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ECOSYSTEMS

Holocene Carbon Accumulation of Fen Peatlands in Boreal Western Canada: A Complex Ecosystem Response to Climate Variation and Disturbance

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ABSTRACT

Understanding the long-term ecological dynamics of northern peatlands is essential for assessment of the possible responses and feedbacks of these carbon-rich ecosystems to climate change and natural disturbance. I used high-resolution macrofossil and lithological analyses of a fen peatland in western Canada to infer the Holocene developmental history of the peatland, to document the temporal pattern of long-term peat accumulation, and to investigate ecosystems responses to climate changes in terms of species composition and carbon accumulation. The peatland has been dominated by sedges and brown mosses during its 10,000-year history, despite interruption by tephra deposition. Peat accumulation rates vary by more than an order of magnitude and decline from 5500 to 1300 cal BP, resulting in a convex depth–age curve, which contrasts with the carbon accumulation patterns documented for oceanic peatlands. The synthesis of regional data from continental western Canada indicates that fens tend to accumulate more carbon than bogs of the same ages. These data suggest that the carbon sink potential of northern peatlands has varied dramatically in the past, so estimates of the present and projected carbon sink strengths of these peatlands need to take this temporal variation into consideration. Widespread slowdown of peat accumulation over the last 4000 years may have resulted from climate cooling in northern latitudes after the Holocene insolation maximum. The findings indicate that long-term peatland dynamics are modified by many local and regional factors and that gradual environmental change may be capable of triggering abrupt shifts and jumps in ecosystem states.

Key words: climate change; carbon dynamics; ecosystem responses; peat accumulation; continental fens; western Canada.

INTRODUCTION

Northern peatlands are wetland ecosystems found in boreal and subarctic regions. Carbon accumulation in peatlands is a function of the balance between the primary production of living plants and the decomposition of all organic material. The processes of both production and decomposition are governed by climate and environmental factors. However, we still do not understand the controls on net carbon balance and storage in northern peatlands; in particular, there is uncertainty regarding the response of these systems to environmental change (for example, Moore and others 1998). Yet these ecosystems potentially provide

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important feedbacks to the climate system and regional hydrology, through peat decomposition and the emissions of trace gases and through modifications of surface runoff and the water table. Understanding the long-term dynamics of carbon storage in northern peatlands is essential for the assessment of ongoing and future responses and feedbacks of these carbon-rich ecosystems to climate change and natural disturbance.

In continental western Canada (the provinces of Alberta, Saskatchewan, and Manitoba), peatlands cover 365,157 km^2 (approximately 20% of the land area) and store approximately 50 Gt C (Vitt and others 2000). Most peatland studies in western Canada and other high-latitude regions have focused on bogs (for example, Clymo 1984; Kuhry and Vitt 1996; Glaser and others 1997). However, the majority of peatlands in continental western Canada are fens (64% of peatland area), and several studies have shown that bogs and fens have different temporal patterns of peat accumulation implying that they are governed by different processes and mechanisms of control (Kubiw and others 1989; Yu and others 2003a). For example, in their detailed record of data for a rich fen in west-central Albert, Yu and others (2003a) found a convex age–depth, curve which is significantly different from the well-documented (concave) peat accumulation patterns in oceanic raised bogs (Clymo 1984). Clymo (1984) proposed that constant productivity coupled with exponential decomposition in these bogs produces a concave cumulative peat mass–age curve, due to greater decomposition of old peat than young peat. The difference between oceanic and continental regions in patterns of peat accumulation may be related to nutrient differences and the moisture limitations characteristic of continental climates (Yu and others 2003a). Other studies of continental bogs have documented also convex age–depth patterns (Kuhry and Vitt 1996; Turunen and others 2001), suggesting that regional variations in climate may be more important than bog–fen differences with respect to peat accumulation. However, more data are needed from a variety of peatland types in both oceanic and continental regions, particularly from fen ecosystems, which have received less study than bogs.

In this study, I present high-resolution lithological and palaeoecological data from an extreme-rich fen in west-central Alberta, Canada. The objectives of the study were to (a) infer the developmental history of the peatland using macrofossil analysis, (b) document the temporal pattern of long-term peat accumulation, (c) assess the responses of peatland vegetation and carbon accumulation to climate change, and (d) compare carbon accumulation patterns both between fens and bogs and among peatlands in different high-latitude regions. I attempted to address the following questions: How variable has peat accumulation been during the Holocene? What are the relative roles of climate change, ecosystem disturbance, and autogenic processes in determining the temporal pattern of carbon accumulation in peatlands? How do these processes and the resulting peat accumulation patterns differ among regions and between peatlands of different type (that is, fens versus bogs)?

METHODS

Study Area and Site

Goldeye Lake Fen (GLF) is located on the eastern slope of the Rocky Mountain Foothills in central Alberta, Canada (Figure 1). The region has a semi-humid continental climate, with a mean annual precipitation of approximately 540 mm and a mean annual temperature of 3°C (Environment Canada 1993). The fen is within the Upper Foothills vegetation subregion, adjacent to the boundary of the Subalpine subregion (Beckingham and others 1996). The upland vegetation is coniferous forest dominated by lodgepole pine (*Pinus contorta* Loud.). White spruce (*Picea glauca* (Moench) Voss) is common in the region, with some balsam fir (*Abies balsamea* (L.) Mill.), white birch (*Betula papyrifera* Marsh), aspen (*Populus tremuloides* Michx.), and balsam poplar (*Populus balsamifera* L.). It is an extreme-rich fen, dominated by the brown moss *Scorpidium scorpioides* (Hedw.) Limpr. and *Carex* species (Cyperaceae). There are scattered tamarack trees (*Larix laricina* (Du Roi) K. Koch) in the peatland. The coring site is about 500 m north and upstream of Goldeye Lake (Figure 1B), which was the subject of a paleoecological study by Schweger (1989).

Field and Laboratory Methods

A 350-cm peat core was collected on 2 November 1999 using a 5-cm–diameter modified Macaulay peat sampler. At the time of coring, the peatland was covered by snow. The 50-cm–long core segments were wrapped in plastic wrap and stored in polyvinylchloride (PVC) pipe during transportation to the laboratory, where they were stored at 2°C.

The subsampling procedure was the same as described for Upper Pinto Fen (UPF) in Yu and others (2003a). The peat core was cut into contiguous 1-cm–thick slices. Subsamples from each of

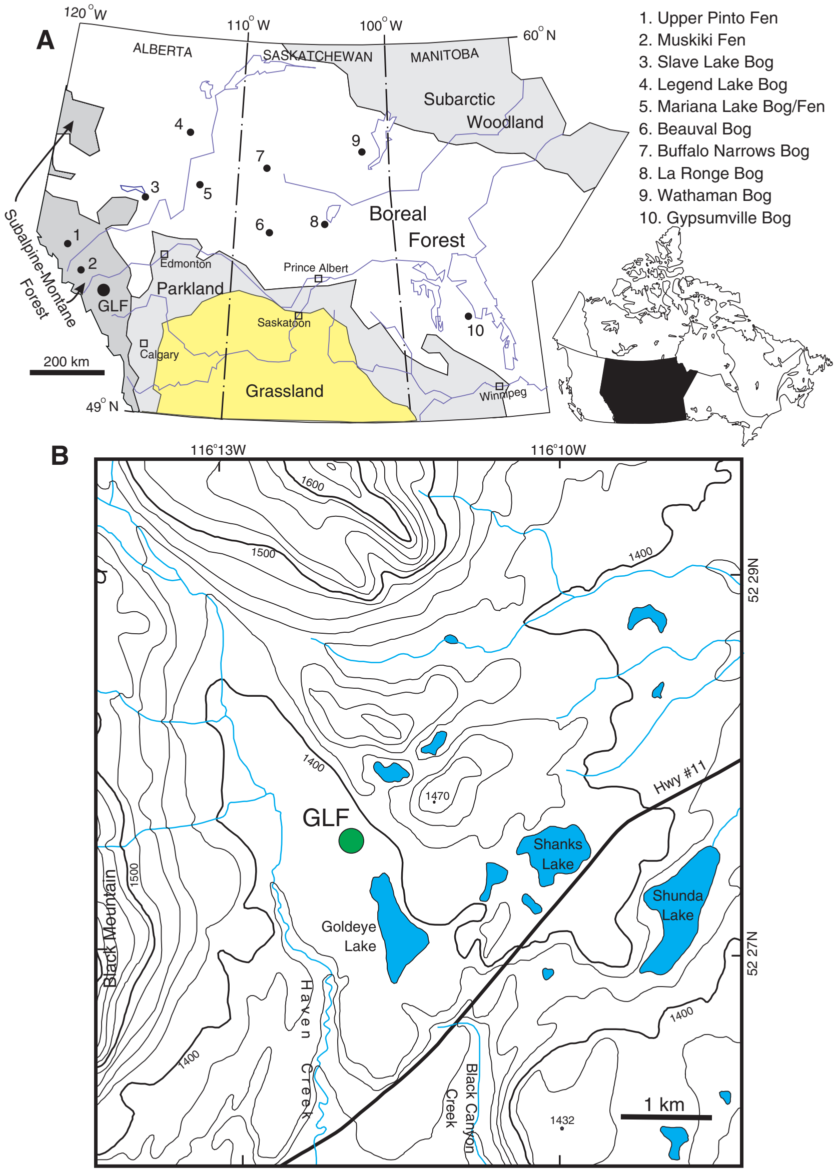

Figure 1. **A** Location of Goldeye Lake Fen (GLF) and other peatland sites in western continental Canada, with major vegetation regions. *Inset*: Three prairie provinces in western Canada. **B** Topographic map showing the setting of study site and the coring location, as represented by a dot north of Goldeye Lake.

these slices were taken with a 1-cm–diameter brass cylinder sampler for loss-on-ignition analysis. The peat subsamples were oven-dried at 100°C for estimation of moisture content, then ashed at 550°C for estimation of organic matter (OM) content. The peat bulk density and ash-free bulk density were calculated from the measurements of subsample volume and OM. Carbonate content was estimated by measuring additional weight loss after burning at 950°C. Six subsamples from selected 1–cm–thick slices were submitted for accelerator mass spectrometry (AMS) radiocarbon dating (Table 1). They were pretreated and prepared for graphite targets at the Limnological Research Center of the University of Minnesota and dated at the AMS Laboratory, University of Arizona. All dates were obtained on the coarse fibrous fraction remaining after a full acid/alkali/acid pretreatment.

I used a semi-quantitative method for macrofossil analysis. Peat subsamples of approximately 1 cm^3 were taken at every 1 or 2 cm and dispersed into a custom-designed picking tray with channels (''channeled plexiglass template''), without chemical treatment and sieving. The subsamples were examined under a dissecting stereo-microscope to identify and estimate the relative abundance of different macroscopic components, including decomposed and unrecognizable fine debris. The identification was aided by reference collections at the Cryptogamic Herbarium of the University of Alberta, Edmonton.

Table 1. AMS Radiocarbon Dates for Goldeye Lake Fen in Alberta, Canada

Depth (cm)	AMS Lab No.	^{14}C date ± 1SE	Age (cal BP)[a]	2σ Rang (cal BP)	δ^{13}C (‰ VPDB)
59–60	AA37418	1015 ± 40	931	991–888	−26.6
109–110	AA37414	1450 ± 45	1330, **1316**, 1314	1418–1280	−26.5
159–160	AA37415	4345 ± 50	4867	5041–4831	−27.1
209–210	AA37416	4850 ± 60	5593	5721–5464	−30.7
274–275	AA37103	6700 ± 50	7572	7664–7474	−27.6
324–325	AA37417	8210 ± 60	9243, 9218, **9204**, 9189, 9174, 9132	9322–9022	−31.1

AMS, accelerator mass spectrometry
[a] *Bold ages used in age model*
VPDB Vienna Peedee belemnite

RESULTS

Lithology and Chronology

The lithology at the base of the core is characterized by a gradual change from shallow pond sediment with visible mollusk shells at 350–343 cm (approximately 20% [OM]) to muddy sediment at 343–328 cm with approximately 50% OM (Figure 2). The peat above 328 cm contains about 80% OM, with two broad intervals having low OM values at 285–265 cm and at approximately 130 cm, which correspond to the known Mazama and St. Helens tephras (Figure 2A). Both major tephra layers were light gray in color, but turned reddish after burning at 950°C. Several other minor ash layers were visible and apparent at 190–191 cm (black), 186 cm (black), 172–174 cm (reddish), and 155–158 cm (greenish). Carbonates were less than 3% at most levels, although they increased to approximately 15% at the base and surface of the core (Figure 2B). The ash-free bulk density generally varies between approximately 0.1 and 0.25 g/cm^3, with an average of 0.176 g/cm^3 (Figure 2E).

The six AMS ^{14}C dates were calibrated using the INTCAL98 data set (Stuiver and others 1998) (Table 1), and an age model was based on linear interpolation between successive calibrated ages, together with ages for the known tephra layers (Luckman and others 1986; Hallett and others 1997) (Figure 3). The temporal sampling resolution ranges from 7.8 to 112.1 years for each contiguous 1-cm interval (mean of 28.9 years), with the coarsest sampling resolution between 3675 and 1320 cal BP and shortly before that (Figure 4A).

Rates and Pattern of Carbon Accumulation

The peat accumulation pattern shown in Figure 5 was based on six calibrated AMS ^{14}C dates and tephra ages and 351 bulk density measurements. Between the Mazama eruption (7500 cal BP) and approximately 1300 cal BP, the peat core shows a convex cumulative peat mass–age curve. Carbon accumulation rates at GLF (Figure 6) were calculated from ash-free bulk density measurements (Figure 2E) and peat vertical growth rates (Figure 3), using the average carbon content of peat OM (51.8 ± 4.7%) derived from 253 measurements in peatlands in continental western Canada (Vitt and others 2000). The estimated rates for each dated peat interval range from 7.8 to 113 g C m^{-2} y^{-1}, with a time-weighted mean of 25.5 g C m^{-2} y^{-1} (Table 2). The uncertainty associated with the conversion from OM to carbon would not change the general pattern and relative rates of peat accumulation.

Macrofossil Record

To facilitate discussion of the macrofossil record, characteristic zones were defined by visual inspection of the dominant macrofossil components (Figure 7). Basal peat (10,050–9400 cal BP) is dominated by *Picea* needles, fine debris, charcoal, and mollusk shells. Few moss fossils occur in this zone (zone GLF-1). Zone GLF-2 contains more moss remains, with up to 40% *Scorpidium scorpioides* and some *Colliergon;* the zone is also characterized by the disappearance of *Picea* needles and mollusk shells. Zone 3 shows a decrease in *Scorpidium scorpioides* and the appearance of *Betula* leaves; an increase in *Colliergon* (up to 70%) occurs at the top of the zone. Zone 4 is dominated by *Scorpidium scorpioides* (up to 60%), with some *Drepanoclodus. Scorpidium scorpioides* decreases again in Zone 5, and fine debris increases. Zone 6 has high *Scorpidium scorpioides* and low fine debris. Cyperaceae and woody materials increase in Zone 7, and sediments from this zone contain about 20% *Scorpidium scorpioides.* Zone 8 (the last 400

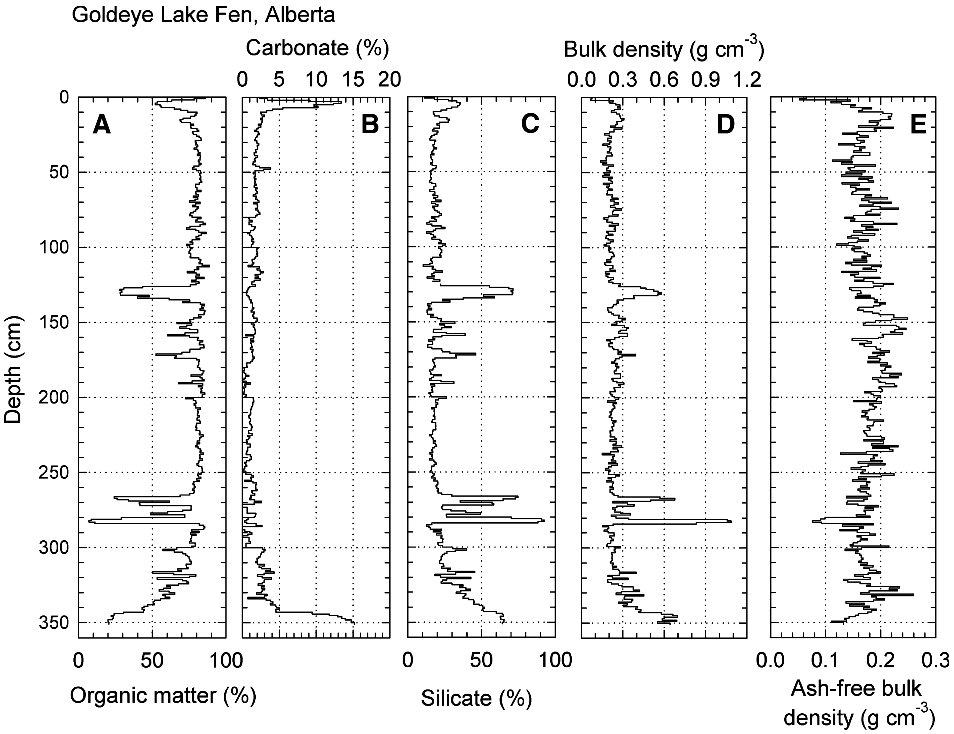

Figure 2. Peat lithology at Goldeye Lake Fen, Alberta. **A** Organic matter. **B** Carbonate. **C** Silicate. **D** Bulk density **E** Ash-free bulk density.

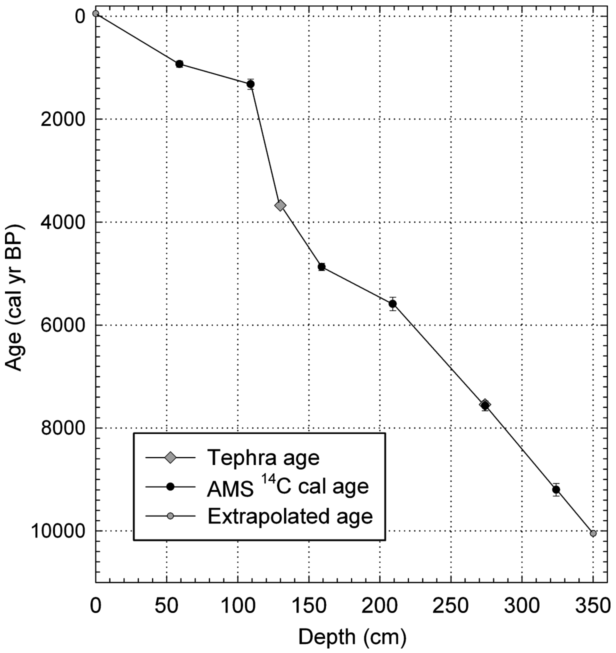

Figure 3. Age–depth plot and age model of Goldeye Lake Fen, Alberta. The dating points include six AMS radiocarbon dates, median ages for two tephra layers (Mazama and St. Helens Yn) (Luckman and others 1986; Hallett and others 1997), and two extrapolated dates at the bottom and top of the core.

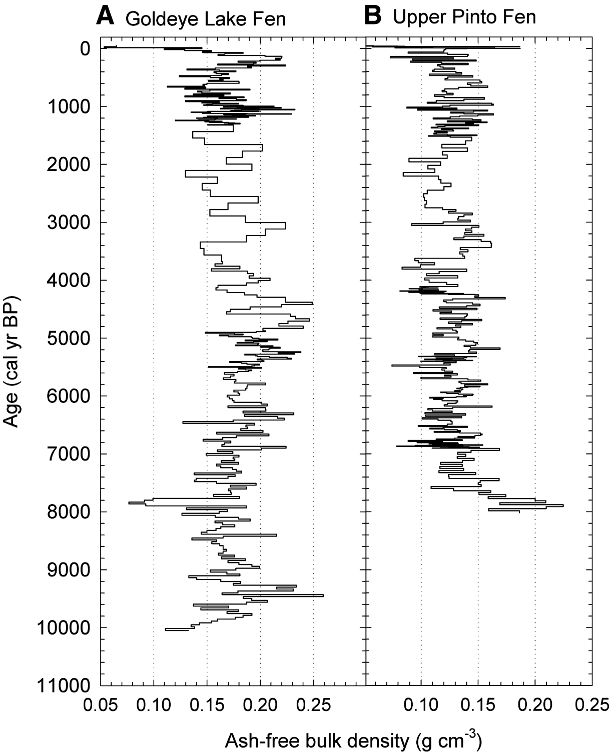

Figure 4. Comparison of ash-free bulk density at **A** Goldeye Lake Fen and **B** Upper Pinto fen (Yu and others 2003a).

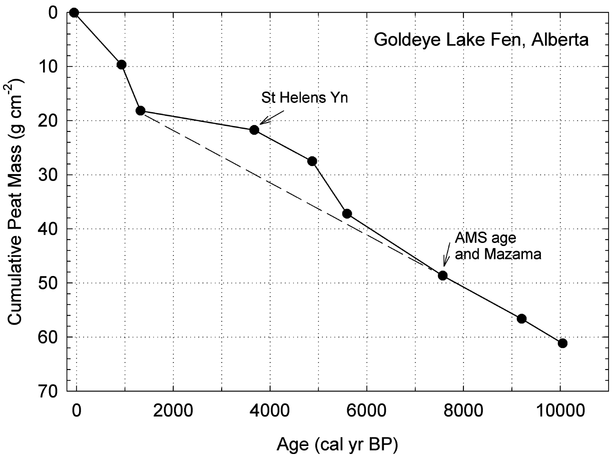

Figure 5. Age versus cumulative peat mass plot at Goldeye Lake Fen, Alberta. The same date points are used as in Figure 4. The curve appears convex during the middle of the core (5500–1300 cal BP)

years) has high debris and wood fragments, with few *Scorpidium* macrofossils. *Scorpidium* tends to increase after deposition of both the Mazama and St. Helens tephras.

DISCUSSION

Peat Accumulation Patterns of Continental Fens versus Bogs

Goldeye Lake Fen shows a convex depth–age curve during the period of 7500–1300 cal BP, as constrained by four AMS ^{14}C dates and ages of known tephra deposition (Figure 5). This convex pattern is in contrast with the concave age–depth curves that often characterize oceanic raised bogs (Clymo 1984; Clymo and others 1998). A similar convex-shaped curve has been clearly documented at a nearby rich-fen site (UPF) (Yu and others 2003a) as well as other sites in the region, including Slave Lake bog and Muskiki fen (Table 2). Yu and others (2003a) modeled the possible causes of such a pattern and argued that the convex pattern occurred in continental peatlands because of the limited availability of water and nutrients and a subsequent long-term decrease in the rate of peat addition (PAR) to the catotelm. This decreasing PAR likely resulted from autogenically induced changes in local hydrology and nutrient availability, which were particularly pronounced in the moisture-limited climate of the region and in peatlands that have strong groundwater influences (Damman 1986; Glaser and others 1997; Yu and others 2003a).

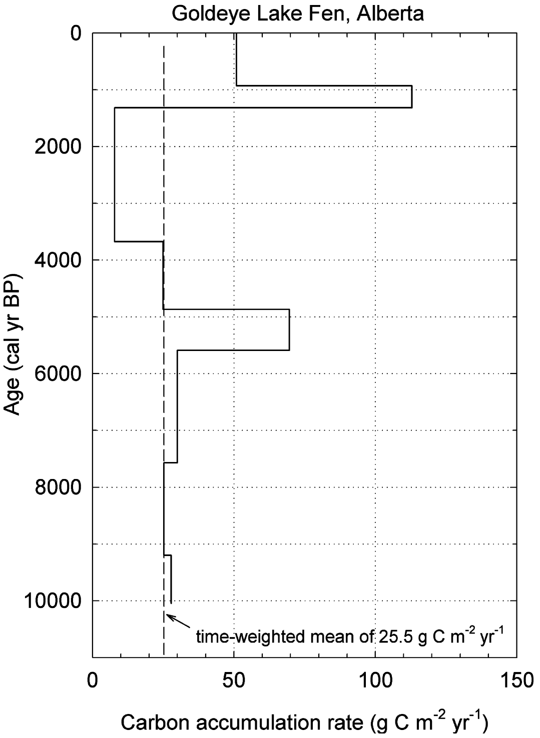

Figure 6. Carbon accumulation rate at Goldeye Lake Fen, Alberta. The apparent rates were calculated as cumulated carbon divided by the time span (bracketed by two dates). The vertical dashed line indicates time-weighted mean of 25.5 g C m^{-2} y^{-1}.

If we assume that the basal ages and cumulative peat mass at a suite of fen or bog sites can be used to capture the regional pattern of temporal peat accumulation, comparisons of these records from western Canada (Table 2) indicate that continental peatlands tend to show a convex cumulative mass–age curve (Figure 8). Obviously, the difference in hydrological and climatic conditions at individual sites would have caused a more complex pattern than was actually observed. Peatlands in western Siberian lowlands also tend to show convex patterns (Turunen and others 2001), as do sedge-dominated peatlands in the eastern Tibetan Plateau (Hong and others 2003; Yu 2006). Finally, fens tend to be older than bogs, at least for fens in the Rocky Mountain Foothills, and fens of the same ages contain more carbon than bogs (Figure 8, and Table 2) in western Canada.

Fens are probably much more important than bogs in the carbon dynamics of northern peatlands in western North America, given that they have accumulated more peat and are more spatially extensive. Also, the fact that fens tend to be more sensitive to climate and hydrological changes (Hilbert and others 2000; Beilman and Yu 2002) implies that fens would

Table 2. Comparison of Cumulative Peat Mass and Ash-free Bulk Density at Different Continental Peatlands in Western Canada

Site No.	Site Name	Latitude; Longitude	Peatland Type	No. of ^{14}C Date	No. of Bulk Density Data	Period (cal y)	Cumulative Peat Mass (g/cm^2)	Mean Ash-free Bulk Density (g/cm^3)	Apparent Rate (g C m^{-2}y^{-1} (range)[a]	Reference
1	Goldeye Lake, AB	52°27°′N; 116°12′W	Rich fen	6	351 (293)	10,048 (8000)	61.2 (51.5)	0.176	25.5 (7.8–113)	This paper
2a	Muskiki, AB, – core 1	52°50′N; 116°51′W	Rich fen	4	N/A	9500	57.3	0.155	31.2 (24.7–39.2)	Kubiw and others 1989
2b	Muskiki, AB – core 2	52°50′N; 116°51′W	Rich fen	4	N/A	8600	49.7	0.138	29.9 (18.0–53.4)	Kubiw and others 1989
2c	Muskiki, AB – core 3	52°50′N; 116°51′W	Rich fen	5	N/A	10,190	73.8	0.162	37.5 (22.7–63.3)	Kubiw and others 1989
3	Upper Pinto, AB	53°35′N; 118°01′W	Rich fen	20	397	8020	50.3	0.127	31.1 (7.2–182.5)	Yu and others 2003a
4	Mariana Lake Site 12	55°54′N; 112°04′W	Poor fen	5	21	7000	37.8	0.068	33.6 (7.0–70.6)	Nicholson and Vitt 1990
5	Slave Lake, AB	55°01′N; 114°09′W	Bog	5	34	9260	43.3	0.124	19.7 (13.6–34.9)	Kuhry and Vitt 1996
6	Legend Lake, AB	57°26′N; 112°57′W	Bog	3	12	8790	15.1	0.129	8.0 (5.0–12.9)[b]	Kuhry 1994
7	Buffalo Narrows, SK	55°56′N; 108°34′W	Bog	3	17	8690	22.4	0.133	12.0 (10.2–14.1)[b]	Kuhry 1994
8	Mariana Lake, Site 16	55°54′N; 112°04′W	Bog	3	11	7550	29.7	0.152	20.4 (18.7–22.3)	Nicholson and Vitt 1990
9	Wathaman, SK	56°57′N; 103°34′W	Bog	2	28	4980	22.2	0.08	22.8 (20.0–25.6)	Kuhry 1994
10	La Ronge, SK	54°48′N; 105°16′W	Bog	2	16	4040	14.7	0.093	17.5	Kuhry and others l992
11	Beauval, SK	54°40′N; 107°49′W	Bog	2	17	2970	16.1	0.096	24.1 (18.7–35.2)	Kuhry 1997
12	Gypsumville, MB	51°46′N; 98°30′W	Bog	1	15	1700	11.3	0.076	34.5[c]	Kuhry 1997

N/A, not available

[a] *Time-weighted means for Goldeye, Upper Pinto and Muskiki fens, and as reported in reference cited for Slave Lake Bog*

[b] *Fires occurrence (Kuhry 1994)*

[c] *Apparent high rate is likely due to the very young age of the core (experienced decomposition for a short period of time)*

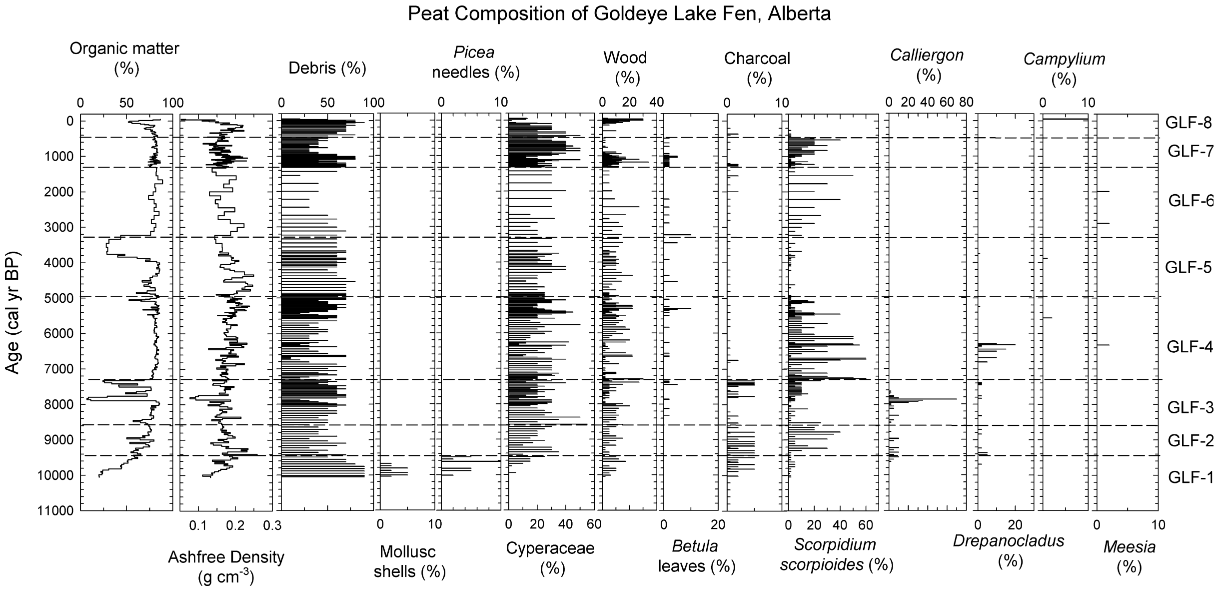

Figure 7. Plant macrofossils at Goldeye Lake Fen, Alberta. Also shown are organic matter and ash-free bulk density on an age scale.

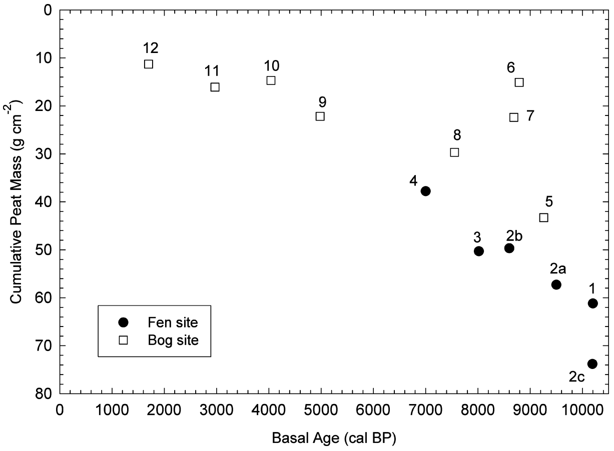

Figure 8. Cumulative peat mass of continental fens and bogs in western Canada. See Table 2 for information and references pertaining the individual sites. Fens tend to be older and accumulate more peat than bogs do, and both fens and bogs seem to show "convex" accumulation trajectories at a regional scale. For bogs, that succeeded from fens, the age for the bog base rather than basal peatland was used.

play a more important role in determining the carbon budget of boreal forests under projected conditions of future climate change.

Disturbance, Climate Variation, and the Peat Accumulation

The lowest rate of peat accumulation at GLF occurred from approximately 4000 to 1300 cal BP, as indicated by several plots from different perspectives (Figures 3–6). Figure 5 suggests that this fen almost reached its growth limit after the St. Helens tephra deposition; thus, the tephra deposition itself might have played a role by altering local hydrology. Similarly very slow UPF peat accumulation occurred at UPF from 4100 to 1500 cal BP (Yu and others 2003a) (Figure 4B). What could have caused this slowdown of carbon accumulation in peatlands within this part of western Canada? It appears that the slowdown may have been related to regional climate and peatland developmental history. Various paleoclimate studies in Alberta and nearby regions have indicated that there was a warming early in the Holocene at about 11,500 cal BP, a dry period from 10,000 to 6000 cal BP, and a cooling and moist trend after 6000 cal BP (Schweger and Hickman 1989). Zoltai (1993) documented the simultaneous occurrence of permafrost initiation and expansion around 4000 cal BP in northern Alberta, owing to "neoglacial" climate cooling. Many peatlands shifted from fens to bogs around the same time elsewhere (for example, Lavoie and Richard 2000). Peatlands in western Canada show slowdown in the increase of carbon stock during the last 3000 years (Vitt and others 2000). It appears that the low rate of carbon accumulation in western Canada was a widespread phenomenon (Table 3).

The abrupt transition at the end of the period of slow accumulation around (1360 cal BP) was likely caused by a combination of site-specific and re-

Table 3. Studies Showing Decline in Carbon Sequestration of Northern Peatlands since about 4000 cal BP

Study Region/Site	Type of Data	Time Intervals of Low Carbon Sequestration (cal BP)	Reference
Regional Synthesis			
North America	418 basal peat dates/peatland initiation and expansion	4000–0	Gorham and Janssens 1992
Southern Finland	71 basal peat dates/peatland initiation and expansion	3000–0	Korhola 1995
West-central Canada	92 or 79 basal peat dates/ peatland initiation and expansion	3000–0	Halsey and others 1998; Campbell and others 2000; Yu and others 2003b
West-central Canada	Carbon storage inventory	3000–0	Vitt and others 2000
Western Siberia lowlands	137 basal peat dates/peatland initiation and expansion	4000–0	Kremenetski and others 2003
Site-specific Studies			
Hay River, Alberta	Permafrost initiation	4000	Zoltai 1993
Siberian peatlands	Peat formation hiatus	4000–0	Peteet and others 1998
Haukkasuo, southeast Finland	LARCA	2500–1500	Mäkilä 1997
Frontenac, Quebec	LARCA	6000–1300; 5000–1500	Lavoie and Richard 2000
Ruosuo, north-central Finland	LARCA	5000–1200	Mäkilä and others 2001
Salyn-Yugan, western Siberia	LARCA/lateral expansion	6200–4200; 4000–800 / 3000–0	Turunen and others 2001
Upper Pinto Fen, Alberta	LARCA	4100–1530	Yu and others 2003a
Goldeye Lake Fen, Alberta	LARCA	4000–1320	This study

LARCA, long-term apparent rate of carbon accumulation, calculated by dividing the peat mass/carbon of an interval by the time span of that interval

gional mechanisms. At UPF, change in species composition shifts the peatland to a new ecological trajectory, whereas at GLF there is no apparent species change at this time. It appears that the abrupt increase in peat accumulation rate could have been induced by gradual changes in ecosystem behaviors.

Implication of the Widespread Slowdown in Carbon Accumulation in Northern Peatlands Beginning around 4000 Years Ago

The slowdown of carbon sequestration due to reduced vertical growth and reduce lateral expansion after approximately 4000 cal BP seems to be a widespread phenomenon in high-latitude peatlands of the northern hemisphere. Several regional syntheses of studies mostly based on basal peat dates from Finland, Siberia, and western Canada suggest that all of these peatlands experienced a marked decline in their rates of formation and expansion (Table 3) (Gorham and Janssens 1992; Korhola 1995; Halsey and others 1998; Campbell and others 2000; Kremenetski and others 2003); in addition a detailed inventory of carbon stock change over time in western Canada indicates that the rate of carbon accumulation slowed after approximately 3000 cal BP (Vitt and others 2000). Also, many site-specific studies found a similar decline in the rate of carbon accumulation at approximately the same time intervals (Mäldlä 1997; Lavoie and Richard 2000; Mäkilä and others 2001; Turunen and others 2001). This slowdown apparently occurred in response to large-scale climatic cooling in high northern latitudes after the Holocene insolation maximum (for example, Schweger and Hickman 1989; Koc Karpuz and Jansen 1992; MacDonald and others 2000).

There appears to be great spatial variability in peatlands' response to this climatic cooling, undoubtedly because peatlands are complex ecosystems whose dynamics are controlled by many biotic and abiotic factors at local and regional scales (for example, Halsey and others 1997; Camill 2000), including regional difference in atmospheric circulation patterns. At UPF, but to a lesser degree at GLF, the peatlands shifted to a new trajectory, triggered by either cooling or autogenically induced drying, after this low-accumulation period;

whereas other peatlands, noticeably in western Siberia, simply stopped accumulating carbon for several millennia (for example, see Peteet and others 1998 and references therein). The fact that these systems, which are often thought to be slow responding, can make abrupt shifts triggered by slow processes indicates show difficulty it is to project the responses of these carbon-rich ecosystems to future climate and environmental changes.

CONCLUSIONS

1. The results of this study further confirm the findings of earlier studies showing that the carbon accumulation patterns of continental peatlands are different from those of oceanic peatlands, presumably due to differences in their peat-accumulating processes. In continental western Canada, fens tend to accumulate more carbon than bogs of the same ages.
2. Because high-resolution data from this and previous studies suggest that the carbon sink potential of northern peatlands has varied dramatically (over more than an order of magnitude) in the past, estimates of the present and projected carbon sink strengths of peatlands need to take this temporal variation into consideration.
3. The slowdown of peat accumulation in the study area over the last 4000 years, caused by climate cooling or autogenically induced drying, indicates that the long-term dynamics of ecosystems can be altered or modified by many local and regional factors. Gradual change may be capable of triggering abrupt shifts and jumps in ecosystem states.

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