, Robinson & Moore 1999, Turetsky et al. 2000, Vardy et al. 2000). This paper presents data for carbon accumulation rates of recently-deposited peat on permafrost-affected peatlands along a transect from the SPZ in the continental peatlands of Alberta, Saskatchewan, and Manitoba, through to the CPZ in the Northwest Territories, Canada, that show a distinct trend in decreasing carbon accumulation rates with decreasing mean annual air temperature (MAAT).

2 SITE DESCRIPTIONS

Peatlands in the boreal ecoregion represent a mosaic of fens, bogs, permafrost features, and areas of recent permafrost thaw. For a regional frozen versus unfrozen comparison of peat accumulation, we sampled in ombrotrophic bogs with no evidence of permafrost since the last deglaciation, and isolated permafrost

Figure 1. Western Canada study sites in the discontinuous permafrost zone (DPZ) and sporadic permafrost zone (SPZ). Also shown is the location of the continuous permafrost zone (CPZ).

mounds with intact permafrost approximately 60 cm below the vegetation surface. Unfrozen bogs in western Canada are dominated by *Picea mariana*, *Ledum groenlandicum*, and *Sphagnum fuscum*. Bogs underlain by permafrost commonly have closed canopies of *P. mariana*; moss cover typically consists of *Pleurozium schreberi* and *Hylocomium splendens*. Our sites include 4 peatland complexes across the prairie provinces (Anzac, Alberta; Sylvie's Bog, Alberta; Patuanak, Saskatchewan; Mooselake, Manitoba) (Figure 1) that range from −1.2 to 0.2°C MAAT and from 444 to 496 mm mean annual precipitation (Environment Canada 1993).

Large bog-fen complexes occur to the west and southwest of Fort Simpson, Northwest Territories (61.8°N, 121.4°W) in the DPZ (Figure 1). Approximately 35% of the Fort Simpson region is covered by peatlands, of which 44% contains permafrost (Aylsworth et al. 1993), although significant permafrost thaw is ongoing (Beilman & Robinson 2003). Fort Simpson is in the continental high boreal wetland region of Canada, slightly south of the transition to low subarctic (National Wetlands Working Group 1988). The mean annual air temperature is –3.7°C, with annual precipitation averaging 374 mm (Environment Canada 1993).The most common peat landforms in this region include poor fen and unfrozen bog subject to only seasonal near-surface frost, and peat plateau bog containing permafrost up to approximately 10 m thick. Rich fens and collapse fens created by the recent thaw of permafrost are present but represent less than 5% of the total peatland area each.

In the CPZ further north (approx. >67°N), peatlands are commonly developed on broad, flat plains. The most common peat landform in this region is the peat plateau bog, often of polygonal surface pattern owing to the presence of ice wedges. Unfrozen peatlands are uncommon in this region, although, in depressions, small fens may be found that have saturated unfrozen near-surface peat, yet are underlain by permafrost at greater depths. Mean annual air temperatures in this region are generally <−7°C, and annual precipitation is often less than 300 mm yr^{-1}. Sylvic peat is the most common peat-former in the peat plateau bogs.

3 METHODS

Data presented for the SPZ in Alberta, Saskatchewan, and Manitoba were obtained using ^{210}Pb dating of short, surface peat cores in both frozen and unfrozen peatlands (Turetsky 2002). This method provides a semi-continuous series of dates within the core dating back no more than 150 years (Turetsky & Wieder, in review). In this paper, carbon accumulation rates calculated over the past 100 years are used. At each of four sites, we sampled within multiple unfrozen bogs and adjacent permafrost mounds.

In the DPZ near Fort Simpson, the 1200 year old White River volcanic ash (Robinson 2001) was used as a chronostratigraphic marker horizon to examine apparent carbon and vertical peat accumulation rates in permafrost and non-permafrost peat landforms (Robinson & Moore 1999). This approach allows the direct comparison among cores collected in various landforms owing to the uniform time scale of carbon accumulation measurement. This technique also allows a large core sample size as other dating methods are not required.

In order to include the CPZ, where detailed near-surface dating is not available, near-surface radiocarbon dates were obtained from sources within the literature as well as several previously unpublished dates. Only radiocarbon dates from sylvic or *Sphagnum* peat within 65 cm of the peat surface were included. Only information from permafrost-affected peat landforms are included in the radiocarbon dataset. The lack of unfrozen peat landforms in the CPZ prevented a frozen *vs*. unfrozen comparison as is presented for the SPZ and DPZ. MAAT was estimated for dated sites based upon Environment Canada's gridded interpolated data.

For datasets in the SPZ and DPZ utilizing ^{210}Pb and chronostratigraphic dating, carbon accumulation rates are calculated based upon unit area carbon mass, derived from bulk density and carbon content for increments within each core and summed to calculate total carbon mass above the dated horizon. Dividing the total carbon mass by the deposition period yields the apparent recent carbon accumulation rate. Original bulk density and carbon content data were not available for the majority of radiocarbon-derived ages, so estimates of carbon content and bulk density were used (Zoltai 1991).

Carbon accumulation rates were calculated over different time spans for each zone in this study. For this reason the rates cannot be compared among zones, as each method incorporates differing periods of decomposition and thus remaining carbon stock. However, comparisons within each zone, where periods over which rates are calculated are similar, are valid, and the overall aim of this dataset is to compare frozen *vs.* unfrozen landforms differences with latitude and MAAT.

4 RESULTS

Carbon accumulation rates over the past 100 years averaged $83.6 \pm 4.9\,g\,C\,m^{-2}\,yr^{-1}$ in frozen and unfrozen peatlands situated in the SPZ, but varied regionally (Figure 2). Accumulation rates within each site do not appear to differ between unfrozen bogs and permafrost mounds, except at the Mooselake site in Manitoba where permafrost mounds accumulated 43% less carbon compared to unfrozen bogs. However, mean accumulation rates among features within each site are often associated with high standard errors, especially at permafrost mound sites (Turetsky 2002). Averaged across all sites, unfrozen bogs and frost mounds accumulated 88.6 ± 4.4 and $78.5 \pm 8.8\,g\,C\,m^{-2}\,yr^{-1}$ over the past 100 years.

While the presence of permafrost has little influence on carbon accumulation in boreal peatlands, it does appear to control rates of vertical peat accumulation. Unfrozen bogs near the southern limit of permafrost across western Canada accumulated 28.2 ± 0.9 cm over the past 100 years. Permafrost mounds, however, accumulated only 15.1 ± 1.6 cm over the same 100 year period.

In the DPZ in the southern Mackenzie Valley near Fort Simpson, mean carbon accumulation rates over the past 1200 years for frozen peat plateau are 13.31 $g\,C\,m^{-2}\,yr^{-1}$ respectively ($n = 20$ cores) (Figure 3). Carbon accumulation rates are significantly greater ($p < 0.01$) in the unfrozen peat landforms of poor fen and bog (20.34 and $21.81\,g\,C\,m^{-2}\,yr^{-1}$ respectively, $n = 20$ cores per landform), and their means are not significantly different from one another ($p > 0.05$). Vertical peat accumulation rates were lowest in peat plateau peat (33.8 ± 1.4 cm over the past 1200 years), compared to poor fen (54.4 ± 2.0 cm) and bog (67.6 ± 1.9 cm), yet the sylvic peat deposited under permafrost conditions had the greatest bulk density

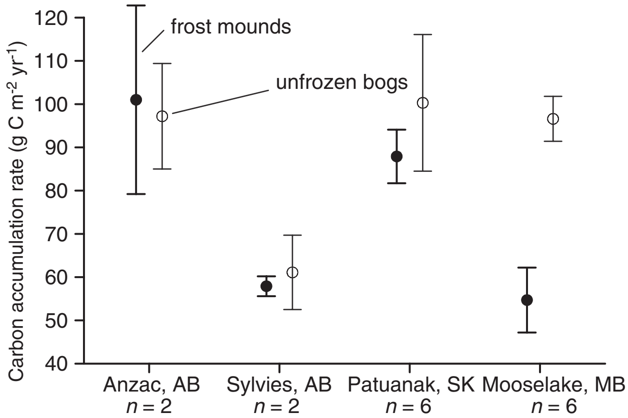

Figure 2. Carbon accumulation rates averaged over the past 100 years for ^{210}Pb-established peat chronologies collected in sporadic permafrost mounds (filled circles) and neighboring unfrozen bogs (open circles). Each data point represents the mean of multiple cores (see *n* on x-axis) ± standard errors.

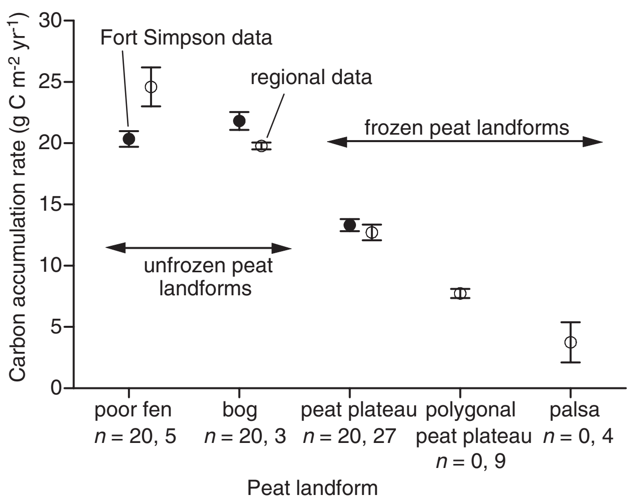

Figure 3. Carbon accumulation rates measured over the past 1200 years in unfrozen and frozen peat landforms near Fort Simpson, N.W.T (filled circles) and in a regional study encompassing the southwestern N.W.T. and southeastern Yukon Territory (open circles). Each data point is the mean of multiple cores (see *n* on x-axis) ± standard error. Data modified from Robinson & Moore 1999 and Robinson 2000.

($0.102\,g\,cm^{-3}$) of all peat types (Robinson & Moore 1999). Robinson & Moore (2000) presented a dataset indicating a decrease in carbon accumulation rate with increasing proportion of sylvic peat in the core. A peat core composed entirely of sylvic peat (and hence permafrost conditions for the entire 1200 years) would likely accumulate carbon at a rate of 9–10 $g\,C\,m^{-2}\,yr^{-1}$ in this region.

The dataset was expanded to incorporate carbon accumulation measurements in similar peat landforms in the southwestern Northwest Territories and southeastern Yukon, again using the White River ash as a marker horizon. Carbon accumulation rates followed the same trend in as in the more local study (Figure 3).

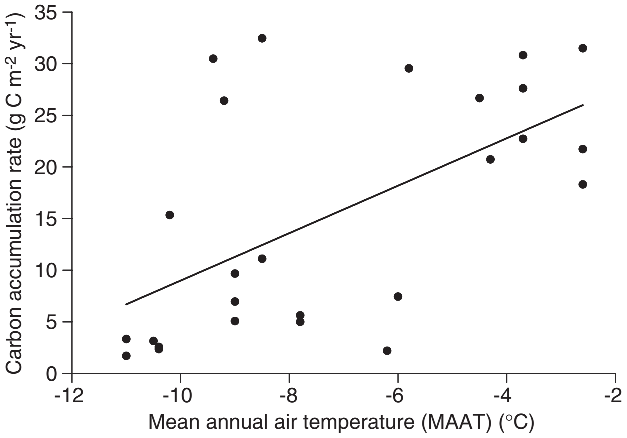

Figure 4. Carbon accumulation rates for near-surface permafrost-affected peatlands vs. mean annual air temperature (MAAT) for the Mackenzie Valley, N.W.T., Canada, based upon radiocarbon dates from the literature, estimated bulk density (Zoltai, 1991) and 50% carbon content and several unpublished dates (Kettles and Robinson, unpublished data. Line of best fit equation C accum. rate (g C m^{-2} yr^{-1}) = 2.3 * MAAT (°C) + 32, $r^2 = 0.35$.

Also included in the regional study were polygonal peat plateaus and palsas, found in the region at higher altitudes and colder MAAT. These permafrost forms stored the lowest amounts of carbon over this period of all landforms in the region.

Utilizing near-surface radiocarbon dates for the DPZ and CPZ, data show a general trend of decreasing carbon accumulation rates with decreasing MAAT. Data from the DPZ indicates that carbon accumulation rates are generally between 20–30 g C m^{-2} yr^{-1} (Figure 4). However, this data is generally consistent with data from Robinson & Moore (1999). A significant break in carbon accumulation rates appears to coincide with approximately −6°C MAAT. At colder temperatures, carbon accumulation rates less than 10 g C m^{-2} yr^{-1} are most commonly found, although there are some peatlands that are accumulating up to 32 g C m^{-2} yr^{-1} at MAAT as cold as −9°C. Caution must be exercised in using this data as the time span of carbon accumulation measurement varies significantly among samples. In general, near-surface data from the DPZ covers a more recent time span than data from the CPZ.

5 DISCUSSION

Previous work has suggested that the development of permafrost diminishes or even terminates carbon accumulation in peatlands. However, data presented in this study suggests that there is a climate-controlled pattern to carbon accumulation in permafrost-affected peatlands. In the SPZ, where MAAT ranges between approximately 0 and −2°C, carbon accumulation rates do not appear to differ significantly between frozen and unfrozen landforms. Carbon accumulation in permafrost-affected peatlands is greatest in boreal peatlands near the southern limit of permafrost in Alberta, Manitoba, and Saskatchewan. In this region of discontinuous permafrost, carbon accumulation rates established by ^{210}Pb-dating average 78.5 ± 8.8 g C m^{-2} yr^{-1} over the past 100 years in permafrost mounds and 88.6 ± 4.4 in unfrozen bogs, with the means not significantly different from one another. Further north, near Fort Simpson (MAAT − 3.7°C), frozen peat plateaus have carbon accumulation rates approximately 60% of those in common unfrozen landforms when measured over a 1200 year time span.

Direct comparisions between the SPZ and DPZ data should not be undertaken owing to the differing time periods of measurement. Future work will aim at applying consistent dating techniques to peatland features in the SPZ and DPZ for a more direct comparison of carbon accumulation rates in boreal and subarctic regions.

Data presenting near surface radiocarbon-based carbon accumulation rates for the DPZ and CPZ show a trend of decreasing carbon accumulation rate with decreasing MAAT. There appears to be a significant drop in carbon accumulation rates at MAAT colder than −6°C. However, there are still some sites within the CPZ that appear to have carbon accumulation rates as high as 30 g C m^{-2} yr^{-1}.

Thus, the results of this study indicate that permafrost development leads to decreased vertical peat accumulation but does not impede carbon accumulation at SPZ sites. Carbon storage is decreased in permafrost peat landforms in the DPZ, but can still be significant. In many locations in the CPZ, carbon accumulation in peatlands is severely retarded.

Peat accumulation represents the balance between organic matter inputs through plant production and carbon losses through microbial decay, dissolved releases and organic matter combustion during fire. While the aboveground production of *Picea mariana* decreases with MAAT in peat plateaus (Camill et al. 2001), the growth response of nonvascular species along this climatic gradient is unknown. However, it seems likely that net primary production (NPP) exerts a strong control on the carbon gradient shown here.

Fire can also contribute to significant peatland carbon losses through combustion (Robinson & Moore 2000, Turetsky & Wieder 2001), especially in raised, dry, and extensive permafrost features. Carbon combustion by fire is thought to be most common in the DPZ, where the combination of extensive peat plateaus and severe fire weather exists.

Due to the good insulation of organic matter, permafrost in peatlands may persist under MAATs warmer than 0°C (Halsey et al. 1995), representing disequilibrium between permafrost and air temperatures. Warmer air and substrate temperatures under future climate change scenarios certainly will influence the patchy nature of permafrost in boreal regions, but may also support higher carbon accumulation rates further north through enhanced NPP. However, increasing fire frequencies predicted for continental regions under a greenhouse gas enhanced-climate may lead to greater rates of carbon loss to the atmosphere through peat combustion, and also must be accounted for in large-scale estimates of carbon stocks at northern latitudes.

6 CONCLUSIONS

This study of carbon accumulation rates in permafrost-affected peatlands of western Canada indicates:

1 There is no significant difference in carbon accumulation between frozen and unfrozen peatlands in the Sporadic Permafrost Zone (SPZ).
2 Peat plateaus in the Discontinuous Permafrost Zone (DPZ) accumulate carbon at a rate approximately 60% of that in unfrozen peatlands of the same region.
3 Carbon accumulation rates decrease with decreasing mean annual air temperatures (MAAT), resulting in restricted accumulation at many sites in the Continuous Permafrost Zone (CPZ).

Permafrost today exists in boreal and arctic regions spanning 0 to -9°C, and ranges from discontinuous coverage in boreal peatlands to continuous coverage further north. Here, we show that increasing permafrost cover in peatlands occurring with colder climates also corresponds to decreasing carbon accumulation as peat. Therefore, the spatial distribution of permafrost as well as general climatic conditions should be considered when scaling site-specific estimates of carbon accumulation to regional peatland carbon budgets.

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