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Response of a warm temperate peatland to Holocene climate change in northeastern Pennsylvania

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ABSTRACT

Studying boreal-type peatlands near the edge of their southern limit can provide insight into responses of boreal and sub-arctic peatlands to warmer climates. In this study, we investigated peatland history using multi-proxy records of sediment composition, plant macrofossil, pollen, and diatom analysis from a ^{14}C-dated sediment core at Tannersville Bog in northeastern Pennsylvania, USA. Our results indicate that peat accumulation began with lake infilling of a glacial lake at ~9 ka as a rich fen dominated by brown mosses. It changed to a poor fen dominated by Cyperaceae (sedges) and *Sphagnum* (peat mosses) at ~1.4 ka and to a *Sphagnum*-dominated poor fen at ~200 cal yr BP (~AD 1750). Apparent carbon accumulation rates increased from 13.4 to 101.2 g C m^{-2} yr^{-1} during the last 8000 yr, with a time-averaged mean of 27.3 g C m^{-2} yr^{-1}. This relatively high accumulation rate, compared to many northern peatlands, was likely caused by high primary production associated with a warmer and wetter temperate climate. This study implies that some northern peatlands can continue to serve as carbon sinks under a warmer and wetter climate, providing a negative feedback to climate warming.

Introduction

Northern (boreal and sub-arctic) peatlands contain a large carbon pool of up to ~500 Gt (1 Gt = 10^{15} g), about one-third of the world's soil organic carbon, although they cover only about 3% of the earth's land surface (e.g., Gorham, 1991; Turunen et al., 2002; Yu et al., 2010). Peat accumulation is determined by the processes of production and decomposition of organic matter. The peat accumulation rate varies among peatlands owing to their differences in latitudes, climate, age, and peatland types (Vasander and Kettunen, 2006). Climatic change (variations in temperature and precipitation) and induced changes in hydrology and vegetation would have significant effects on the rate of peat decay, the rate of peat addition into the anaerobic layer (the catotelm), and therefore the peat accumulation rates. Changes between carbon source (peat degradation) and carbon sink (peat accumulation) in peatlands, especially in response to climate change, can significantly affect the global carbon cycle.

Peat accumulates whenever the rate of organic matter production exceeds the rate of decay. Peat accumulation rates increase for two reasons: higher production at the peat surface or lower decomposition. Warmer climate with a longer growing season and/or higher moisture conditions can favor primary production in peatlands (Belyea and Malmer, 2004). A longer growing season and/or higher temperature may result in greater evaporation and a longer seasonal drawdown of water table, which exposes more peat to be oxidized; meanwhile, the decomposition rate is positively correlated with soil temperature (Carroll and Crill, 1997; Frolking et al., 2001). However, wetter climate or higher precipitation would affect the dynamics of hydrology in peat, likely resulting in higher primary productivity and higher water table, which impedes decomposition of peat. A good number of carbon dynamics studies have been focused on peatlands in boreal and subarctic regions (e.g., Ovenden, 1990; Warner et al., 1993; Charman et al., 1994; Botch et al., 1995; Tolonen and Turunen, 1996; Yu et al., 2003; Roulet et al., 2007), whereas responses of peatland carbon dynamics to climatic variations under a warmer climate have been poorly understood (Wieder and Yavitt, 1994).

In this study, we used multi-proxy data derived from peat cores to document the peat accumulation pattern and accumulation rate, peat decomposition, and climate variations at a temperate tree-covered poor fen. The results were compared with data from northern peatlands to evaluate the differences between temperate and boreal peatlands, and to understand the effects of warmer climate on peat accumulation. Climate change was inferred from regional vegetation, local vegetation and moisture conditions using pollen, plant macrofossil, and diatom analysis, to study the influence of climate change on local vegetation change and peat carbon accumulation.

Regional setting and study site

Tannersville Bog (also called Cranberry Swamp) is located near the edge of the Pocono Mountains in Monroe County, Pennsylvania (75°16′W, 41°02′N; Fig. 1), with a surface area of 3 km^2. The

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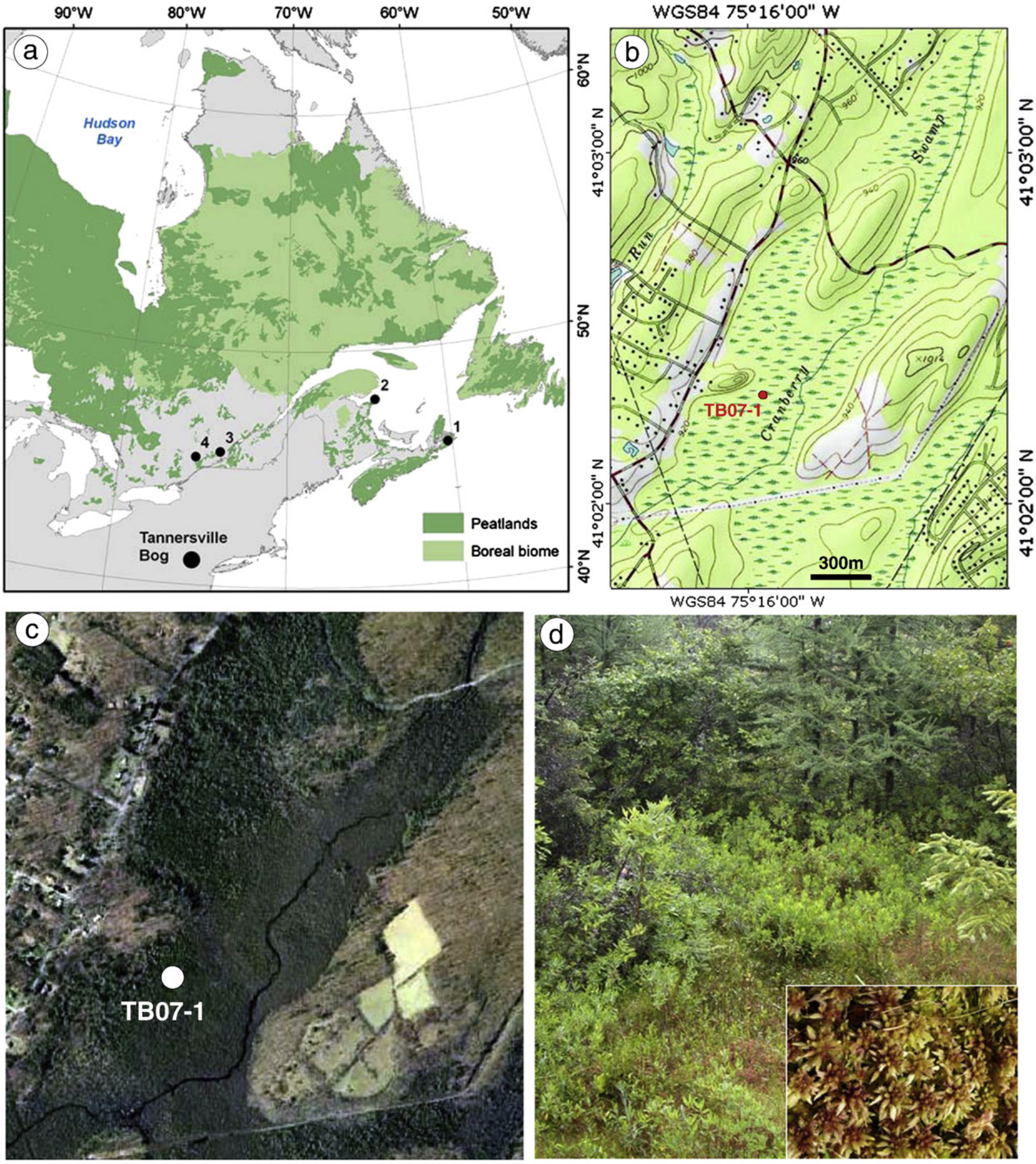

Figure 1. Maps and setting. (a) Map showing the location of Tannersville Bog in Pennsylvania (large circle) related to the distributions of boreal biome and northern peatlands in northeastern North America (map modified from Yu et al., 2009). The peatland areas (dark green) represent regions with abundant peatlands (≥5%; Tarnocai et al., 2002). Other carbon accumulation sites are: (1) Fourchou, Nova Scotia (Gorham et al., 2003); (2) Miscou, New Brunswick (Gorham et al., 2003); (3) Mirabel Bog, Québec (Muller et al., 2003); and (4) Mer Bleue, Ontario (Roulet et al., 2007). (b) Topographic map showing the coring location of core TB07-1 in Tannersville Bog (also called Cranberry Swamp); (c) air photo of Tannersville Bog (from Google Earth Image); and (d) ground photo of Tannersville Bog, Pennsylvania, with inset showing ground layer dominated by peat mosses (*Sphagnum*).

bedrock in the region consists of gently dipping Paleozoic age (570–225 Ma) strata containing sandstones and shales; during the Pleistocene the landscapes were eroded by advancing glaciers and covered by glacial deposits (Hirsch, 1977). Tannersville Bog was occupied by a glacial valley before the Holocene and developed by the lake-infilling process (Watts, 1979). The study area has a temperate climate with a mean annual temperature of ~10°C and mean annual precipitation of 1256 mm (Stroudsburg weather station, about 10 km from Tannersville Bog). Tannersville Bog is located in the extreme warm end of climate space for northern peatlands (Fig. 2; Yu et al., 2009).

The upland vegetation around Tannersville Bog is mostly secondary oak (*Quercus* spp.) forest. *Pinus rigida* (pitch pine) is present locally, and large *Fagus* (beech) occurs generally in the Pocono Mountains (Gehris, 1964; Watts, 1979). Open areas in the middle of Tannersville Bog are dominated by *Sphagnum* (mostly *S. magellanicum*) with patches of *Vaccinium macrocarpon* (cranberry), *Ledum groenlandicum* (Labrador tea), and *Chamaedaphne calyculata* (leatherleaf). Dominant trees are *Picea mariana* (black spruce) and *Larix laricina* (tamarack) rooted in hummocks of *Sphagnum* moss. Tannersville Bog is one of the southern-most (41°N) low-altitude (277 m above sea level) *Sphagnum*-dominated poor fens along the

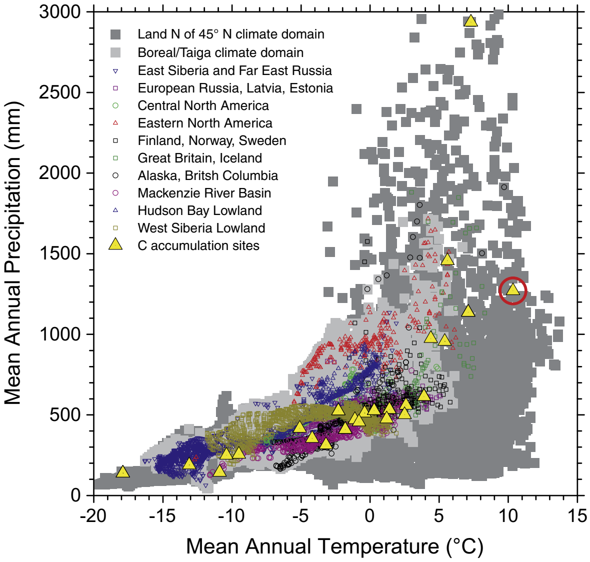

Figure 2. Mean annual temperature–mean annual precipitation climate space of northern peatlands in different peatland regions (small symbols) of northern high latitudes, in the context of boreal biome and all land area north of 45°N latitude. Large triangles show the 33 peatland sites with carbon accumulation data as in Yu et al. (2009). Tannersville Bog is located at far right with annual temperature of 10°C and annual precipitation of 1200 mm (red circle).
Figure modified from Yu et al. (2009).

eastern seaboard in North America (Fig. 1), and one of the Nature Conservancy's first preserves.

Tannersville Bog is fed mainly through precipitation and surface water (Luebbe, 2007). Although it is called "bog", it is actually an acidic poor fen with a pH of ~5. Cranberry Creek, a first-order stream, flows through Tannersville Bog. The water discharge and the flux of dissolved organic carbon (DOC) in Cranberry Creek are greatest from summer into early-fall and generally vary with average air temperature (Luebbe, 2007). In 2006, the DOC concentration ranged from 3 to 23 mg/L in Cranberry Creek, with an annual DOC flux of 12.2 g m^{-2} yr^{-1} (Luebbe, 2007).

In terms of species composition and ecosystem processes, Tannersville Bog is similar to many boreal peatlands, especially forested peatlands in North America. In many boreal regions tree-covered peatlands are a dominant type of peatland. For example, in western Canada 64% of peatlands are treed (Vitt et al., 2000). Despite the same tree and shrub species on these peatlands, these woody plants are much larger and presumably grow more rapidly at Tannersville Bog (see Fig. 1d) than in boreal peatlands. These similarities and differences allow us to examine and compare the outcomes of natural experiments that have been carried over the Holocene in these peatlands under different climates. Our paleo-record will provide useful insight into understanding possible responses of northern peatlands to a warm climate, just as warming experiments in the laboratory and field would provide similar insight into evaluating the sensitivity of these C-rich ecosystems to climate change.

Materials and methods

Field core collection

A 1073-cm sediment core (TB07-1) was collected on 24 March 2007 at Tannersville Bog (coring location coordinates: 41°2.29′N, 75°15.95 W at an altitude of 277 m above sea level), about 10 m away from boardwalk west of the Cranberry Creek. The top 183 cm were recovered using a 10.2-cm-diameter modified Livingstone piston corer (Wright et al., 1984), and lower sediments were collected using a 5-cm-diameter modified Livingstone piston corer. Core segments, mostly 100 cm long, were extruded in the field and wrapped with plastic wrap and stored in polyvinylchloride pipe during transportation to the laboratory, where they were stored at 4°C in a cold room. There was minimal core compression observed during coring.

Laboratory analyses

AMS (accelerator mass spectrometry) radiocarbon analysis on hand-picked plant macrofossils was used to date the peat core. Macrofossils were washed by water, and only those from non-aquatic plants (e.g., *Sphagnum* stems and leaves, Ericaceae leaves, charcoal, or ligneous non-root plant fragments) were used for dating to avoid possible hard-water effect (as some aquatic plants take up bicarbonate dissolved from limestone). AMS samples were analyzed at the W. M. Keck Carbon Cycle Accelerator Mass Spectrometry Laboratory (KCCAMS) in the Department of Earth System Science at the University of California, Irvine. Thirteen peat samples from selected 1-cm-thick slices at approximately 100-cm sampling intervals were submitted for AMS radiocarbon dating, of which twelve radiocarbon dates were obtained (one sample was too small to produce a date). Radiocarbon dates were calibrated with IntCal04 data set (Reimer et al., 2004) using the program Calib v5.01 (Stuiver et al., 1998). One of the twelve radiocarbon dates at depth of 375–376 cm (Table 1) was rejected, due to slight dating reversal (Fig. 3). The eleven accepted calibrated ages were used in the age-depth model using a cubic polynomial regression curve (Fig. 3). All the regression coefficients are statistically significant ($p < 0.0001$). On the basis of this age model, the temporal sampling resolution ranges from 4 to 18 yr for each

Table 1
AMS radiocarbon dates obtained from core TB07-1 at Tannersville Bog, Pennsylvania.

Depth (cm)	Material dated	AMS lab no.[a]	^{14}C yr BP	Calibrated yr BP[b] (2σ range)
99–100	Needles, Ericaceae leaves, woody fragments	38081	340 ± 30	395 (326–473)
199–200	Ericaceae leaves, woody fragments	38082	1250 ± 30	1218 (1170–1265)
235–236	Ericaceae leaves, woody fragments, seed	42064	1540 ± 25	1439 (1370–1519)
299–300	Ericaceae leaves	38083	2010 ± 30	1959 (1923–1995)
375–376[c]	Ericaceae leaves, needles, woody fragments, sedge seed	42065	1535 ± 25	1420 (1381–1509)
498–500	Ericaceae leaves, woody fragments, sedge leaves	38084	4305 ± 40	4857 (4836–4877)
598–600	Ericaceae leaves, woody fragments, sedge leaves	38085	5555 ± 50	6349 (6299–6398)
698–700	Ericaceae leaves, woody fragments, sedge leaves	38086	7320 ± 80	8107 (8018–8196)
711–713	Peat	42066	7365 ± 25	8183 (8046–8307)
799–800	Ericaceae leaves, woody fragments, sedge leaves	38087	7420 ± 40	8252 (8185–8318)
898–900	Ericaceae leaves, woody fragments, sedge leaves	38088	8910 ± 50	10,047 (9916–10,178)
1013–1014	Ericaceae leaves, woody fragments, sedge leaves	38089	9565 ± 40	10,913 (10,745–11,080)

[a] AMS ^{14}C dates were measured in KCCAMS UCI.
[b] Calibrated ages are the median of 95% probability.
[c] Date at depth of 375–376 cm was rejected and not used in the age model.

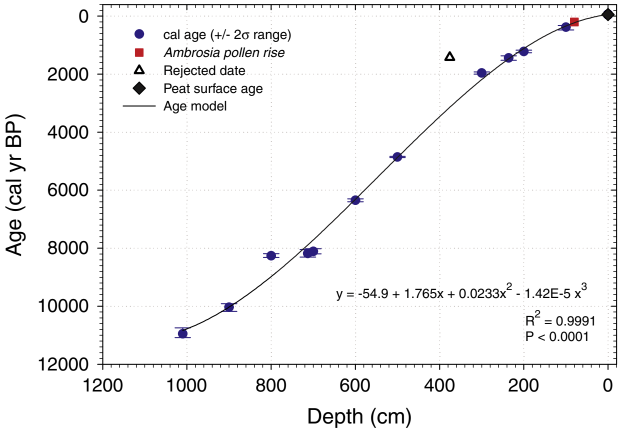

Figure 3. Age–depth model of core TB07-1 from Tannersville Bog, Pennsylvania based on a cubic polynomial regression of calibrated ages and the surface age.

contiguous 1-cm interval. A time scale based on this age model is used in the following discussion.

Sequential loss-on-ignition (LOI) analysis was used to estimate the water, organic and carbonate contents of sediments (Dean, 1974; Heiri et al., 2001). Volumetric samples (1.4 cm^3) were selected using a calibrated spoon for LOI analysis from 1-cm-thick slices at 2-cm intervals for the upper 400-cm peat core and at 10-cm interval for the lower 673-cm peat core from Tannersville Bog. Bulk density measurements were calculated using sample volume and dry weight.

A semi-quantitative method for macrofossil analysis following Yu et al. (2003) was used to estimate the relative abundance of plant macrofossils preserved in peat profiles as a proxy of local vegetation changes (Barber et al., 1994). Peat subsamples of approximately 1 cm^3 were taken every other centimeter for the upper 400-cm section and every 20-cm for the lower 673-cm section. Each sample was dispersed into a custom-designed picking tray with channels ("channeled plexiglass template") without chemical treatment and sieving. The macroscopic components are usually composed of recognizable plant remains including *Sphagnum*, brown mosses, herbs (Cyperaceae), ligneous (woody materials from shrubs or trees and charcoals), and unrecognizable fine debris (Yu et al., 2003). The relative abundance of unrecognizable fine debris independently reflects the degree of decomposition of each measured sample. Identification was aided by Lévesque et al. (1988). The plant macrofossil remains were quantified on a percentage basis. In this study, we did not attempt to identify macrofossils to a lowest possible taxonomy level quantitatively, but this approach allows us to derive a semi-quantitative data set at a much higher temporal resolution in supporting our discussion on the relationship between carbon accumulation and environment on the peatland.

Pollen analysis was conducted on 1-cm-thick slices at 10-cm interval for the upper 340-cm section. The preparation method for samples from this section follows the procedure in Booth (2007), which involves the removal of large *Sphagnum* remains and collection of materials between 355 and 15 μm in size. The lower 730-cm section was analyzed at 20-cm intervals with a modified standard method for pollen preparation (Fægri and Iversen, 1989), including HCl, KOH and acetolysis. *Lycopodium* spore tablets were added to each pollen sample to calculate pollen concentration. Pollen and spores were identified and counted following the illustrated key by McAndrews et al. (1973), aided by reference collections at Lehigh University Paleoecology Laboratory.

Diatoms represent a group of algae whose siliceous valves are usually well preserved in sedimentary deposits. Diatom growth is optimal in open water and in low acid environments, so its abundance indicates the moisture conditions and types of peatlands (Smol, 1990). We estimated the concentration of diatoms, without identifying to specific taxa, on pollen slides from the upper 340-cm section (without acetolysis or other acid treatment). The calculation of diatom concentration was performed using the same spike as described above. We assume that diatom dissolution and selective preservation were minimal during the last 3000 yr.

Data analysis and carbon accumulation calculations

For the core TB07-1 from Tannersville Bog, eight calibrated radiocarbon ages and 232 ash-free bulk density measurements over the last 8.2 ka were used to calculate cumulative peat mass and apparent peat accumulation rates. An exponential peatland growth model (Clymo, 1984), in the form of $x = \frac{p}{\alpha}(1-e^{-\alpha t})$, was used to estimate long-term peat-addition rates and catotelm decomposition rate at Tannersville Bog. The models were fitted for different time periods to evaluate the difference in peat-addition rate (p) and decomposition rate (fractional mass loss rate; α) with time (t) and cumulative peat mass (x).

Long-term apparent rates of carbon accumulation range were calculated from ash-free bulk density measurements (Fig. 4e) and peat vertical growth rates (Fig. 3) using the average carbon content of peat organic matter (51.8%) derived from peatlands in continental western Canada (Vitt et al., 2000). We acknowledge possible errors in carbon accumulation calculations, as carbon content of peat likely varies along the core due to differences in botanical composition and degree of decomposition. However, we believe that this caveat would not affect our discussion and conclusions.

Results

Sediment lithology and composition

The peat water content of core TB07-1 ranges from 90% to 75% (Fig. 4a). The organic matter (OM) content increases from <30% at the base of the core to ~50% from 9 to ~1.4 cal ka BP, reaching the highest value (~96%) in the last 1.4 ka (Fig. 4b). The remaining dry material consists of carbonate and non-carbonate silicate minerals. The carbonate content of the dry material is lowest in the last 1.4 ka, and increases to 10% between ~3.4 and 1.4 cal ka BP (Fig. 4c). Non-carbonate material (mostly silicate) is lowest in last 1.4 ka, but highest at the base of the core (Fig. 4d). The ash-free (OM) bulk density ranges from 0.03 to 0.11 g/cm^3, with an average of 0.065 g/cm^3 (Fig. 4e). The basal sediments have relatively lower values for water and ash-free bulk density, attributable to low organic matter content and high non-carbonate minerals.

Macrofossil record and local vegetation

Six plant macrofossil zones were identified by visual inspection of dominant components (Fig. 5). The macrofossil results show that the basal sediments (11–9 cal ka BP) contain filamentous green algae, woody materials and charcoals with low abundance of brown moss leaves, suggesting an open-water environment (zone M-1; Fig. 5). Zone M-2 (9–5 cal ka BP) is dominated by brown moss leaves and stems with low abundance of woody materials and Cyperaceae leaves, suggesting a rich fen wetland, which is consistent with high carbonate (~5%). Zone M-3 (5–2.7 cal ka BP) is characterized by decline of brown mosses, almost absence of Cyperaceae and increase in fine organic debris, likely indicating a dry wetland vegetation and great decomposition. Although a wet peatland pool environment would also induce high decomposition, the lack of algae remains in our record at that time suggests that this is less likely. Zone M-4 (2.7–1.4 cal ka BP) shows a recovery of brown moss abundance with a decrease of fine detritus component toward the top of the zone and a return of wet rich fen vegetation, with high carbonate abundance (Fig. 4c). Most brown mosses were from *Drepanocladus*

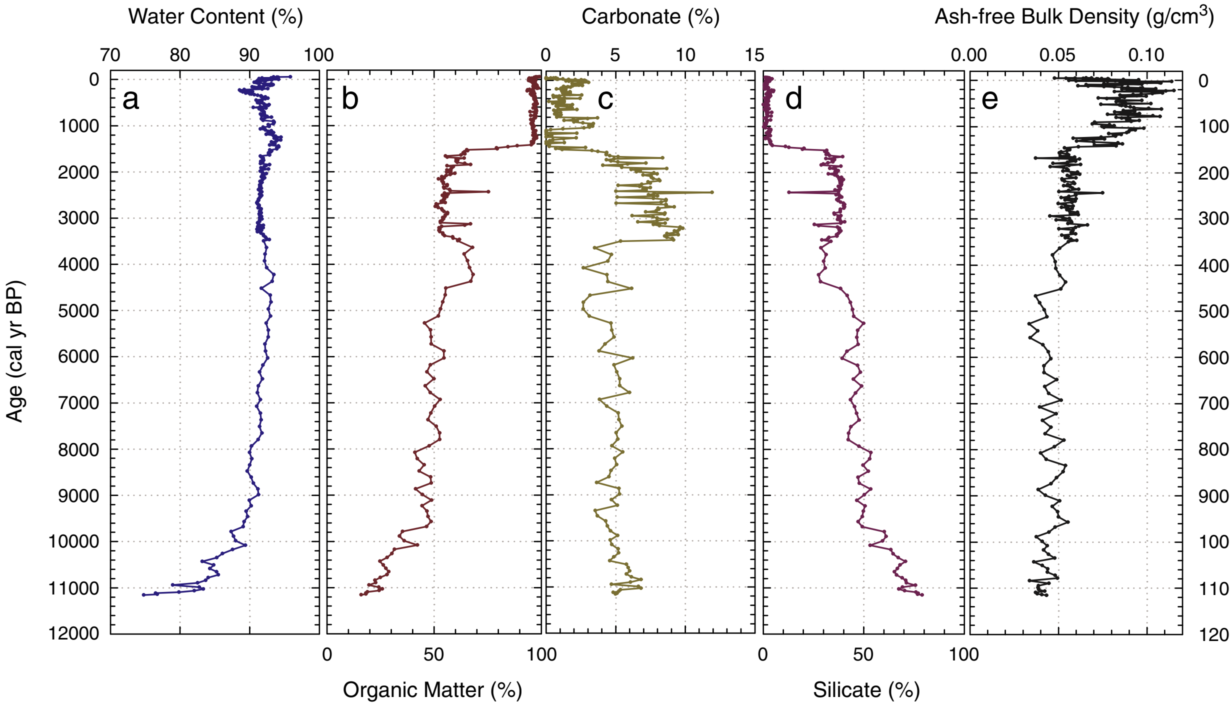

Figure 4. Sediment composition of core TB07-1 from Tannersville Bog, Pennsylvania. (a) Water content; (b) organic matter content; (c) carbonate content; (d) non-carbonate mineral (silicate) content; (e) ash-free (organic matter) bulk density.

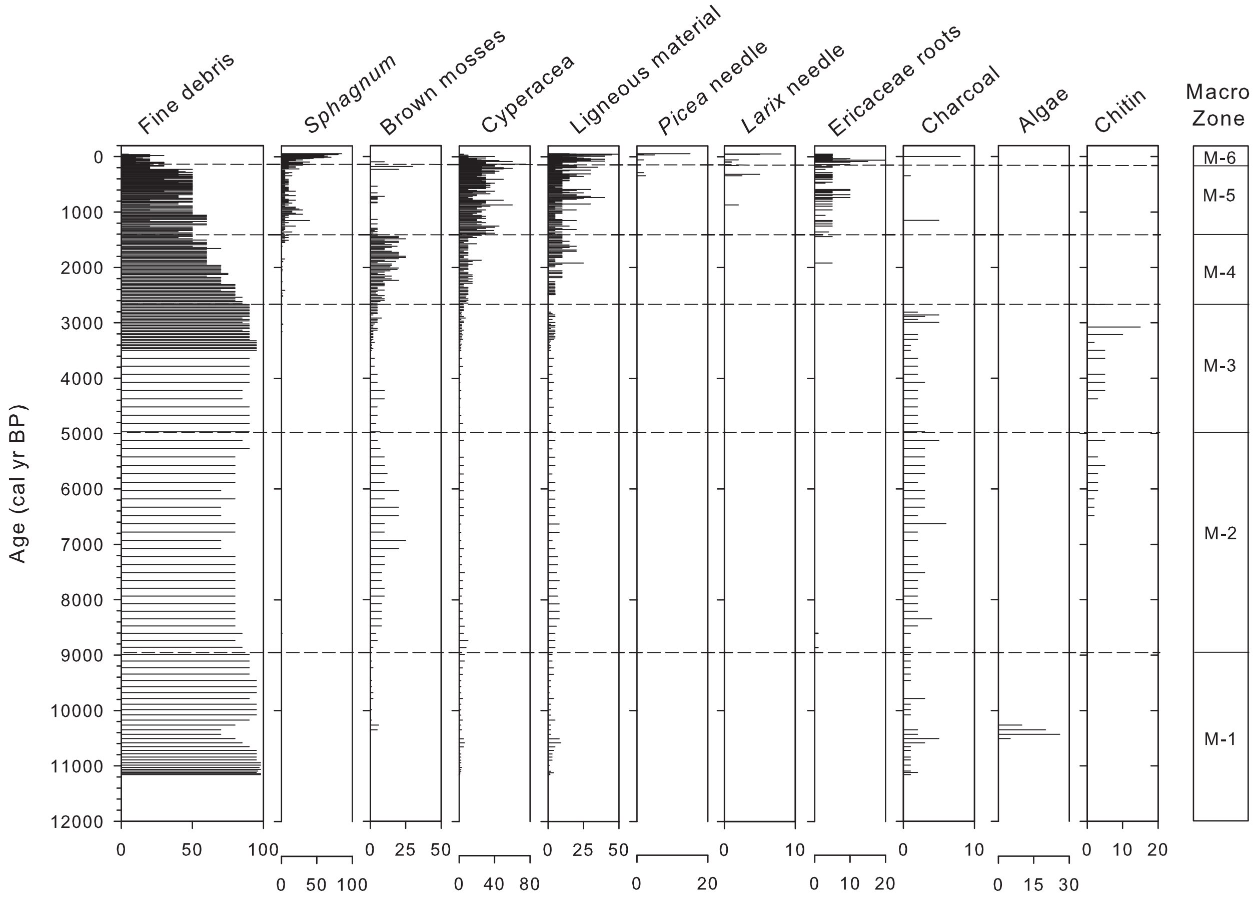

Figure 5. Percentage plant macrofossil diagram of core TB07-1 from Tannersville Bog, Pennsylvania.

spp. There is a major shift of dominant plant macrofossils from zones M-4 to M-5. Zone M-5 (1.4–0.2 cal ka BP) is characterized by the high abundance of Cyperaceae leaves and roots, increasing abundance of *Larix* needles, Ericaceae leaves and roots, and woody fragments, continuous presence of *Sphagnum* leaves, and the absence of brown mosses. Zone M-6 (0.2 cal ka BP—present) is dominated by *Sphagnum* leaves and stems, *Picea* and *Larix* needles, Ericaceae leaves and roots, and decreased Cyperaceae leaves and roots. In this zone, brown moss leaves are only present in a few samples dated to ~250–200 cal yr BP. Microscopic charcoal pieces are present in all five zones, except zone M-4, and tend to be more abundant and continuous before 3 cal ka BP.

Pollen record and regional vegetation

Pollen diagram was divided into six pollen zones based on CONISS dendrogram using the pollen types with a minimum abundance >2% (Figs. 6 and 7). The basal zone P-1 (11.1–11 cal ka BP) is dominated by *Pinus* (>50%). This zone represents the end of the spruce (*Picea*) — dominated woodland before the Holocene in this region (Deevey, 1939; Watts, 1979). Zone P-2 (11–9.8 cal ka BP) corresponds to a mixed forest at the very early Holocene. Zone P-3 (9.8–4.9 cal ka BP) is dominated by *Quercus* pollen (50–60%) and *Tsuga* (~20%), with <10% of *Pinus*, *Betula*, *Fagus* and others, representing a mixed oak forest during the early and mid Holocene. High abundance of *Equisetum* in the early part of zone P-3 suggests a wet and variable wetland environment. Compared with zone P-3, zone P-4 (4.9–2.9 cal ka BP) is characterized by very low *Tsuga* (<2%), increases in *Pinus* (10–20%) and *Alnus* (~10%), and return of *Picea* (~5%). In zone P-5 (2.9–0.22 cal ka BP), *Tsuga* pollen recovered to 10%, associated with increase in *Picea*, *Carya*, Ericaceae, *Nuphar*, *Salix*, Poaceae pollen (Cai, 2008) and in *Sphagnum* spores. The very top zone P-6 (the last 270 yr) is characterized by a sudden increase in *Ambrosia*, Ericaceae and Cyperaceae pollen. *Sphagnum* spores are present almost throughout the profile with noticeable increase in zones P-5 and P-6 (the last 3000 yr). The pollen concentration calculated for each zone ranges from 20,000 to 500,000 grains/cm^3 (Fig. 6).

Diatom abundance and local environment

We have diatom data only for the last 2.7 ka. Diatoms have the highest concentration of up to 8×10^6 valves/cm^3 in the lower part of the analyzed section (2.7–1.4 cal ka BP; Fig. 8). From 1.4 to 0.23 cal ka BP, diatoms were lower than 8000 valves/cm^3 or even absent. There were no diatoms observed in the upper part of the sediment spanning the last 230 yr. The high abundance of diatoms corresponded with the high abundance of brown moss macrofossils and the high carbonate content at 2.7–1.4 cal ka BP, suggesting wet or even open-water environments (Fig. 8), consistent with our interpretations based on plant macrofossils.

Peat accumulation pattern and carbon accumulation rates

The cumulative peat mass-age profile over the last 8.1 ka, based on eight calibrated ^{14}C ages and 232 ash-free bulk density measurements, shows a concave curve (Fig. 9). Fitted curves from different intervals of peat deposits and estimated parameters are shown in Table 2. The apparent carbon accumulation rates calculated using the eight AMS radiocarbon dates ranges from 13.4 to 101.2 g C m^{-2} yr^{-1} with a clearly increasing trend in the last 8 ka (Fig. 10a). The young peat has a much higher apparent carbon accumulation rate compared to old peat and non-peat sediments. The long-term (time weighted) average rate of carbon accumulation for the core TB07-1 from Tannersville Bog is 27.2 g C m^{-2} yr^{-1} for the last 11.1 ka, or 27.3 g C m^{-2} yr^{-1} for the last 8.2 ka.

Discussion

Holocene peatland development at Tannersville Bog

Tannersville Bog was a lake after the ice retreat and before the development of a peatland, as indicated by the abundant silicate (Fig. 7) and the presence of aquatic fossils (e.g., green algae) (Fig. 5). A gradual increase in organic matter content and presence of brown

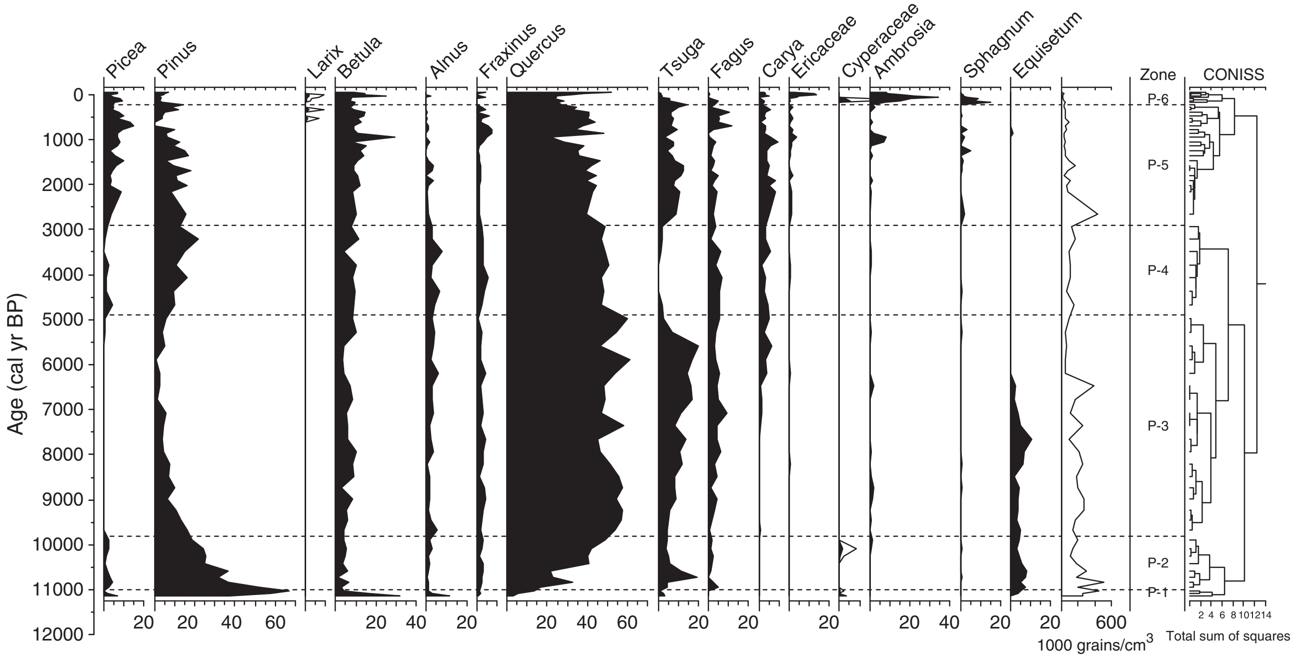

Figure 6. Summary percentage pollen diagram of core TB07-1 from Tannersville Bog, Pennsylvania.

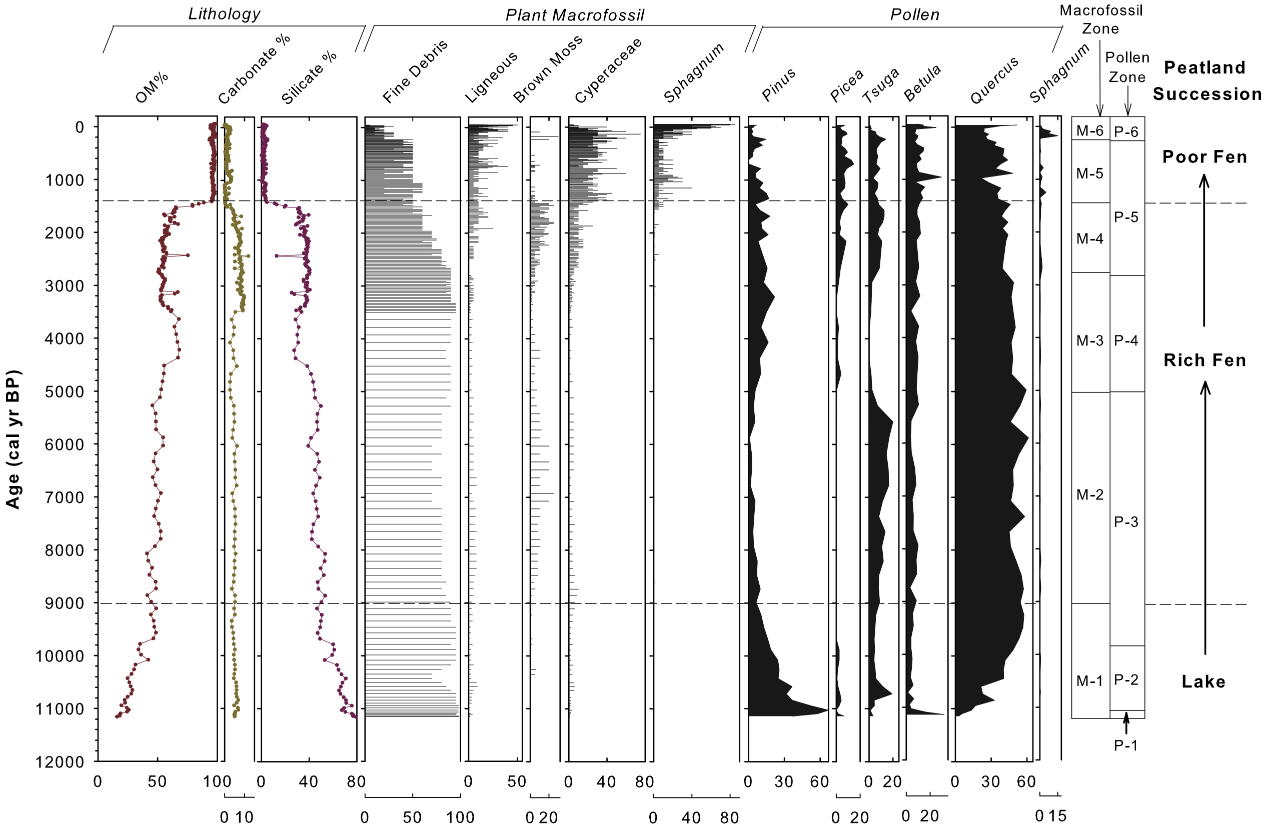

Figure 7. Correlation of sediment composition, plant macrofossil and pollen records during the Holocene from core TB07-1 from Tannersville Bog, Pennsylvania.

mosses from 11 to 9 ka (Fig. 7) suggest an increase in primary productivity of aquatic plants. Brown mosses started to increase at 9 cal ka BP, probably suggesting the expansion of rich fen. Previous studies at the site show similar early development sequence but with different timings. For example, Gehris (1964) and Hirsch (1977) observed that the peat is underlain by gray silty clay over bedrock at Tannersville Bog. Watts (1979) indicated that the lake-infilling process started shortly after 8 cal ka BP, and the "bog" (poor fen) environment had been established at about 4 cal ka BP.

The continuous dominance of brown mosses and the absence of *Sphagnum* in the macrofossil record from 9 to ~5 cal ka BP suggest a stable rich fen environment at Tannersville Bog. The high hemlock and

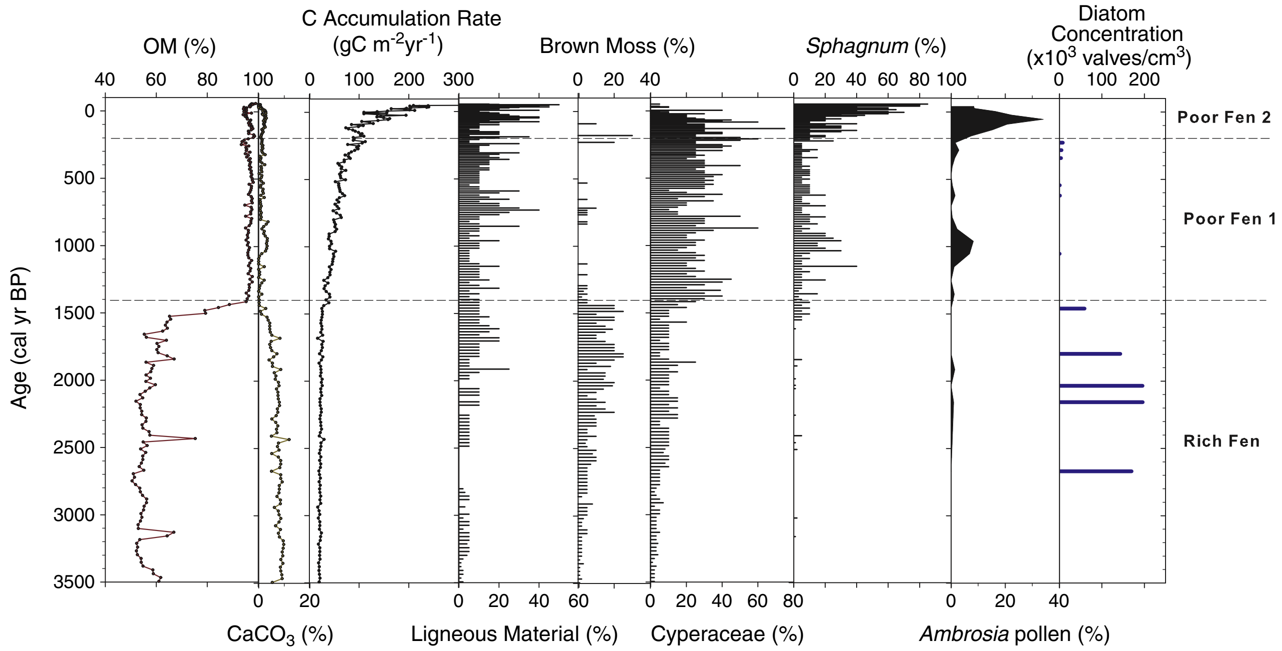

Figure 8. Close up of major lithologic change in organic matter and carbonate content, apparent carbon accumulation rate, selected plant macrofossils, *Ambrosia* (ragweed) pollens, and diatom concentration from core TB07-1 at Tannersville Bog for the last 3500 yr.

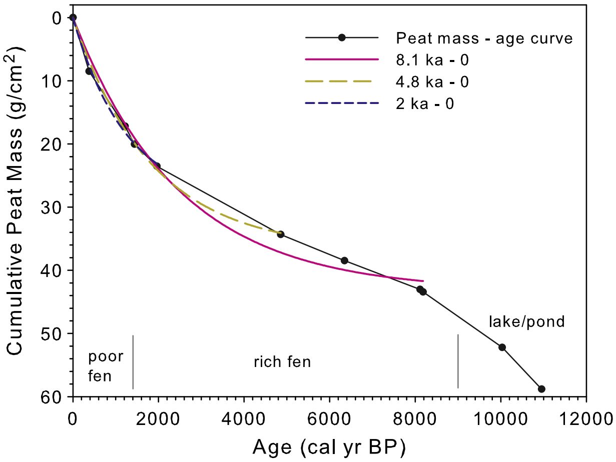

Figure 9. Cumulative peat carbon mass-age profile and fitting curves for TB07-1 from Tannersville Bog. The fitted values of parameters are listed in Table 2.

Table 2
Estimates of long-term peat accumulation parameters (peat-addition rate and decomposition rate) using a single exponential decay model.

Age range (cal ka BP)	Peat-addition rate (p; g m^{-2} yr^{-1})	Decomposition rate (α; yr^{-1})
8.1–0	174.4	0.0004
4.8–0	198.9	0.00054
2–0	232.6	0.00079

low pine pollen abundance suggest a wet regional climate, consistent with the climate history in New England (Shuman et al., 2004). Brown moss macrofossils decline and maximum fine debris (detritus) (>90%) from ~5 to 2.7 cal ka BP (Fig. 7) suggest increased decomposition, likely during a dry climate interval. This time period also corresponded with the minimum hemlock pollen from 5.5 to 3 cal ka BP at Tannersville Bog. The decline of hemlock pollen has been documented in many studies (e.g., Foster et al., 2006), which corresponded to a dry time period as inferred from low lake levels in northeastern North America (e.g., Yu et al., 1997; Shuman et al., 2004). Our peat record along with pollen data supports the notion that the mid-Holocene hemlock decline was related to a dry climate. At our site, slight increases of *Alnus* (alder) and *Fraxinus* (ash) pollen could reflect a local reaction of the vegetation to better drained soil conditions. After 2.7 cal ka BP, brown mosses increased to a level similar to pre-6 cal ka BP, along with increase in the abundance of sedges and high carbonate content since 3.5 cal ka BP, both suggesting a wet environment and climate.

The transition from a rich fen to a poor fen at ~1.4 cal ka BP was documented by a sharp decrease in brown mosses, increases in sedges, and continuous presence of *Sphagnum* macrofossils. This transition was also associated with a decrease in carbonate content, suggesting an environment with lower pH, though less input of groundwater and nutrients to the peatland is also a possible reason (Figs. 7 and 8). The high organic matter content after the transition at 1.4 cal ka BP mostly reflects reduced input of detrital minerals from the watershed and of biogenic silicate from diatoms (Fig. 8). Lower abundance of fine debris (<50%) during the poor fen phase is due to the young ages of peat and the slow decomposition of *Sphagnum* litters (van Breemen, 1995; Verhoeven and Liefveld, 1997). Watts (1979) showed a very similar shift in organic matter content at about 1.4 cal ka BP at Tannersville Bog.

Autogenic and allogenic controls of peatland transitions

It has been suggested that autogenic processes play a major role in the development of peatlands, such as a succession from aquatic environment to rich fen, poor fen, and eventually to a *Sphagnum*-dominated bog (Tansley, 1939; Rydin and Jeglum, 2006). However, many paleoecological studies on peatlands show that allogenic factors, such as climate change and human impact, can affect the pattern of change and the timing of the transitions along the general pathway of peatland development (Walker, 1970; Foster, 1984; Campbell et al., 1997; Huber and Markgraf, 2003; Booth et al., 2004). The transition at Tannersville Bog from a rich fen to a poor fen at ~1.4 cal ka BP corresponded with a major lithology change to high organic matter and lower carbonate content as well as a decrease in diatom abundance (Fig. 8), suggesting that the shift could be triggered by allogenic factors such as hydrologic and climatic changes. A dry climate event at ~1.3 cal ka BP has been inferred from low lake levels based on paleomagnetic records at White Lake in northern New Jersey (Li et al., 2007). It is very likely that this dry event was also recorded by the hydrologic change at ~1.4 cal ka BP at Tannersville Bog, because slight age offsets between these two records are within the uncertainties of radiocarbon dating at both sites. Li et al. (2007) suggested that the dry event, with the other three low lake level intervals at about 3.0, 4.4 and 6.1 cal ka BP, is likely a response to the cold periods in the North Atlantic Ocean during the Holocene (Bond et al., 2001). A dry climate at 1.3 cal ka BP probably caused the low level at White Lake and triggered a major ecosystem shift at Tannersville Bog.

The spike of brown mosses at ~200 cal ka BP (AD 1750; Fig. 8) corresponded to the major rise of *Ambrosia* (ragweed) pollen abundance that marks the European settlement horizon in North America (Russell, 1980; Willard et al., 2003). This brief period of wetness on the peatland probably reflected the peatland response to the hydrological change induced by human activities. For example, anthropogenic deforestation in the surrounding watershed could reduce evapotranspiration and increase regional water table (e.g., Campbell et al., 1997; Bunting et al., 1998; Lamentowicz et al., 2007).

Carbon accumulation rates in temperate peatlands

The apparent carbon accumulation rates at Tannersville Bog began to increase ~8 cal ka BP and reached the highest value in the last 400 yr. The long-term average rate of carbon accumulation of 27.3 g C m^{-1} yr^{-1} for the peatland period during the last 8.2 ka at Tannersville Bog is higher than the rates of subarctic and boreal peatlands. For example, in a data synthesis analysis of northern peatlands, Yu et al. (2009) found that Western Canada has the highest Holocene carbon accumulation rate in North American peatlands of 20.3 g C m^{-2} yr^{-1} based on seven sites, while Eastern Canada has a lower rate of 18.4 g C m^{-2} yr^{-1} on the basis of three sites (see Fig. 1a for locations; Fourchou in Nova Scotia, and Miscou in New Brunswick, Gorham et al., 2003; and Mirabel Bog in Québec, Muller et al., 2003; also see Yu et al., 2009). The overall average carbon accumulation rates from boreal, subarctic and arctic peatlands are 18.6 g C m^{-2} yr^{-1} based on 33 sites in the northern hemisphere (Fig. 10b; Yu et al., 2009). Mer Bleue in Ontario, Canada has a mean carbon accumulation rate of 21.9 g C m^{-2} yr^{-1} during the late Holocene (3000–400 cal yr BP) (see Fig. 1a for location; Roulet et al., 2007), which is also lower than Tannersville Bog, despite its young age and relatively southern location.

The high rate of carbon accumulation at Tannersville Bog, compared to many northern peatlands in North America, could result from high primary production, low peat decomposition or both. The significantly higher peat addition rate ($p = 174$–233 g m^{-2} yr^{-1}) and similar or higher peat decomposition rate ($\alpha = 0.0004$–0.00079 yr^{-1}) at Tannersville Bog (Table 2, Fig. 9), compared to those in boreal peatlands ($p = 20$–50 g m^{-2} yr^{-1}, $\alpha = 0.0001$ yr^{-1}) (Clymo, 1984; Yu et al., 2001), indicate that a high primary production is most likely responsible for the high rate of carbon accumulation at Tannersville Bog. The high decomposition rate is also indicated by the constantly high abundance

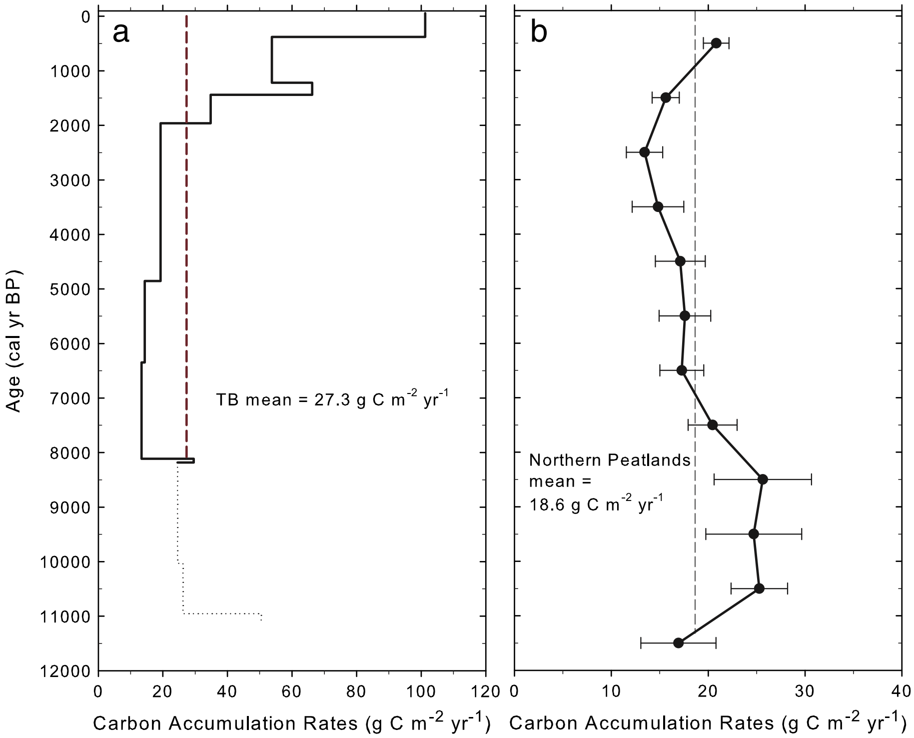

Figure 10. Apparent carbon accumulation rates. (a) Core TB07-1 from Tannersville Bog (non-peat section shown as dotted line); and (b) mean C accumulation rates from northern peatlands (based on 33 sites) and standard errors at 1000-yr bins (modified from Yu et al., 2009). Vertical dotted lines in both plots represent the long-term means. Both Tannersville Bog and all 33 sites in the synthesis curve are plotted on the climate space as yellow triangles in Fig. 2.

of fine debris from macrofossil analysis (Figs. 5 and 7), compared to peatlands in boreal region (e.g., Yu et al., 2003). It has been reported that the net primary production of peatlands in temperate regions is around 1800 g m^{-2} yr^{-1} (Wieder et al., 2006), which is more than three times the estimated production of ~500 g m^{-2} yr^{-1} in peatlands of boreal regions (Carroll and Crill, 1997).

The mean annual temperature at Tannersville Bog is much higher than most boreal peatlands (Fig. 2), which provides a favorable environment for plant growth under a long growing season and short freezing period. Although higher decomposition rates have been expected under higher temperature (Davidson and Janssens, 2006) and observed at Tannersville Bog, high primary production and resultant high peat-addition rate to the catotelm (lower anoxic peat layer) probably overcome the high decomposition, resulting in a high long-term carbon accumulation rate. Furthermore, higher precipitation in this region (Fig. 2) and partially floating nature of the peatland prevent significant water-table drawdown, making carbon accumulation more sensitive to temperature-induced changes in production and decomposition. The observation of high carbon accumulation rate at Tannersville Bog with high temperature and high precipitation implies that some peatlands will continue to serve as carbon sinks in a warmer climate, as long as the minimum moisture condition is maintained.

Conclusions and implication

(1) Peat accumulation at Tannersville Bog began with lake infilling of a postglacial lake at ~9 cal ka BP followed by the establishment of a rich fen dominated by brown mosses. The transition to a *Sphagnum*-dominated poor fen at ~1.4 cal ka BP was likely triggered by a dry climate as supported by independent paleoclimate records in nearby New Jersey. This suggests that both autogenic and allogenic processes are important in peatland formation and transition.

(2) The mid-Holocene hemlock (*Tsuga canadensis*) decline at Tannersville Bog corresponded with the decrease in brown-moss macrofossil abundance and the highest fine organic debris content at ~5–2.7 cal ka BP, suggesting enhanced peat decomposition under a dry climate. This provides new peat-core evidence to support the idea that the mid-Holocene hemlock decline might have been caused by a dry climate across northeastern North America. However, this dry climate event did not trigger a major shift in vegetation and peatland types as occurred at 1.4 cal ka BP, suggesting that ecosystem sensitivity to climate change depends on autogenic processes as well.

(3) The high long-term carbon accumulation rate of 27.3 g C m^{-2} yr^{-1} at Tannersville Bog, as a result of high peat-addition rate of ≥174 g m^{-2} yr^{-1} and high peat decomposition rate of ≥0.0004 yr^{-1}, suggests that high primary production, rather than slow decomposition, plays a major role in rapid carbon accumulation in a warm and wet temperate climate.

(4) The results of this study imply that some northern peatlands may continue to serve as carbon sinks, owning to stimulated plant production under a warm climate in the future, if there is adequate moisture to maintain the peatlands.

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